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Economical Evaluation of a Low-Enthalpy Geothermal Resource Located in an Arid-Zone Area

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Abstract: In this work an economical evaluation that established the viability of a low enthalpy geothermal resource as an energy source in north Africa is presented. The factors considered included the payback period, average rate of return, net present value, and net benefit-cost ratio. The model was based on utilising the energy source to energise four models that comprised thermal equipment consisting of water/air cooled single/half effect lithium bromide water mixture absorption chillers and an R-245fa organic Rankine cycle. These modelled cycles were based on the energy demand for Waddan city a community in southern Libya which has a demand for combined cooling/electricity only or cooling/electricity with district hot water supply. The results revealed that all of the proposed simulated stand-alone models, except the water-cooled half effect chiller, are not economically viable unless they are heavily subsidized or combined with the district hot water supply at least in the winter season.

Key words: Libya, low-temperature geothermal resources, economical analysis, IPSEpro, organic Rankine cycle, absorption chillers.

Nomenclature

<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ORC</td>
<td>Organic Rankine cycle</td>
</tr>
<tr>
<td>PBP</td>
<td>Payback period</td>
</tr>
<tr>
<td>ARR</td>
<td>Average rate of return</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
</tr>
<tr>
<td>NBCR</td>
<td>Net benefit-cost ratio</td>
</tr>
<tr>
<td>TCI</td>
<td>Total capital investment</td>
</tr>
<tr>
<td>CFN</td>
<td>Cash flow net</td>
</tr>
<tr>
<td>r</td>
<td>Discount rate</td>
</tr>
<tr>
<td>NP</td>
<td>The average annual net profit</td>
</tr>
<tr>
<td>PI</td>
<td>Profitability index</td>
</tr>
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</table>

Subscripts

J \quad \text{Time}

1. Introduction

Currently available geothermal heat resources vary in temperature from 50 to 350 °C and can either be dry steam, a mixture of steam and water, or just water. The degree of resource temperature is the main key factor in determining the most suitable type of technology that can be successfully adopted to utilise the energy. During recent years there has been a great interest in small geothermal resources, which can be found practically in every country in the world. These resources are of particular importance in areas with few or none of the conventional energy resources, or in arid zone locations with high ambient temperatures. In addition, the isolated communities located in remote places could greatly benefit from exploitation of any readily available high potential low-temperature geothermal resource. These resources would contribute to solving some local problems, raise living standards and could also motivate local societies to share the world’s concern about producing clean green energy (even at small-scales). They could reduce the growing demand for electrical power generation and elevate the environmental problems of thermal pollution.

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Recently many large industrial countries have taken important decisions to directly subsidize many renewable projects because they have realized the size of the severe damage that energy generation has caused to the climate (current global warming). Based on this fact many projects [1-4] have confirmed the successful operation of absorption refrigeration and binary fluid plants (ORC (organic Rankine cycles) for electricity generation) when powered by low temperature resources (in the range of 70-75 °C) and cooled at low sink cooling temperatures < 15 °C (inlet coolant temperature to the condensers). Since the temperature requirements for absorption cycles fall into the low to moderate temperature range, and there is a significant potential for electrical energy savings and reduction in emission of CO₂, a single/half effect absorption chillers was coupled with a geothermal source for space cooling air-conditioning applications [5]. Binary cycle power plants are also the most common technology for utilizing medium and low temperature geothermal sources for producing electrical power in the range 0.5-5 MW. There are many different technical variations of binary cycle plants including those known as ORC. This cycle can successfully use low-level waste heat from different resources in the range of 70-100 °C but at low cycle efficiencies of 5%-9% [6].

The most economical way to utilize geothermal resources of energy is to use them as a direct powering source for conventional systems such as absorption heating and cooling, direct central heating, hot water supply, or energizing binary cycles for generating electricity e.g. with ORC. However, despite lower annual running costs of geothermal plants, a geothermal project requires a relatively large initial capital investment. More clearly a geothermal power facility consists of wells, pipelines, main plant and occasionally a re-injection systems, which could weigh heavily on investment costs. Therefore, a careful economical analysis must be carried out before launching a project.

To date no attempts have been made to produce an economical appraisal of an absorption cooling or electrical generation using binary fluids, at a source temperature of 73 °C and a cooling sink temperature of 25 °C. The work in this paper was carried out to investigate the economic viability of such a system using various Microsoft Excel modules and a well known software package called IPSEconomy [7]. The thermodynamic modelling results have revealed that the most suitable way to utilize these low-temperature geothermal resources of energy is to use them as a powering source for low temperature heat powered cycles such as water/air cooled single/half effect lithium bromide water mixture absorption chillers and R-245fa organic Rankine cycles. These two cycles can provide cooling, heating and electrical power at acceptable economical limits without causing any damage to the climate.

2. Methodology

The energy source for the proposed cycles was one of four existing artesian wells situated at Waddan city 265 km south of the Libyan north coast. The well identification number is T/2D/0013/0/88 and it is located at global coordinates of $X = 16^\circ09'46''$, $Y = 29^\circ07'06''$ at an elevation of 291 m above the sea level. This is shown as 18 in Fig. 1. The well delivers 114 kg/s of water at a temperature of 73 °C. The proposed absorption refrigeration and ORC cycles were configured to fully utilize the geothermal energy supply. The geothermal water supply first energized the generator of the refrigerator and the evaporator of the ORC units then was further cooled in another heat exchanger to heat water that can be used for domestic heating purposes. For water-cooled cycles, the rejected heat from the absorber and the condenser was carried away by water at an average fixed temperature of 25 °C, which was pumped out from shallow cold reservoirs that surround the geothermal resources. In the case of an air-cooled single effect absorption chiller the absorber and the condenser were cooled indirectly by the ambient air through an induced-draught air-cooler.
Economical Evaluation of a Low-Enthalpy Geothermal Resource Located in an Arid-Zone Area

Fig. 1  Schematic diagram of water-cooled half effect absorption chiller powered by one of four existing artesian wells.

The ambient temperature was selected to be varied from 28 to 40 ºC at an average relative humidity of 44%.

An economic validation was performed on the following four models:

1. Water-cooled single effect LiBr-H$_2$O absorption chiller;
2. Air-cooled single effect LiBr-H$_2$O absorption chiller;
3. Water-cooled half effect LiBr-H$_2$O absorption chiller;

The first three models provide either cooling only for one complete year (8,322 operation hours including chiller unit availability of 95%) or provide both cooling in summer (2,862 operation hours) and district heating energy in winter (2,175 operation hours). The fourth model provides either electricity only for one complete year (8,585 operation hours including plant availability of 98%) or provides electricity in spring, summer and autumn (6,453 hours) and district heating energy only (no electricity) in winter (2,175 hours).

Various profit measures such as PBP (payback period), ARR (average rate of return), NPV (net present value), and NBCR (net benefit-cost ratio) were used in this work. The criterion used to compare the viability of different models/systems was the ESP (energy selling price). The straight line depreciation method for the value of the proposed system was assumed in this work, as it was found to be the most common method used in the engineering industry. The project life of 20 years was assumed to be the reasonable estimated length of time for the proposed systems. During the profitability assessment and comparison between different models, several assumptions were necessary. Firstly the electricity price had to be low enough to encourage people to remain in Waddan city and not move to the other cities on the coast. This was assumed to be a key aim of the Libyan authorities who subsidise fully or partially sustainable energy projects. These assumptions are realised by:

- Zero taxation on all expenditures and revenues of the selected plant;
- Zero discount rate;
- Constant price inflation rate (2.5%).
The only variable, which can affect the profitability, when the above assumptions are considered, is the energy selling price. Despite an actual electricity generation cost of 0.11 £/kWh, the current energy selling prices are heavily subsidized by the Libyan government, in particular the domestic electricity tariff of 0.02 £/kWh.

3. Profitability Assessment

The profitability assessments for the main simulated models were carried out using four profit measures. Each model was evaluated either to provide cooling/electricity only or to provide cooling/electricity with district hot water. Therefore, eight different model configurations were evaluated as shown below:

- Water cooled half effect chiller providing cooling only;
- Water cooled half effect chiller providing cooling and hot water;
- Water cooled single effect chiller providing cooling only;
- Water cooled single effect chiller providing cooling and hot water;
- Air cooled single effect chiller providing cooling only;
- Air cooled single effect chiller providing cooling and hot water;
- Organic Rankine cycle providing electricity only;
- Organic Rankine cycle providing electricity and hot water.

The following are the definitions of the profitability measures used in this work.

3.1 PBP (Payback Period)

The payback period refers to the length of time required for the cash inflow received from the project to recover the original cash outlays required by the initial investments. Mathematically this is defined as:

$$TCI = \sum_{j=1}^{PBP} CFN_j$$

(1)

3.2 NPV (Net Present Value)

The net present value of an investment is defined as the difference between the sum of all the net cash flow and the initial total capital investment. The net present value can be either positive or negative. A positive NPV for a project/system indicates the present value of the net gain corresponding to the cash flows. In addition systems with negative present values should be rejected and systems with the highest net present values should be given the highest preference. Mathematically this is defined as:

$$NPV = \sum_{j=1}^{l} \frac{CFN_j}{(1+r)^j} - TCI$$

(2)

3.3 ARR (Average Rate of Return)

The average rate of return is defined as the ratio between the average annual net profit and the total capital investment. Mathematically this can be written as:

$$ARR = \frac{NP}{TCI}$$

(3)

3.4 NBCR (Net-Benefit Cost Ratio)

The benefit cost ratios are defined as the ratio of the net present value of future net cash flow to the initial investment over its entire life. They are simply defined as PI (profitability index). They are good tools for ranking projects. A ratio of one is logically the lowest acceptable measure on the index. Any values lower than one would indicate that the project’s net present value is less than the initial investment. Mathematically this can be written as:

$$NBCR = \frac{NPV}{TCI}$$

(4)

4. Sensitivity Analysis

4.1 PBP (Payback Period)

When the lifetime of plant is fixed at 20 years, and all the expenditures and the revenues are exempt from taxation, putting zero discount rates and fixing the
price inflation rate at 2.5%, the profitability measures were found to be sensitive only to the energy selling price. This is the only economical fluctuating parameter. Figs. 2-5 demonstrate the effects of the variations of the energy selling prices on the selected profitability measures.

Fig. 2 illustrates the effects of the variations of the selling prices on the payback period profitability measures. As can be seen, the highest payback periods were 33, 29 and 14.5 years, which sharply exceeded the least preferred payback period of 6 years [8]. These long periods were obtained from the air-cooled single effect chiller (cooling only), the organic Rankine cycle (electricity only), and the water cooled single effect chiller (cooling only) respectively.

When the selling price was increased from 0.02£ to 0.1£ per kWh, the first two payback periods were gradually reduced but did not reach even the maximum preferred payback period because of the high initial costs. The third payback period was steeply reduced and quickly reached the preferred payback period but at the selling price of 0.04 £/kWh. This was due to the low initial costs of the water-cooled single effect chiller.

If the selling prices was chosen to be 0.02 £/kWh, to match the Libyan domestic electricity selling price (electricity tariff), the lowest marked payback periods would have been 1.85, 2.2 and 3.6 years. These short payback periods were considered to be much more attractive for investment because they were less than the minimum acceptable preferred payback periods (≈ 6 years). These short periods were obtained from water-cooled single effect chiller (cooling and hot water), water-cooled half effect chiller (cooling and hot water), and organic Rankine cycle (electricity and hot water) respectively. It can be clearly noticed from the comparison of the results of the eight models shown in Fig. 2 that when the revenues from the district hot water energy were added to the basic model revenues, the payback periods were highly reduced and reached the preferred values. The only standalone model (without utilizing hot water) that was found within the minimum acceptable payback period was the water-cooled half effect chiller due to the high cooling capacity produced, and hence high revenues obtained.

Fig. 2 Payback period versus variation of the energy selling prices.
It is worth mentioning here that if the selling price of the different energies was equal to the subsidised Libyan government selling price (0.02 £/kWh), the three stand alone models that produced single energies (cooling or electricity), except the water-cooled half effect, were economically non-viable due to long payback periods. It can be concluded that when the selling price of 1 kWh was fixed at 0.02£, the shortest payback period (1.85 years) was obtained from the water-cooled single effect chiller (cooling and hot water) despite an increase of the energy selling price.

4.2 NPV (Net Present Value)

The net present values of the simulated models versus the variation of the energy selling prices are shown in Fig. 3. For the selling price of 0.02 and 0.04£/kWh both the air-cooled single effect chiller (cooling only) and the organic Rankine cycle (electricity only) were economically non-viable as their NPV dropped below zero and became negative due to the high initial and operation costs. This reveals that when the selling prices were as low as 0.02 and 0.04 £/kWh, the total cash flows were less than the total initial and operation costs of the units. If the selling price of the energies was in line with the subsidised Libyan government selling price (0.02 £/kWh), both the air-cooled single effect chiller (cooling only) and the organic Rankine cycle (electricity only) were economically unprofitable.

The highest net present values, over the entire selling prices range, (0.02-0.1 £/kWh) were obtained from the water-cooled half effect chiller (cooling and hot water). This is mainly because of the high cash flows received from the high cooling capacity and the hot water energy. It is clearly seen from Fig. 3 that the top highest NPVs, over the selling price range, were obtained from water-cooled half effect chiller (cooling and hot water), water-cooled single effect chiller (cooling and hot water), organic Rankine cycle (electricity and hot water), and air-cooled single effect chiller (cooling and hot water) respectively. It can be seen also that, as the selling prices increased the net present value of all models increased, and the net present values were much more improved when the hot water revenues added to the cooling/electricity revenues. It can be concluded that projects with negative NPVs were economically non-viable unless they were heavily subsidised.

4.3 ARR (Average Rate of Return)

The ratio of the average annual net profit to the total capital investment versus the variation of the energy selling prices is shown in Fig. 4. It can be seen that when the selling prices were 0.02 and 0.04 £/kWh both the air-cooled single effect chiller (cooling only) and the organic Rankine cycle (electricity only) were not profitable. Whereas both the water-cooled single effect chiller (cooling and hot water) and the water-cooled half effect chiller (cooling and hot water) were the most profitable models over the entire selling price range. This was mainly due to low initial cost of the single effect chiller and the high revenues of the half effect chiller.

It is noticed from Fig. 4 that, over the entire energy selling prices, both the air-cooled single effect chiller (cooling only) and the organic Rankine cycle (electricity only) gave very small annual profits against total large capital investment. It can be seen that all the models were profitable when the energy is priced at 0.06 £/kWh. The water-cooled single effect (cooling and hot water) was the most profitable model among the other seven models. Generally speaking, adding the hot water energy revenue to the cooling or electricity revenues yields a great improvement in profit and makes most of the models much more economically acceptable.

4.4 NBCR (Net-Benefit Cost Ratio)

The net-benefit cost ratio, also known as the PI (profitability index), versus the selling price range is shown in Fig. 5. It can be seen that both the air-cooled single effect chiller (cooling only) and the organic Rankine cycle (electricity only) were not economically attractive as no profit could be obtained at selling
Fig. 3  Net present value versus variation of the energy selling prices.

Fig. 4  Average rate of return versus variation of the energy selling prices.
Fig. 5  Net-benefit cost ratio versus variation of the energy selling prices.

prices of 0.02 and 0.04 £/kWh, and their profitability indexes were negative (-0.989 & -0.5). The NBCR confirmed the results obtained from the ARR and the NPV. Again the highest profitable models were the water-cooled single effect chiller (cooling and hot water) and the water-cooled half effect chiller (cooling and hot water) over the entire energy selling price range. The other three models: the organic Rankine cycle unit (electricity and hot water), water-cooled half effect chiller (cooling only), and the air-cooled single effect chiller (cooling and hot water) respectively show also remarkable positive profit but not as much as the highest profit that was obtained from the water cooled single effect and the water cooled half effect chillers (cooling and hot water).

5. Conclusions

Four models were compared in order to determine the most suitable system configuration that can provide the community in Waddan city with, at least, part of their needs of electricity/cooling energies only or electricity/cooling with district heating energy supply. With the assumption of zero taxation, zero discount rate, fixed price inflation rate (2.5%) and 20 years project life, the sensitivity analysis in this study revealed the great influence of the variations of the energy selling prices on four different economic evaluation criteria (PBP (payback period), NPV (net present value), ARR (average rate of return) and NBCR (net-benefit cost ratio)).

If the selling price of the energy is fixed (in line with the subsidized Libyan government selling price (0.02 £/kWh)) and the cooling air-conditioning system is the only choice for the Waddan communities without utilizing hot water energy, then the water-cooled half effect chiller model (cooling only) is probably the best system to be installed due to the large cooling capacity produced with an acceptable chilled water temperature (5 ºC). This model is also economically acceptable and profitable over the entire range of the energy selling price, with a reasonable payback period of 6 years. On the other hand if both the air-conditioning and the
district heating energy supply systems are desired, in summer and winter only, then the water-cooled single chiller system (cooling and hot water) has to be selected.

If electricity is required over the entire year without utilizing district heating energy (during winter), then the ORC electricity generation system is economically unprofitable due to high initial and operation costs (e.g. PBP > 28 years, NPV = negative, ARR = negative and NBCR < 1.0). Conversely, if electrical energy (in spring, summer and autumn) with utilization of district heating energy (in winter) is desired, then the organic Rankine cycle with utilization of district heating energy (electricity and hot water) has to be selected.

When short payback periods, positive NPVs, positive ARRs, and higher NBCRs are desired, then the stand alone models that deliver cooling or electricity only have to be combined with the district heating energy supply system in order to increase the revenues. Otherwise the energy selling prices have to be increased to at least 0.08£ for each kWh.

References

Assessment of CDM Activities by a Generation Planning Model of the Chinese Power Grids

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Abstract: A generation planning model of six main power grids in China is developed to evaluate the potential of advanced power generation technologies into the Chinese power system as CDM (clean development mechanism). It is investigated how delivered coal price, on-grid power price, and environmental protection may influence the potential of advanced thermal power generation as CDM projects. One finding from the baseline analysis is that coal price, on-grid power price, and environmental protection policy have only a small significance to the grid-wide specific CO2 emissions of thermal power generation up to the year 2026, while the best thermal generation mix is influenced largely by environmental protection policy. And it is found that not only the price of CER (certified emission reduction) and the length of crediting period but also on-grid power price and the reduction of air pollutants in the baseline have a significant influence on the potential of the CDM activities.

Key words: Clean development mechanism, generation planning model, China, advanced thermal power generation.

Nomenclature

\begin{align*}
    s & \quad \text{Index to years} \\
    i & \quad \text{Index to hours} \\
    j & \quad \text{Index to generation plant types} \\
    k & \quad \text{Index to fuel types} \\
    \text{env} & \quad \text{Air pollutants (CO}_2, \text{SO}_x, \text{NO}_x) \\
    M(s, i) & \quad \text{Demand at the hour } i \text{ on the load duration curve of the year } s \\
    N(s, i) & \quad \text{Input to pumped storage plant at the hour } i \text{ in the year } s \\
    Y(s, i, j) & \quad \text{Output of generation plant of type } j \text{ at the hour } i \text{ in the year } s \\
    X(s, j) & \quad \text{Capacity of generation plant of type } j \text{ added in the year } s \\
    Z(s, j) & \quad \text{Capacity of generation plant of type } j \text{ existing in the year } s \\
    G(s, j) & \quad \text{Electricity generated by generation plant of type } j \text{ in the year } s \\
    R(s, j, j') & \quad \text{Capacity of plant retrofitted from type } j \text{ to type } j' \text{ in the year } s \\
    F(s, j, k) & \quad \text{Consumption of fuel } k \text{ by generation plant of type } j \text{ in the year } s \\
    E(s, env) & \quad \text{The emission of pollutant } env \text{ in the year } s \\
    \text{CER}(s) & \quad \text{The amount of certified emission credit obtained in the year } s \\
\end{align*}

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Assessment of CDM Activities by a Generation Planning Model of the Chinese Power Grids

\[ \text{pcer} \quad \text{The price of certified emission reduction} \]
\[ \text{shrp} \quad \text{Share of profit rate} \]
\[ A \quad \text{The threshold value of internal rate of return for CDM project} \]
\[ D \quad \text{Discount rate} \]

1. Introduction

CDM (clean development mechanism) is one of the market-based mechanisms included in the Kyoto Protocol. Though it is still unclear if CDM itself will survive after the first commitment period or not, the importance of technology transfer will surely remain unchanged. Fig. 1 outlines CDM briefly.

Suppose that CO₂ (carbon dioxide) emission within a designated area decreases due to implementing a CDM project, in which a project proponent usually builds and operates a low-carbon or a carbon-free plant in the area. The reduction of the CO₂ emission from the baseline level is called CER (certified emission reduction) after being validated, verified, and certified by the operational entity. An important feature about a CDM project is the additionality. It is required generally that IRR (internal rate of return) of the project exceeds a specified threshold value only with the help of the revenue from the sales of CER, which is obtainable during the crediting period. CDM project participants have two options about the length of crediting period: a single ten-year period (fixed crediting period) or a seven-year period possibly renewable at most twice (renewable crediting period) [1]. Renewable crediting period is often chosen in the proposal of CDM projects.

The purpose of this study is to evaluate the potential capacity of cutting-edge thermal power plants such as IGCC (integrated gasification combined cycle) and USC (ultra super critical), and NGCC (natural gas combined cycle) power plants into the Chinese power sector by way of CDM.

Ref. [2] contains a comprehensive analysis of methodological issues and case studies about CDM in China. It also assesses CDM potential by using the marginal abatement cost curves of CO₂ emission from the total energy system of China. The marginal abatement cost curve method is a powerful analytical tool but it is different from the methodology to evaluate CDM projects approved by UNFCC (United Nations Framework Convention on Climate Change). ACM0013 [3], which is the approved baseline methodology for new grid connected fossil fuel fired power plants, says that baseline to evaluate CDM activities should be determined with respect to the power grid to which the project plant will be connected. This means that we need a method to evaluate CDM potential on a grid-wide scale.

Ref. [4] discusses policy instruments to promote the market penetration of clean coal technologies in China. In the study, a two-region electricity system model of China is developed and the penetration of advanced coal power generation technologies such as USC and IGCC are analyzed considering carbon tax, sulfur emission tax, and subsidies. But CDM is out of the scope of the study and the regions in the model are not related to the Chinese power grid areas.

In this study, a generation planning model of six main power grids in China is developed to evaluate the CDM potential of advanced power generation
Assessment of CDM Activities by a Generation Planning Model of the Chinese Power Grids

2. Electricity Supply and Demand in China

Most part of the Chinese electric power system is currently composed of six major power grids, which are North China Grid, Northeast Grid, East China Grid, Central China Grid, Northwest Grid, and China Southern Power Grid.

2.1 The Current Status of Electricity Supply

The total electricity generation capacity of the six power grids amounted to about 620 GW in 2006. The largest grid is East China Grid, followed by North China Grid. They have generation capacity over 140 GW. The smallest grid is Northwest Grid. Thermal power generation is predominant in North China Grid, East China Grid, and Central China Grid. Hydropower generation plays more important role in the other grids. The average fuel consumption per kWh of thermal power plants at the sending end [5] ranges from 352 gce (10.31 MJ) in East China Grid to 387 gce (11.34 MJ) in Northwest Grid. The improvement of generation efficiency is an urgent question in the Chinese electricity industry. Besides enlarging the unit capacity of newly built generation plants and abolishing small coal power plants below 10 MW, they started to operate a few advanced power plants such as NGCC power plants and USC coal power plants recently.

2.2 The Current Status and the Future Prospect of Electricity Demand

The electricity demand of China amounted to about 284 billion kWh in 2006. It is forecasted to grow at about 3.3 percent annually up to 2026 on average [6]. The annual peak demand of the six power grids at the receiving end in 2006 are also shown in Table 1.

2.3 Environmental Protection

It is another urgent question to reduce the emissions of air pollutants, especially sulfur oxides. The Chinese government is promoting the flue-gas desulfurization of thermal power plants strongly. According to its plan [7], the average emission of sulfur oxides per kWh of thermal power generation in 2010 will be less by half than that in 2005. Reducing nitrogen oxides emission does not seem to have priority until now. But the average emission of nitrogen oxides per kWh of thermal power generation is also decreasing gradually due to the improved thermal efficiency. NOx emission control just came in use recently.

3. Generation Planning Model

3.1 Basic Equations

This generation planning model is a linear programming model developed on PC using GAMS (general algebraic modeling system). The model’s time frame is from 2006 to 2026. The model to determine the baseline scenarios contains the following equations.

Balance of energy relation:

\[ M(s, i)(1 - t_{def}) + N(s, i) = \sum_j Y(s, i, j) \]  

(1)

Availability of capacity relation:

\[ Y(s, i, j) \leq avl(j) \cdot Z(s, j) \]  

(2)

Peaking relation:

\[ \sum_j avl(j) Z(s, j) \geq (1 + err) M(s, i)(1 - t_{def}) \]  

(3)

Output order relation:

\[ Y(s, i, j) \geq Y(s, i + 1, j) \]  

(4)

Capacity transfer relation:

\[ Z(s, j) = Z(s - 1, j) + X(s, j) - dem(s, j) \]  

\[ - \sum_j r(s, j, j') + \sum_j r(s, j', j) \]  

(5)

Balance of pumped storage relation:

\[ psef \sum_i N(s, i) = \sum_i Y(s, i', 'Pumped storage') \]  

(6)

Amount of generated electricity relation:

\[ G(s, j) = 0.5 \sum_i \{ Y(s, i, j) + Y(s, i + 1, j) \} h(i) \]  

(7)

Annual capacity utilization relation:

\[ G(s, j) \leq 8760 \text{ cf}(j) Z(s, j) \]  

(8)
Table 1  Six major power grids in 2006.

<table>
<thead>
<tr>
<th>Power grid</th>
<th>Generation capacity (GW)</th>
<th>Thermal efficiency (gce/kWh)</th>
<th>Peak demand (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North China</td>
<td>137.15</td>
<td>3.73</td>
<td>370</td>
</tr>
<tr>
<td>Northeast China</td>
<td>40.61</td>
<td>6.40</td>
<td>33.57</td>
</tr>
<tr>
<td>East China</td>
<td>128.83</td>
<td>18.46</td>
<td>106.54</td>
</tr>
<tr>
<td>Central China</td>
<td>76.66</td>
<td>52.52</td>
<td>65.29</td>
</tr>
<tr>
<td>Northwest China</td>
<td>29.63</td>
<td>14.07</td>
<td>23.19</td>
</tr>
<tr>
<td>Southern China</td>
<td>70.95</td>
<td>34.77</td>
<td>58.15</td>
</tr>
</tbody>
</table>

Fuel consumption relation:

\[ F(s, k) = \sum_{j} g_{ef}(j, k) G(s, j) \]  

(9)

Emission relation:

\[ E(s, env) = \sum_{j, k} e_{f}(k, env) r_{d}(j, env) F(s, j, k) \]  

(10)

System cost:

\[ \cos t(s) = \sum_{j} a_{fx}(j, inv(j)) \sum_{s'} X(s', j) \]
\[ + \sum_{j} a_{fx}(j, j') \sum_{i'} X(i', j') R(s, j, j') \]
\[ + \sum_{j} p_{r}(s, k) F(s, k) + \sum_{j} v_{om}(j) G(s, j) \]  

(11)

Objective function:

\[ OBJ = \sum_{j} (1 + D)^{-s} \left( \sum_{j} o_{gr}(s, j) G(s, j) - \cos t(s) \right) \]  

(12)

3.2 Annual Load Duration Curves

Since the annual load duration curves of the six power grids are not available to the public, they are constructed based on published information. Used information about each power grid includes the monthly peak demand, the monthly average load factor of daily load, and the monthly electricity sales available on the web sites of State Grid Corporation of China and China Southern Power Grid. Representative daily load curves of each power grid found in Ref. [8] are used too. The shapes of load duration curves estimated for the base year (2006) are shown in Fig. 2.

Demand on the vertical axis is normalized by the annual peak demand of each power grid. It is assumed that the annual load duration curves of power grids change in proportion to the annual peak load when demand for electricity grows in the future.

3.3 Characteristics of Key Technologies

Table 2 shows key characteristics of thermal power plants used in this study. Investment cost in this table is estimated referring to Ref. [9], and does not include emission control equipment cost. It is assumed that USC coal power plant is built by imported technology in 2006 but by completely domestic technology in 2016. Therefore, the investment cost of USC coal power plant goes down from 5,335 Yuan/kW in 2006 through 4,880 Yuan/kW in 2011 to 4,420 Yuan/kW in 2016. It is assumed that coal power plant below 10 MW is abolished before 2016 at a constant pace and IGCC comes into the first commercial use in the year 2016. The investment cost of IGCC power plant is assumed to be 50 percent higher than that of new domestic coal power plant in the year 2016 and to go down gradually to 6,030 Yuan/kW in the year 2026. Annual load factors are assumed to be at most 70 percent for all the plant types. The model incorporates nuclear power plants, hydropower plants, and wind power plants in addition. The investment costs of nuclear power plant and wind power plant are assumed to be 11,852 Yuan/kW and 9,000 Yuan/kW, respectively. The investment cost of hydropower plant is assumed to range from 4,398 to 9,115 Yuan/kW.
Table 2 Characteristics of thermal power plants and equipments.

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Fuel consumption rate (gce/kWh)</th>
<th>Annual load factor (%)</th>
<th>Investment cost (Yuan/kW)</th>
<th>(a) Power plants (with no environment protection)</th>
<th>(b) Environment protection equipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcritical coal</td>
<td>344</td>
<td>70</td>
<td>3,904</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Supercritical coal</td>
<td>311</td>
<td>70</td>
<td>3,983</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>USC coal</td>
<td>293</td>
<td>70</td>
<td>5,335 (in 2006)</td>
<td>Flue gas desulfurization 90 %</td>
<td>250 (in 2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4,880 (in 2011)</td>
<td>Selective catalytic reduction 80 %</td>
<td>210 (in 2026)</td>
</tr>
<tr>
<td>Small coal smaller than 10 MW</td>
<td>483</td>
<td>Adjusted</td>
<td>Not applicable</td>
<td>Low NOx burner 35 (for coal) 50 (for gas)</td>
<td>30</td>
</tr>
<tr>
<td>IGCC coal</td>
<td>285</td>
<td>70</td>
<td>6,350 (in 2016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC natural gas</td>
<td>272</td>
<td>70</td>
<td>6,030 (in 2026)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3,005</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

USC = ultra supercritical, CC = combined cycle, IGCC = integrated gasification combined cycle. 1 gce = 27.3 kJ.

depending on its rated capacity. The growth of total generation capacity of these technologies in China is given as scenario following expert’s vision [10-12], while their capacity in each power grid is determined by the model optimization. Emission control equipment costs are assumed as follows [13]: flue-gas desulfurization equipment and flue-gas NOx control (selective catalytic reduction) equipment are 250 Yuan/kW in 2006 and go down constantly to 210 Yuan/kW in 2026. Low-NOx burner is 30 Yuan/kW. Emission reduction rates of control technologies are assumed as follows: flue-gas desulfurization cuts 90 percent of SOx from coal power plant, low-NOx burner cuts 35 percent of NOx from coal power plant and 50 percent of NOx from gas power plant. SCR (selective catalytic reduction) cuts 80 percent of NOx in the flue-gas.

3.4 Coal Price Model

The assumption on the regional coal price is made based on the estimation of FOB (freight on board) price in the major coal producing provinces, the transportation distances between the coal producing provinces and the load centers, and freight rates. The FOB prices of raw coal in the major coal producing provinces between 2006 and 2008 [14] are adjusted on the basis of the same calorific value (5,500 kcal per ton). The ratios of adjusted local FOB price to the average price range from about 0.5 (Xinjiang, Ningxia) to about 1.4 (Anhui, Zhejiang, Shanghai, Fujian).

The approximate distances for railway transportation between the coal producing provinces and the power grids are derived by averaging the distances between principal railway stations weighted with the quantity of coal transported by railway [15]. The freight rate of railway transportation is assumed to be 0.09 Yuan per ton-kilometer. Maritime transportation from Qinhuangdao Port is the other important way of shipping coal to East China Grid and China Southern Grid. The freight rates per ton coal of maritime transport from Qinhuangdao Port are estimated by the following equations, which are derived from data reported by the NDRC (National Development and Reform Commission) from January 2007 to April 2008 [16].

\[ Y = 0.07x + 89 \]  
\[ 400 \leq x \]

\[ Y \]: FOB price at Qinhuangdao (Yuan per ton);  
\[ x \]: FOB price at Qinhuangdao (Yuan per ton);  
\[ 400 \leq x \]

\[ Y = 0.44x - 53 \]  
\[ 400 \leq x \]

\[ Y \]: Transportation fee to Shanghai (Yuan per ton);  
\[ x \]: FOB price at Qinhuangdao (Yuan per ton);  
\[ 400 \leq x \]

\[ Y \]: Transportation fee to Guangdong (Yuan per ton).

Table 3 summarizes the result of estimating local prices of delivered domestic coal in 2007 in the way described above. The price for China Southern Grid is the highest, while the price for Northwest China Grid is the lowest. The mean delivered coal price in East China Grid is reported 510 Yuan per ton [17], which is well approximated by the value estimated here.
Table 3  Estimated delivered coal prices for the six power grids in 2007.

<table>
<thead>
<tr>
<th>Transportation mode</th>
<th>Coal price delivered to power grids (Yuan per ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price by rail transport</td>
<td>North</td>
</tr>
<tr>
<td>(Share of rail)</td>
<td></td>
</tr>
<tr>
<td>Price by sea transport</td>
<td></td>
</tr>
<tr>
<td>(Share of sea)</td>
<td></td>
</tr>
<tr>
<td>Mean price</td>
<td></td>
</tr>
</tbody>
</table>

3.5 Fuel Price Scenario

The scenario of delivered domestic coal price is developed up to 2026 on the assumption that the ratios between local FOB coal prices to the national mean FOB coal price are constant. Annual escalation rate of coal price is 0.5% in the LCP (low coal price) scenario and 2.0% in the HCP (high coal price) scenario. The scenario of natural gas price and international coal price is based on the projection by IEA (International Energy Agency) [18]. For nuclear power plant, 10,000 Yuan/kgU is used as nuclear fuel price, which is cited from Ref. [9]. No price escalation is assumed about nuclear fuel. Table 4 shows the scenario of fossil fuel prices in this study. The calorific value of coal is adjusted to 5,500 kcal/kg. Natural gas and international coal are assumed to be available in North China Grid, Northeast China Grid, East China Grid, and China Southern Grid. It is assumed that imported coal is used in these grids when it is cheaper than domestic coal.

3.6 Environmental Protection

The following two scenarios are considered for SOx and NOx emission with different reduction levels. DeSOx only (DSO) scenario

Emission constraint is imposed on SOx emission in order that the nationwide average SOx emission per kWh of thermal power plants may become less by half every five year until 2021. The nationwide average SOx emission per kWh of thermal power plants will be 0.6 g SO2/kWh after 2021. No constraint is imposed on NOx emission in this scenario. This scenario reflects the current policy of promoting desulfurization in power industry.

DeSOx-DeNOx (DSN) scenario

Emission constraints are imposed on both SOx emission and NOx emission in order that both the national average SOx emission per kWh and the national average NOx emission per kWh of thermal power plants may become less by half every five year until 2021. This scenario implies an enhanced policy to reduce air pollution.

Three types of emission control for coal power plant (EC1-3) and two types of emission control for gas power plant (EC4-5) are prepared in the model. They are tabulated in Table 5. IGCC coal power plant has intrinsic emission control for SOx and NOx comparable with EC3.

3.7 On-Grid Power Price

On-grid power price is the price of electricity sold to power grids by the producers of electricity. It is one of influential factors to the economic viability of power generation business and CDM projects. According to Ref. [19], on-grid power price lies currently in a range of 0.258-0.44 Yuan/kWh for thermal power generation, 0.148-0.395 Yuan/kWh for hydropower generation, and 0.39-0.49 Yuan/kWh for nuclear power generation, respectively. The range of on-grid power price for wind power generation is 0.51-0.58 Yuan/kWh, depending on the grade of wind resources.

To explore the impact of on-grid power price on the thermal power plant mix and the potential CDM projects, two different values are assumed in this study as the on-grid power price for thermal power plants in the starting year: 0.30 Yuan/kWh (LOG scenario), and 0.40 Yuan/kWh (HOG scenario).
Table 4  Fuel price scenarios.

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2011</th>
<th>2016</th>
<th>2021</th>
<th>2026</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>North China Grid</td>
<td>295</td>
<td>397</td>
<td>406</td>
<td>415</td>
<td>424</td>
<td>Yuan/ton</td>
</tr>
<tr>
<td>Northeast China Grid</td>
<td>331</td>
<td>437</td>
<td>445</td>
<td>455</td>
<td>465</td>
<td></td>
</tr>
<tr>
<td>East China Grid</td>
<td>419</td>
<td>613</td>
<td>630</td>
<td>647</td>
<td>665</td>
<td></td>
</tr>
<tr>
<td>Central China Grid</td>
<td>329</td>
<td>435</td>
<td>445</td>
<td>454</td>
<td>464</td>
<td></td>
</tr>
<tr>
<td>Northwest China Grid</td>
<td>255</td>
<td>340</td>
<td>348</td>
<td>355</td>
<td>363</td>
<td></td>
</tr>
<tr>
<td>China Southern Grid</td>
<td>437</td>
<td>725</td>
<td>751</td>
<td>776</td>
<td>804</td>
<td></td>
</tr>
<tr>
<td>Natural gas (common to all the power grids)</td>
<td>2.05</td>
<td>2.23</td>
<td>2.43</td>
<td>2.64</td>
<td>2.87</td>
<td>Yuan/m³</td>
</tr>
<tr>
<td>Imported coal (common to all the power grids)</td>
<td>661</td>
<td>708</td>
<td>615</td>
<td>687</td>
<td>706</td>
<td>Yuan/ton</td>
</tr>
</tbody>
</table>

Table 5  Emission control for thermal power plants.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Control type</th>
<th>Flue-gas desulfurization</th>
<th>Low-NOx burner</th>
<th>Selective catalytic reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>EC1</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>EC2</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>EC3</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Gas</td>
<td>EC4</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>EC5</td>
<td>*</td>
<td></td>
<td>*</td>
</tr>
</tbody>
</table>

Each control type is equipped with control devices marked with *.

4. Results of Baseline Optimization

4.1 Baselines

Eight different baseline emission scenarios are developed in this study corresponding to two air pollution reduction scenarios (DSO, DSN), two coal price scenarios (LCP, HCP), and two different values of the on-grid power price for thermal power plant (LOG, HOG). The objective function to be maximized for the baseline analysis is the present value of aggregate revenue minus system expenditure of the six power grids expressed by Eq. (12). Adopted value of the annual discount rate is 6.21 percent.

4.2 Baseline Thermal Efficiency and Emissions

As for the average fuel consumption per kWh and the average emissions of CO₂, SO₃ and NOₓ per kWh of all the thermal power plants in the six power grids, difference due to the on-grid power price scenarios is found to be negligible. Between 2006 and 2026, average fuel consumption and CO₂ emission per kWh is improved about 20 percent in LCP scenarios and about 16 percent in HCP scenarios. It is found that a higher coal price has a tendency to make thermal energy efficiency and CO₂ emission per kWh worse.

NOₓ emission per kWh is improved about 18 percent even in the DSO scenario, not to mention that the improvement of NOₓ emission is much more enhanced in the DSN scenario. It is found that NOₓ emission reduction results in a slightly better fuel efficiency and CO₂ emission per kWh.

4.3 Thermal Power Plant Mix

The aggregate thermal power plant mix in China in DSO-LCP and DSN-LCP scenarios are shown in Fig. 3. In the DSO scenario, thermal power plants newly built in 2011 are subcritical coal power of Type EC1 (flue gas desulfurization), USC coal power without emission control, USC coal power of Type EC1, and subcritical coal power without emission control. Then in 2016, USC coal power of Type EC1 is mostly installed and part of USC coal power without emission control built in 2011 is converted into Type EC1. The conversion is completed in 2021 and small amount of IGCC power plant is introduced in the same year. NGCC power plant is mostly installed in 2026 though it is built on a small scale as early as in 2016 if coal price is high. Subcritical coal power of
Type EC1 plays a larger role in the high coal price scenario than in the low coal price scenario. In the DSN scenario, subcritical coal power of Type EC3, USC coal power without emission control, USC coal power of Type EC2 (flue gas desulfurization plus low NOx burner), and supercritical coal power of Type EC2 are newly built in 2011. Moreover, subcritical coal power of Type EC1 existing in 2006 is converted into Type EC3 in the same year. In 2016, USC coal power without emission control built in 2011 is converted into Type EC3 by retrofit, and IGCC and USC coal power of Type EC3 are newly built. In 2021, the USC coal power plants without emission control and of Type EC2 are completely converted into Type EC3, and more USC coal power of Type EC3 is newly installed. NGCC power plant, as in the DSO scenario, is mostly installed in 2026 though it is built on a small scale as early as in 2016 if coal price is high. Subcritical coal power of Type EC3 plays a larger role in the high coal price scenario than in the low coal price scenario.

4.4 Grid-Wide Average CO₂ Emission per kWh of Thermal Power Plants

Two kinds of baseline CO₂ emission factor are used in the practice of evaluating power generation CDM projects: OM (operating margin) and BM (build margin) [21]. OM reflects the short term impact, only taking the substitution of generated electricity into account. BM reflects the long-term impact of CDM project on the CO₂ emission, considering the substitution of power units. A recommended way of calculating OM is to average the emission factors of all the thermal power units excluding zero-fuel cost facilities and must-run facilities. As emission factor corresponding to OM in this study, the average grid-wide CO₂ emission factor of all the thermal power plants excluding small scale coal power units are calculated, as shown in Table 6. A recommended way of calculating BM is to average the emission factors of five power units that have been built most recently. As analogue of BM in this study, the average grid-wide CO₂ emission factors of thermal power plants newly built in 2011 and 2016 in the baseline scenarios are calculated and summarized in Table 7.

Both in the DSO scenario and in the DSN scenario, most of new power plants built in 2011 are supercritical coal power plants and subcritical coal power plants in the six power grids except for East China Grid and China Southern Grid, where USC coal
Table 6  Average CO₂ emission per kWh of thermal power plants in 2011 and 2016.

<table>
<thead>
<tr>
<th>Year</th>
<th>2011</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DSO-LCP</td>
<td>DSN-LCP</td>
</tr>
<tr>
<td>North China Grid</td>
<td>248</td>
<td>248</td>
</tr>
<tr>
<td>Northeast China Grid</td>
<td>244</td>
<td>242</td>
</tr>
<tr>
<td>East China Grid</td>
<td>231</td>
<td>231</td>
</tr>
<tr>
<td>Central China Grid</td>
<td>239</td>
<td>240</td>
</tr>
<tr>
<td>Northwest China Grid</td>
<td>260</td>
<td>261</td>
</tr>
<tr>
<td>China Southern Grid</td>
<td>248</td>
<td>231</td>
</tr>
</tbody>
</table>

DSO = DeSOₓ only, DSN = DeSOₓ-DeNOₓ, LCP = low coal price, HCP = high coal price.

Table 7  Average CO₂ emission per kWh of newly installed thermal plants.

<table>
<thead>
<tr>
<th>Year</th>
<th>2011</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LCP-DSO</td>
<td>LCP-DSN</td>
</tr>
<tr>
<td>North China Grid</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>Northeast China Grid</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>East China Grid</td>
<td>204</td>
<td>204</td>
</tr>
<tr>
<td>Central China Grid</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>Northwest China Grid</td>
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<td>203</td>
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<tr>
<td>China Southern Grid</td>
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</table>

DSO = DeSOₓ only, DSN = DeSOₓ-DeNOₓ, LCP = low coal price, HCP = high coal price.

power plants are installed, too. In 2016, almost all the new thermal power plants are USC coal power plants with the exception that new thermal power plants built in East China Grid and China Southern Grid are IGCC coal power plants in the DSN scenario. It is noticeable that CO₂ emissions per kWh of new thermal power plants are remarkably small in East China Grid and China Southern Grid than in the other power grids in the DSN scenario.

5. Optimization with CDM

The following equations are added to Eqs. (1)-(11) in order to evaluate CDM activities. It is also considered that the construction and operation of so-called must-run power plants (nuclear, hydro, and wind) is not influenced by CDM activities.

(1) CER definition

It is recommended to use a weighted average of OM and BM for the first seven years of renewable crediting period and BM for the rest of the crediting period to define the baseline CO₂ emission factor for electricity systems [21]. In this study, CO₂ emission per kWh of all the thermal power plants excluding small scale coal power units shown in Table 6 is used as OM and CO₂ emission per kWh of new thermal power plants in the same table is used as BM. CER is obtainable only in the crediting period of the CDM project. So the amount of CER is defined as follows. The share of profit is 2 percent.

\[
CER(s) = \sum_{j \in \text{CDM}} \left( \frac{1 - \text{share}}{\text{OM}} \sum_{j \in \text{CDM}} G(s,j) \left[ \text{blef}(s,CO_2') - \left( \sum_{k \in \text{CDM}} (k,CO_2') \right) \right] \right) 
\]

where \( \text{blef}(s,CO_2') = (\text{OM} + \text{BM})/2 \) for the first seven years of renewable crediting period;

\( \text{blef}(s,CO_2') = \text{BM} \) for the second and the third seven years of renewable crediting period.

(2) Additionality relation

Suppose that a CDM project starts in the year \( s' \). Eq. (13) means that the internal rate of return of the CDM project is lower than \( A \). On the contrary, Eq. (14) means that the internal rate of return of the CDM project exceeds \( A \) with the help of the sales of CER. CER is counted only in the crediting period. Eight percent is used as the value of \( A \).
\[
\sum_j (1 + \alpha)^{-1} [ -afx(j)inv(j)x(s', j) + \{ogpr(s, j) - vom(j) \} - \sum_k pr(k, ges(k, j))g(s, j)] \leq 0
\]
\[
\sum_j (1 + \alpha)^{-1} [-afx(j)inv(j)x(s', j) + \{ogpr(s, j) - vom(j) \} - \sum_k pr(k, ges(k, j))g(s, j) + \text{pcer} \times CER(s)] \leq 0
\]
\[(3)\] Emission reduction relation

Eq. (16) requires that any CDM project should actually reduce the emissions of CO2 and air pollutants below the baseline level.

\[
\sum_j G(s, j) \text{som}(s, env) - \sum_k ges(k, env)rd(j, env)ges(k, j) + E(s, env) \leq \text{ebl}(s, env)
\]
\[(16)\] New objective function

Eq. (17) defines the objective function of the model optimization with CDM, and is used in place of Eq. (12) in the baseline case. It includes the revenue from the sales of CER, which is counted only in the crediting period.

\[
\text{NEWOBJ} = \sum (1 + D)^{-1} \left[ \sum \text{ogpr}(s, j)g(s, j) - \cos t(s) + \text{pcer} \times CER(s) \right]
\]
\[(17)\] 6. Results about CDM Potential

In this chapter, the potential of CDM activities by means of advanced thermal power generation is evaluated using the method described in the previous chapter. USC coal power plant with emission control (Type EC3), IGCC power plant, and NGCC power plant with emission control (Type EC5) are selected as candidates for CDM. It is assumed that USC CDM and NGCC CDM are possible in 2011 and in 2016, but IGCC CDM is able to be realized only in 2016. Seven years are used as the crediting period length of USC CDM, and fourteen years are used for IGCC CDM and NGCC CDM.

6.1 Potential Capacity of CDM Projects Realized in DSO Scenarios

The evaluated potential generation capacity of USC CDM, IGCC CDM, and NDCC CDM in the DSO-LCP scenarios is illustrated in Fig. 4, using $10, $20, $30, $40, and $50 as CER price expressed in USD per ton CO2. It is known from the result that there is no room for USC CDM in the DSO-LCP scenarios. Since thermal power plants newly built in 2011 in the DSO scenarios are subcritical coal power of Type EC1, USC coal power without emission control, USC coal power of Type EC1, and subcritical coal power without emission control, CDM project to build USC coal power of Type EC3 is too expensive while the improvement of CO2 emission factor is not enough to validate the project. It is also shown that NGCC CDM in East China Grid and China Southern Grid is only realizable with CER price as high as $50 per CO2.

As for IGCC CDM in 2016, it is found that it has a large potential in North China Grid, Northwest China Grid, and Northeast China Grid when on-grid power price is low and the price of CER is high above $40 per CO2. But if on-grid power price is high, it is shown that IGCC CDM loses economic additinality and NGCC CDM is only realizable in East China Grid and China Southern Grid in that case.

Similar results are obtained in the high coal price scenarios (DSO-HCP scenarios).

6.2 Potential Capacity of CDM Projects Realized in DSN Scenarios When Coal Price is Low

In the DSN-LCP scenarios, in which subcritical coal power of Type EC3, USC coal power without emission control, USC coal power of Type EC2, and supercritical coal power of Type EC2 are newly built in 2011, USC CDM becomes relatively less expensive and is found to be realizable in 2011 in the low coal price grids such as Northeast China Grid, Northwest China Grid, Central China Grid, and North China Grid, as shown in Fig. 5. The regional distribution of potential capacity of USC CDM is found to be dependent on coal price and on-grid power price. If both coal price and on-grid power price are low (DSN-LCP-LOG scenario), USC CDM is valid in Northeast China Grid, Northwest China Grid, and
Assessment of CDM Activities by a Generation Planning Model of the Chinese Power Grids

Fig. 4  The potential capacity of CDM activities in DSO-LCP scenario.

Fig. 5  The potential capacity of CDM activities in DSN-LCP scenarios.
Central China Grid. But if on-grid power price is high (DSN-LCP-HOG scenario), it is shown that the potential of USC CDM in 2011 vanishes because it loses economic additionality, which is expressed by Inequality (14). Instead NGCC CDM is found to become realizable in East China Grid and China Southern Grid with low price of coal and high price of CER above $40 per CO₂. The potential of NGCC CDM becomes smaller in the DSN-LCP scenarios than in the DSO-LCP scenarios because the baseline CO₂ emission factors applied to the second seven years of the crediting period of NGCC CDM in East China Grid and China Southern Grid in the DSN-LCP scenarios are smaller than in the DSO-LCP scenarios.

As for CDM potential in 2016, the potential of IGCC CDM in North China Grid, Northwest China Grid, and Northeast China Grid is still large in the DSN scenarios if both coal price and on-grid power price are low (DSN-LCP-LOG scenario). On the contrary, the potential of NGCC CDM in East China Grid and China Southern Grid vanishes notwithstanding the on-grid power price scenarios because of the improvement of the baseline CO₂ emission factors applied to CDM projects in these power grids in 2016. There is no possibility of USC CDM in 2016 both in the DSO-LCP and DSN-LCP scenarios.

The influence of higher coal price scenario is observed in Fig. 6, which shows CDM potential of IGCC in North China Grid and Northeast China Grid both in the low and high on-grid power price (DSN-HCP-LOG and DSN-HCP-HOG) scenarios. This is because the additionality of IGCC CDM projects is validated due to higher coal price in these power grids.

7. Conclusions

A generation planning model of six main power grids in China is developed and a method to evaluate the potential of transferring advanced power generation technologies into the Chinese power system as CDM activities is proposed. The annual load duration curves of the power grids and the scenarios of regional coal price are developed. Eight scenarios are prepared to examine how various factors such as delivered coal price, on-grid power price, and environmental protection may influence the potential of advanced coal power generation and NGCC power generation as CDM projects. One finding from the baseline analysis is that coal price, on-grid power price, and environmental protection policy have only a small significance to the grid-wide specific CO₂ emissions of thermal power generation up to the year 2026 but the best thermal generation mix is influenced largely by environmental protection policy.

From the evaluation of the potential of the CDM projects, it is found that not only the price of CER and the length of crediting period but also on-grid power price and the reduction of air pollutants in the baseline have a significant influence on the result. The findings of this scenario study are as follows.

**Fig. 6** The potential capacity of CDM activities in 2016 in DSN-HCP scenario.
If SO\textsubscript{x} emission reduction is only considered in the baseline, USC CDM is found little promising. IGCC CDM and NGCC CDM are found to be realizable if the price of CER is high enough (about $50 per Ton CO\textsubscript{2}). If both SO\textsubscript{x} and NO\textsubscript{x} reductions are required in the baseline, USC CDM comes up as a valid CDM project realized in 2011 even if the price of CER is $20 per ton CO\textsubscript{2}. And IGCC CDM is found promising as CDM project planned in 2016 while NGCC CDM planned in 2016 becomes little effective in this scenario.

Acknowledgments

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Optimization with Genetic Algorithms of PVT System

Global Efficiency

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Abstract: PV (photovoltaic) solar panels generally produce electricity in the 6% to 12% efficiency range, the rest is being dissipated in thermal losses. To recover this amount, hybrid photovoltaic thermal systems (PVT) have been devised. These are devices that simultaneously convert solar energy into electricity and heat. It is thus interesting to study the PV/T system as part of a closed loop single phase water CDU (coolant distribution unit) in laminar forced convection. In particular, the analysis was conducted on the optimal cooling performance of the thermal part, testing polynomial channel profiles of varying order (from zero to fourth) for channels of a real industrial module heat sink, under the following conditions: ideal flux of 1,000 W/m² on one side, insulation on the opposite side, periodic conditions on the remaining sides, fully developed thermal and velocity profile in laminar flow of water. Through the use of a genetic algorithm, we have optimized the shape of the channel’s sidewalls in terms of heat transfer maximization. In terms of Nusselt number, results show that fourth order profiles are the most efficient. When limits to allowable pressure loss and module weight are introduced, these bring generally to a lower efficiency of the system than the unconstrained case.

Key words: Fins, genetic algorithms, multi objective optimization, cooling, PVT systems.

1. Introduction

Photovoltaic solar panels generally produce electricity in the 6% to 12% efficiency range, while most of the incident radiation is lost to the environment as thermal energy, whereas, in comparison, a solar thermal collector can operate in the 40% to 70% efficiency range. A lot of work has been done in the past to improve efficiency of PV (photovoltaic) panels, to reduce manufacturing costs and to integrate PV panels into walls and roofs of buildings. On the contrary, very little effort has been devoted in the past decades to the recovery of the dissipated thermal energy. By integrating the PV modules into a system designed to collect the heat lost to the environment, a solar cogeneration system is possible which holds enormous potential for improving the cost-benefits ratio of PV integrated roof and wall systems. Good results are expected also for stand alone applications.

Hybrid PV/T (photovoltaic/thermal) air-water collectors are devices that simultaneously convert solar energy into electricity and heat.

A significant amount of research on PV/T collectors has been carried out over the last decade. The review by Zondag [1] covers analytical and numerical models, simulation and experimental work, and qualitative evaluation of thermal/electrical output.

A PV/T collector typically consists of a PV module on the back of which an absorber plate (a heat extraction device) is attached. The purpose of the absorber plate is twofold. Firstly, to cool the PV module and thus improve its electrical performance (electrical efficiency losses amount to 0.4% for each degree of increase of cell temperature with reference to STC (standard test conditions): 25 °C, q" = 1,000 W/m²) and secondly to collect the thermal energy...
As reported by Zondag et al. [2] the electrical and the thermal performance of PV/T collectors is lower than that of separate PV panels and conventional thermal collectors.

However, they emphasized that two PV/T collectors together produce more energy per unit surface area than one PV panel and one thermal collector next to each other.

A lot of parameters affects PV/T performance (both electrical and thermal) such as covered versus uncovered PV/T collectors, optimum mass flow rate, absorber plate parameters (i.e. tube spacing, tube diameter, fin thickness), absorber to fluid thermal conductance and configuration design types. Based on an exergy and cost analysis, water PVT glazed flat plate collector system results the most promising to develop [2].

Moreover, in the last few decades, in the field of electronic components the request for power dissipation continued to increase rapidly following Moore’s law (the number of transistor in a microprocessor would double every 18 to 24 months). Advanced air cooling solutions like heat pipes or high flow rate fans were developed to manage the heat load in CPU and GPU devices at the expense of significant increase in noise level, energy cost and weight. At last, new liquid cooling CDU (coolant distribution unit), after late 1980s stopping, looked strategically to meet the combined high heat loads with low thermal resistance.

Thus, it seems interesting to improve the thermal efficiency of a PV/T system as part of a closed loop single phase water CDU in laminar forced convection.

To study this problem, a mathematical model for the heat sink is used which is able to analyze the thermal and fluid dynamical alterations induced by changes in the channel profile. To optimize the performance of the heat sink in terms of heat transfer to the fluid, a genetic algorithm is employed to maximize the equivalent Nusselt number $N_u e$ and compared effectiveness $E_c$ under pressure and maximum material constraints. The velocity and temperature distributions in the channel’s cross section under conditions of uniform, imposed heat flux at one wall, periodicity at two walls and insulation at the other are computed with the help of a finite element model (a global heat transfer coefficient is calculated). Fabbri [3] already proposed a genetic algorithm optimization for the thermal efficiency of a heat sink analyzing different profiles for its fins (asymmetrical and symmetrical longitudinal wavy fins). In 2009 Copiello and Fabbri [4] proposed a multi-objective genetic optimization of the heat transfer from longitudinal wavy fins. Regarding an industrial module dissipator with a reference internal profile, looking for better thermal efficiency, we have imposed an ideal flux of 1,000 W/m². By means of a genetic algorithm we optimize polynomial upper and lower channel profiles, which are polynomial in nature, whereas the side walls are straight.

2. The Mathematical Model

Let us consider a modular heat sink composed of a large number of identical ducts where a coolant fluid flows in laminar regime under the same conditions, as shown in Fig. 1. A heat flux $q''$ is uniformly imposed on one surface of the heat sink, while the opposite is thermally insulated.

![Fig. 1  Geometry of the heat sink characteristic module.](image)
The inner surface of the ducts is divided into four stretches, each corresponding to one side of the perimeter of its cross section. Of these, two are kept straights, and two (the side walls) can vary their shape according to a polynomial law. Externally, it is delimited by two flat surfaces and two sides having matching shapes which allow two adjacent ducts to be assembled together. In particular, on one side two trapezoidal protrusions are located, while on the opposite side are two trapezoidal cavities. In general, the duct wall must be sufficiently thick to ensure the mechanical consistence of the heat sink. Moreover, on the side where the heat flux is imposed, it must be sufficiently thick to allow screws to be inserted to assemble the heat sink to the system to be cooled. Therefore, some limits must be imposed to the wall thickness on the four sides of the duct in our reference prototype (Fig. 2).

Let us choose an orthogonal coordinate system, where the $x$ axis is laid along the coolant flow direction and the $y$ axis is orthogonal to the surface where the heat flux is imposed. Moreover, let $a$ be the internal duct height in the $y$ direction, $b$ the thickness of the wall where the screws are inserted, $d$ the external duct height, $e$ the external duct width, $f_1(y)$ and $f_2(y)$ arbitraries functions which describe the profiles of the two wavy internal surfaces of the duct, and $\Omega_1$ and $\Omega_2$ the external contour line of the duct cross section on the side where fins and cavities are, respectively.

Since the dynamic and thermal behavior of the whole heat sink is periodic in the $z$ direction, the analysis can be limited to a single duct. The following hypotheses are now introduced:

- the system is at steady state;
- velocity and temperature profiles are fully developed;
- fluid and solid properties are uniform and temperature independent;
- viscous dissipation within the fluid is negligible;
- natural convection is negligible in comparison to the forced convection.

Under such conditions the coolant flow is described by the momentum equation, Eq. (1):

$$\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = \frac{1}{\mu} \frac{\partial p}{\partial x}$$

where $u$ is the fluid velocity, $p$ is the generalized pressure, which includes the gravitation potential, and $\mu$ is the dynamic viscosity. Eq. (1) must be integrated by imposing, as a boundary condition, that the velocity is zero on the contact surface between the fluid and the solid wall.

In the fluid, the temperature $T_c$ must satisfy the following energy balance Eq. (2):

$$\frac{\partial^2 T_c}{\partial y^2} + \frac{\partial^2 T_c}{\partial z^2} = \frac{\rho c_p}{k_c} \frac{\partial T_c}{\partial x}$$

$\rho$, $c_p$, and $k_c$ are being the fluid density, specific heat and thermal conductivity, respectively. In the finned plate, the temperature must instead satisfy the energy equation for a solid, Eq. (3):

$$\frac{\partial^2 T_f}{\partial y^2} + \frac{\partial^2 T_f}{\partial z^2} = 0$$

where $T_f$ is the temperature of the fin.

Eqs. (2) and (3) must be integrated by imposing boundary conditions corresponding to the following:

- the temperature and the heat flux in the normal direction at the interface between the solid and the fluid are identical;
- the heat flux in the normal direction is zero on the insulated flat surface and is equal to $q^*$ on the opposite flat side of the duct.
Optimization with Genetic Algorithms of PVT System Global Efficiency

\[ T(y, \omega_1(y)) = T(y, \omega_2(y)) \]  

(4)

\[ \left[ \frac{\partial T}{\partial N} \right]_{y, \omega_1(y)} = \left[ \frac{\partial T}{\partial N} \right]_{y, \omega_2(y)} \]  

(5)

where functions \( \omega_1(y) \) and \( \omega_2(y) \) provide the value of the z coordinate in \( \Omega_1 \) and \( \Omega_2 \) respectively, and \( N \) is normal to the two lines. It is also necessary to impose a temperature value in one point of the studied domain. Due to the complexity of the problem velocity and temperature distributions must be determined in a numerical way. The finite volume method described in Refs. [3, 5] can also be conveniently applied to the investigated case. In these works parameters \( a, b, d, e \) and the profile functions \( f_1(y) \) and \( f_2(y) \) describe the geometry of the finned conduit. In the studied domain, z coordinate is equal to \( f_1(y) \) on a lateral fin profile and to \( 2e - f_2(y) \) on the other. Dimensionless variables can be obtained by normalizing all geometrical parameters with \( d \):

\[ a = \frac{a}{d}, \beta = \frac{b}{d}, \epsilon = \frac{e}{d}, \eta = \frac{y}{d} \]

\[ \varphi_1(\eta) = \frac{f_1(\eta d)}{d}, \varphi_2(\eta) = \frac{f_2(\eta d)}{d} \]

After determining the velocity and temperature distributions, bulk temperature, global heat transfer coefficient, the equivalent Nusselt number \( Nu_e \), the compared effectiveness \( Ec \) and normalized hydraulic resistance can be defined and calculated as in Refs. [3, 6]. In particular, the equivalent Nusselt number, Eq. (6), is defined as the Nusselt number which would be obtained if the same heat flux removed by the modular dissipator and that dissipated in a flat wall channel with the same hydraulic resistance (Eq. (8)), and the normalized hydraulic resistance \( \xi \) (Eq. (7)) is the ratio between the hydraulic resistance of the modular dissipator and that of a flat wall channel of the same height.

### 3. Geometry Optimization

To optimize the geometry of the duct in order to maximize the equivalent Nusselt number and the compared effectiveness, a genetic algorithm has been used. A polynomial form has been assigned to the functions \( f_1(y) \) and \( f_2(y) \). These functions have then been represented by \( n_1 + 1 \) and \( n_2 + 1 \) parameters, consisting of the values of the functions in \( n_1 + 1 \) and \( n_2 + 1 \) equidistant points in the domain, \( n_1 \) and \( n_2 \) being the polynomial orders. Besides the \( R_{p_{\text{max}}} \) limits the condition of constrained finned plate volume has been taken into account imposing the average thickness \( \sigma_v \). Moreover by imposing, for example, limits on the values of the derivatives of \( f_1(y) \) and \( f_2(y) \) at the end points (corresponding to constraints on the profile’s curvature), the number of possible finned tube geometries can be reduced. After fixing the order of the polynomial function which describes the fin profile (from 1st to 4th order) a new profile is chosen as a prototype (Fig. 2).

The prototype is then reproduced with random mutations uniformly distributed between \(-10\%\) and \(+10\%\), in order to compose an initial population of 10 samples (including the prototype).

For each sample the compared effectiveness is computed. The two samples with the best rank are selected and reproduced with the mutation rule described above. The new generation is evaluated, selected and reproduced in the same way. The process continues until there is no significant improvement in the compared effectiveness of the best sample or is reached a set number of simulations.
The population dimension is chosen on the basis of the polynomial order. With low orders very numerous populations are not required to keep the algorithm from stopping in correspondence of a local maximum whereas larger populations are required for higher order profile functions. In the algorithm it is also possible to impose a local fin thickness (an upper and a lower limit to the fin profile by rescaling the parameter before evaluating the performances).

4. Results

Several tests using the GA (genetic algorithm) have been carried out in order to find the geometries of the channel which maximize the Nusselt number $N_u_e$ and $E_c$ (compared effectiveness).

We start from the unconstrained industrial module heat sink (Fig. 3).

The module fitness rapidly increases with the channel squeezing towards the heated side but industrial manufacturing by extrusion would not be possible and $R_p$ becomes too high.

Now we show (Figs. 4 and 5) the best profile functions in terms of equivalent Nusselt number with second, third or fourth polynomial order with bonds only on $\sigma_s/d$ (fixed volume).

Now for a more realistic analysis a constraint was imposed on $R_p$, namely 50, 100, 500, 1,000 and 2,000 times the standard normalized reference value of a rectangular channel, Eq. (9):

$$R_{ps} = \frac{6\eta}{d^3}e$$

which corresponds to the starting geometry. This has the consequence of decreasing the maximum cold plate efficiency. Stagnation occurs at the corners, which dampens the convective effect (Figs. 6-10).

Lowering the maximum limit of the hydraulic resistance down 10 $R_{ps}$ we note that algorithm can not operate for physical limits of the problem serching optimal thermal solutions.

Fig. 11 shows how $\sigma_s/d$ ratio for different constraints and 4th polynomial order influence module fitness.

Accepting for our profile high hydraulic resistance value up to 2,000 $R_{ps}$, we can observe a monotonous curve until the $\sigma_s/d$ ratio is equal to 0.85.

After this value pressure losses are too high as the energy cost to pump the water inside the heat sink. With a different objective (maximize heat sink channel profile fitness with low pressure loss) lower $\sigma_s/d$ ratio...
near 0.7 gives good result in terms of dissipating efficiency.

Now the authors show the ratio between compared efficiency $E_c$ as a function of the hydraulic resistance of the channel for the 4th order profiles evaluated (Fig. 12).

It is interesting to underline that is not so linear the graph with the dependent variable, but for a particular value of $R_p$, $E_c$ remains almost constant and then returns to increase (effect of profile’s local convective thermal exchange).
5. Conclusions

It is outstanding that the efficiency improving of the heat sink is due to channel profile modifications from 2nd to 4th order.

For a realistic analysis it is important, anyway, to reach an optimum compromise for the profile regarding constraints as fixed volume, hydraulic resistance and profile’s local convective thermal exchange in order to obtain the best working solution.

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Channel Transmission Behavioral Modeling Dedicated to WSNs

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Abstract: The design, manufacture and deployment of embedded systems become increasingly complex and multidisciplinary process. Before the steps of manufacturing and deployment, a simulation and validation phase is necessary. Given the increasing complexity of systems such as telecommunications systems, control systems and others, a specific simulation and validation process must take place. This simulation ideally made in a single development environment should cover different areas and all components of the system. In this paper, the authors briefly describe the behavioral models of the elements of a large scale WSN (wireless sensors network) used to create simulator, focusing specifically on the model of the transmission channel, and how it can retrieve results from the behavioral simulator. Inside to legacy network simulator, for the testing and modeling of communication protocols, this simulator should not omit WSN specific aspect, in accuracy it covers the modeling of node platforms, protocols, and real world phenomena.

Key words: WSN, VHDL-AMS, BER, PER.

1. Introduction

In the design of complex embedded systems, a simulation procedure for validation and verification must be made. It is a time consuming procedure and it is the most challenging factor in determining the “time to market”. To accelerate the design process and reduce the “time to market”, a fast simulation and a high performance should be available to the designer [1, 2].

In order to make decisive, the results of a functional simulation, in particular for architectural exploration (network organization), behavioral models of basic components of the system must replace the real elements and their influences and their responses to any external or internal phenomenon: disturbance, attenuation, delay, power consumption…

WSN (wireless sensor network) applications are diverse ranging from toys to military systems. Typical challenges for WSN are large scale (hundreds of sensors in the case of SHM (structural health monitoring) applications), constantly changing network topology, and error prone communications, while in WSN nodes, processing and storage capacities, as well as energy resources are limited. Most often WSNs are requested to be robust against environmental strains, and able to autonomously recover from error situations. Further, depending on the applications and the interaction with environment, time synchronization and security, requirements can be strict [3, 4].

However, the design space (degrees of freedom for the designer) is very large and makes the design automation the most important challenge for real working WSNs. A designer, simply, can not handle all the parameters, functions, and their complicated dependencies without a tool support [5].

The legacy network simulators can be classified into two categories depending on the nature of the
simulation results. In other words, these simulators are usually designed to respond to developments in WSNs specified by their constraints: communication (protocol and communication stack, auto configuration, communication latency, errors…) or on nodes constraints (size, matching sensors, processing latency…).

The first group of simulators, such as “SensorSim” [6], “NRL (Naval Research Laboratory’s) sensor network simulator” [7], “sQualnet” [8], “SWAN (Simulator for Wireless Ad-hoc Networks)” [9], “sensim” [10], “simulation template” for “EYES” [11], “J-Sim simulator sensor” [12], “VisualSense” [13], “Prowler” [14], “H-MAS” [15] and “SENSE” [16], uses the network concept: it is based on the simulation of computer networks (for computers) such as NS-2 [17], GloMoSim [18], QualNet [19], OPNET [20], OMNeT [21], SSF (Scalable Simulation Framework) [22], and J-Sim [23]. These simulators are focused on the behavior of the wireless network and the protocol stack operation. These simulators are based on existing simulators that have realistic means of transmission, protocol stacks, models of transmission channels vary in their complexity and the phenomena that they include.

The network-oriented simulators model the means of transmission in detail and are more suited to the simulation of large-scale WSNs. These simulators are specialists in the field of networks: they study protocols, allow the addition or removal of elements, the search for an optimal communication path… These simulators are more suitable for people who work on the above constraints and on the development of software platforms for WSNs.

The second group of simulators, such as “TOSSIM” (TinyOS Simulator) [24], “ATEMU” (Atmel Emulator) [25], “TOSSF” (TinyOS Scalable Simulation Framework), an extension of “SWAN” [26], “SENS” [27], “EmSim” [28] and “SNAP” (Sensor Network Asynchronous Processor) [29], focuses mainly on the operation of a single node while implementing a lightweight communication model. These simulators are specific to well-defined nodes and the operating systems that are integrated and verify the compatibility of a node to a given application by responding to its demands.

In these simulations, the transmission channel is simplified: it is achieved either by a simple BER (bit error rate) or by special or ideal models. Similarly, the protocol stacks are simplified or described by the user.

In the following the work for the development of a large scale wireless autonomous sensors network simulator is presented. To do this, a simulator based on the creation of behavioral models, describing each network element has been developed. It is then possible for each type of chosen architecture, to perform a simulation (here in the system vision environment from mentor graphics), to evaluate the performance that will be associated with it, and to draw up a comparative table.

2. The WSN Basis

The elements of sensors networks can be reduced to the five following items:

- Sensor;
- Node;
- Router;
- Hub;
- Transmission channel.

In addition to these objects some "probes" that monitor the relevant parameters throughout the simulation have been developed. They look for example at the BER, the PER (packet error rate), the packet-loosen counter, the latency (time after which data are available to the operator), the energy consumption in real time to meet the specific problem of embedded systems, the desynchronization. Therefore, developed objects models should be generic and configurable to facilitate architectural exploration.

3. The Simulator

The wireless sensors network is a complex system
that combines several areas: analog and digital electronics, energy conversion, power management, wireless technologies, communication protocols, signal processing, thermal effects... To simulate such system in a single environment, with a reduction of the risk of errors, the network models are described in VHDL-AMS (VHSIC hardware description language-analog mixed signal) [30]. It supports the description of mixed-signal systems, multi-disciplinary including electrical, mechanical, hydraulic, etc., at different levels of complexity. Therefore it is possible, given the uniqueness of the description language, to share and to combine models from different domains without having to translate them manually. Fig. 1 shows the role and position of the simulator in the design phase of a system. Based on the description sheet of the WSN specifications can be defined:

- Number and nature of input-output (digital, analog bandwidth, signal amplitude, tolerances...);
- Functions supported;
- Environmental setting;
- Lifetime;
- Restrictions permitted...

Based on these specifications a preliminary design phase defines the technical solutions to use. This design is followed by a functional decomposition of the system which led to propose hardware architecture that defines the technologies and the implemented components. The definition of an architecture that meets the specifications does not imply the feasibility of the product, so a phase of adequacy study of technical solutions with the need is indispensable. Furthermore, it is necessary to ensure consistency between the various techniques of various fields used in the architecture. For this purpose, the simulator must cover in the first hand the gap between architecture level and the physical tests level and in the second hand the gap between different areas. The behavioral patterns of all the system components can be described as following, and the transmission channel model will be detailed later.

3.1 Sensor

The sensor block consists of a physical sensor followed by a conditioning circuit and an analog to digital converter circuit. In the behavioral model, sensor block is modeled by a memory whose contents are swept periodically depending on the sampling frequency and analog/digital conversion frequency. The memory’s content is in respect with the specificity of the physical signals to be simulated: dynamic range, noise, bandwidth...

This general model is parameterized to specify the real sensor in use. So, based on the project’s requirements it can be chose the analog/digital conversion frequency, the sampling frequency, and based on workroom test the power profile, the delays, the type of sensor and its status can be specified.

3.2 Node

The node is an element that collects a maximum of eight data sensors. Its task is to insert a header (address, dating), to organize data using the selected communication protocol, to add an error correction code and to send the data wirelessly via a transmission channel to a router according to a predetermined modulation type.

This general model of node is parameterized to specify the real architecture and techniques used. So based on the project’s datasheet, theory of communication type and correction code, we can choose the header and footer length, and based on
workroom test we can also choose the power profile, the delays, and the number of activated sensors that are associated with this node.

### 3.3 Router

An important task in WSNs consists in delivering the data gathered from the environment to a hub for further processing and evaluation. In most sensor networks the communication is upward (toward the hub: the final recipient) and therefore there is no communication between the sensors. The router appears to be a simple repeater, with delays, incorporating, or no, the functions of error correction.

### 3.4 Hub

The hub is the monitoring center. In wireless sensors networks, it acts as a receiver and data processing unit. The hub applies correction rules included in the error correction code, and it adds corresponding delays.

### 4. The Transmission Channel Model

The transmission channel is the channel through which data are transmitted from a transmitter to a receiver. This part of the transmission line is the hardest part to be modeled because some data are lost and/or modified depending on media quality… The behavior of this element depends on many factors: the type of modulation, the bit rate, the nearby elements, the crosstalk between channels, the noise, the trajectory length…

On the other hand, WSNs often take place in SHM (structural health monitoring) applications, and in this case, it has to be operated under severe constraints, particularly the large variations of the temperature.

The main stage of behavioral model is based on a pseudo random error generator (Fig. 2) that introduces errors in the data flow according to the desired BER. This model is proposed for studies of structural of high fidelity systems like aircraft and aeronautic systems. The BER is computed from two axes:

An experimental setup [31] which allows evaluating the influence of the distance between emitter and receiver, the modulation type, the quality of the media, the number of active channels … on the BER value;

An analytical model for the influence of the temperature and the bandwidth on the BER value.

Taking into account these points, the quality of transmission is defined by the signal to noise ratio:

\[
\text{SNR} = \frac{S}{N} \quad (1)
\]

\(S\) is the power of the signal and \(N\) is the noise power.

This ratio may also be given in dB, in this case:

\[
\text{SNRdB} = 10 \log_{10} \left( \frac{S}{N} \right) \quad (2)
\]

![Fig. 2 Functional blocks of the transmission channel.](image)
The error rate introduced by the transmission line is defined based on the SNR value.

4.1 BER Calculator

The pseudo random generator injects errors into the transmitted packet with a statistical distribution and at a density calculated from the parameters settings and given by the BER. Three steps are needed to do this:

From a preliminary experimental study on the transmission channel, the attenuation of the input signal for different frequencies is measured (Fig. 3). The results are recorded in tabular form in the channel model, and once the architecture is fixed by setting the distance, the power input (PSE) and the frequency, the output power (PS) is computed.

\[
PS \ (\text{dBm}) = \text{PSE} \ (\text{dBm}) - \text{attenuation} \ (\text{dB}) \quad (3)
\]

In a second time the SNR is evaluated. To do this the corresponding block takes the values of the temperature T, bandwidth Bp and seeks the value of the equivalent temperature power noise PB(dBm) from the Eq. (4) where \( K \) is the Boltzmann constant. This noise generally is in the microwatt to mW range, but in WSN, the energy sources are limited, transmission power is less than 0.1 mW so this noise should not be neglected.

\[
P_B \ (\text{dBm}) = 10 \log(Bp \times K \times T) \quad (4)
\]

\[
\text{SNR} \ (\text{dB}) = PS \ (\text{dBm}) - PB \ (\text{dBm}) + N_{\text{Eff}} \ (\text{dB}) \quad (5)
\]

\( N_{\text{Eff}} \ (\text{dB}) \) is a factor of effective noise measured from the experimental setup and depending on the characteristics of the structure under test.

In a third time the value of the BER is related to the value of the SNR by theoretical functions for each modulation technique (Fig. 4). Tables describing these functions are stored in memories and a block can calculate this value. Thus, specifying as input parameters, the modulation type and value of SNR provided by the previous block, the value of the corresponding BER which is expressed in % (number of errors related to the data transmitted) will be calculated.

4.2 Error Generator

To generate errors with respect to the BER value, these ones should be created with a mean period:

\[
\tau = \frac{1}{\text{BER}} \quad (6)
\]

But if one error will be created for each period (\( \tau \)), a uniform distribution will be generated that does not represent real world. To surpass this problem, i.e. respecting BER, but allowing the presence of errors in all possible repartition, a block that generate simultaneously \( k \) errors during \( (k \times \tau) \) had been created. These \( k \) errors are generated by different pseudorandom process. The schematic of the error generator in the transmission channel, extracted from the system vision environment from mentor graphics, is shown in Fig. 5.
4.3 Simulation Results

The implementation of the simulator requires the following steps:
(1) Propose an architecture of WSN (design);
(2) Parameterize the associated models;
(3) Set the output elements to control;
(4) Simulate and evaluate the output elements;
(5) Accept or test a different architecture.

To test this model of transmission channel, a minimized complex network used to measure pressure on the wings of an aircraft during takeoff, flight and landing with a profile of temperature leaving from 300 K to 220 K then 300 K again had been simulated. Each network node contains eight pressure sensors stuck on the wings, the sampling frequency is 22 KHz, the modulation type is 4-PSK and the system architecture is described in Fig. 6 (distances between nodes/routers and routers/hub are in meters).

After simulation results can be illustrated as shown in Fig. 7: (a) the temperature profile; (b) the corresponding variation of the value of the BER; (c) the errors injected and their distribution and (d) the number of errors per packet. In this example, different results will help us to choose the right architecture and parameters that meet the requirements.

5. Conclusions

When networks are studied, two different studies can take place:

- A study of communication protocol taking into account the protocol’s layers, the composition of the frame, the adopted modulation, the reconfiguration, the search of communication path… These studies are common to any network, embedded or not, wired or unwired and are the fields of network specialists;
- A technical feasibility study that examines the environment in which this network should work, disturbing noises, the used techniques influences, the source of communication data, energy consumption, real-time performance…

In the context the authors are interested in the second study by proposing a behavioral simulation tool for WSNs, to reduce simulation time, to facilitate architectural exploration and to converge more quickly towards an acceptable solution from the viewpoint of the requirements.

References


Electricity Generation and the Present Challenges in the Nigerian Power Sector

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Abstract: National development requires adequate electricity supply of which all activities—generation, transmission and distribution leading to it are capital-intensive in terms of funds, natural and human resources. The dwindling power sector government funding coupled with low private sector participation and weak level political will require creative and innovative solutions in addressing the power supply problem in Nigeria. Hence, this paper seeks to examine power sector privatization as a viable option.

Key words: Energy resources, electricity generation, power, development, demand and supply.

1. Introduction

Nigeria is a vast country with a total of 356,667 sq miles (923,768 sq km), of which 351,649 sq miles (910,771 sq km or 98.6% of total area) is land. The nation is made up of six geo-political zones subdivided into 36 states and the FCT (federal capital territory). Furthermore, the vegetation cover, physical features and land terrain in the nation vary from flat open savannah in the north to thick rain forests in the south, with numerous rivers, lakes and mountains scattered all over the country. These national physical and political attributes themselves present challenges for the effective provision of power needs to all nooks and crannies of the country.

To provide adequate power in order to ensure that Nigeria is among the industrialized nations, three critical activities must be effectively achieved:

- Adequate power must be generated;
- The power must effectively be transmitted to all parts of the country;
- Finally the power must be efficiently distributed to the consumers.

Since development and population growth in any country are highly dynamic, these three activities must also be carefully addressed in a dynamic, creative and logical manner.

Adequate power supply is an unavoidable prerequisite to any nation’s development, and electricity generation, transmission and distribution are capital-intensive activities requiring huge resources of both funds and capacity. In the prevailing circumstances in Nigeria where funds availability is progressively dwindling, creative and innovative solutions are necessary to address the power supply problem.

The administration of President Umaru Musa Yar’adua has already unveiled a mission, setting an agenda of industrializing Nigeria by 2020, which is in the next 10 years. This conference is therefore one of the highest and administrative governing structures that must consider and proffer practicable solutions to the
Electricity Generation and the Present Challenges in the Nigerian Power Sector

This paper therefore presents a brief history of the attempts and efforts to supply power to the nation. It also briefly reviews the current status of energy resources, energy demand and supply, power generation, transmission and distribution, power sector national policy, summary of the major challenges and the way forward.

2. Overview

To discuss the power sector in Nigeria in a realistic and practical context, some brief review is necessary to give an insight into the sector since independence.

Electricity supply in Nigeria dates back to 1886 when two small generating sets were installed to serve the Colony of Lagos. By an Act of Parliament in 1951, the ECN (Electricity Corporation of Nigeria) was established, and in 1962, the NDA (Niger Dams Authority) was also established for the development of hydroelectric power. However, a merger of the two was made in 1972 to form the NEPA (National Electric Power Authority), which as a result of unbundling and the power reform process, was renamed PHCN (Power Holding Company of Nigeria) in 2005.

The Nigerian power sector is controlled by state-owned PHCN (Power Holding Company of Nigeria), formerly known as the NEPA (National Electric Power Authority). In March 2005, President Olusegun Obasanjo signed the Power Sector Reform Bill into law, enabling private companies to participate in electricity generation, transmission, and distribution.

The government has separated PHCN into eleven distribution firms, six generating companies, and a transmission company, all of which will be privatized. Several problems, including union opposition, have delayed the privatization, which was later rescheduled for 2006. In February 2005, the World Bank agreed to provide PHCN with $100 million to assist in its privatization efforts.

The Nigerian government has made an effort to increase foreign participation in the electric power sector by commissioning IPPs (independent power projects) to generate electricity and sell it to PHCN. In April 2005, Agips 450-MW plant came online in Kwale in Delta State. The NNPC and JV (Joint Venture) partners, ConocoPhillips and Agip, provided $480 million to construct the plant. IPPs currently under construction include the 276-MW Siemens station in Afam, Exxon Mobils 388-MW plant in Bonny, ABBs 450-MW plant in Abuja, and Eskoms 388-MW plant in Enugu. Several state governments have also commissioned oil majors to increase generation including Rivers State, which contracted Shell to expand the 700-MW Afam station. The Nigerian government also approved the construction of four thermal power plants (Geregu, Alaoji, Papalanto, and Omotosho), with a combined capacity of 1,234 MW to meet its generating goal of 6,500 MW in 2006. In addition, 14 hydroelectric and natural gas plants were planned for kick-up but yet to commence since then. Chinese EXIM Bank Su Zhong and Sino Hydro have committed to funding the Mambilla (3,900-MW) and Zungeru (950-MW) hydroelectric projects. In addition, Sino Hydro proposed that it should construct the two power projects. Also, NNPC, in a JV with Chevron are to construct a 780-MW gas-fired thermal plant in Ijede, Lagos State. The project is expected to be constructed in three phases, with the first two phases expected to have capacity of 256 MW each. The plant is expected to be operational in 2007 but yet to commence construction.

While Nigerians development of the Oil sector has been good for the country’s economy, oil sector development has had an adverse impact on the country’s environment. Oil extraction in the Niger Delta region has caused severe environmental degradation, owing to the legacy of oil spills, lax environmental regulations, and government complicity during military regimes that once governed the country. Although the situation is improving with more stringent environmental regulations for the oil industry,
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Marine pollution is still a serious problem. Air pollution from natural gas flaring, exhaust emissions from the explosion in car ownership, and electricity generators continue to leave Lagos which is the most industrialized and the most populated city shrouded in smog. The use of solid biomass, such as fuel wood, is prevalent and constitutes a major energy source for rural Nigerians. The production and consumption of commercial renewable energy in Nigeria remains quite limited. With Nigerians population continuing to increase, the pressure on the country’s environment appears likely to increase as well, even with the added focus on cleaning up the Niger Delta and tightening environmental laws and regulations.

3. Energy Resources in Nigeria

Nigeria is Africa’s energy giant. It is the continent’s most prolific oil producing country, which, together with Libya, accounts for two-thirds of Africa’s crude oil reserves. It ranks second to Algeria in natural gas. Most of Africa’s bitumen and lignite reserves are found in Nigeria. In its mix of conventional energy reserves, Nigeria is simply unmatched by any other country on the African continent. It is not surprising, therefore, that energy export is the mainstay of the Nigerian economy. Also, primary energy resources dominate the nation’s industrial raw materials endowment.

Electricity energy production in Nigeria over the last 40 years varied from gas-fired, oil-fired, hydroelectric power stations to coal-fired with hydroelectric power system and gas-fired system taking precedence.

This is predicated by the fact that the primary fuel sources (coal, oil, water, gas) for these power stations are readily available. Nigeria’s coal reserves are large and estimated at 2 billion metric tonnes of which 650 million tonnes are proven reserves. About 95% of Nigeria’s coal production has been consumed locally; mainly for railway transportation, electricity production and industrial heating in cement production.

Nigeria has an estimated 176 trillion cubic feet of proven natural gas reserves, giving the country one of the top ten natural gas endowments in the world and the largest endowment in Africa. Natural gas is a natural occurring gaseous mixture of hydrocarbons gases found in underground reservoirs. It consists mainly of methane (70%-95%). With small percentage of ethane, propane, butane, pentane and other heavier hydrocarbons with some impurities such as water vapour, sulphides, carbon dioxides, etc. [1]. Apart from the export potential of the Nigerian gas, local demand opportunities are power generation, cement industry, iron and steel plants. The largest single consumer of natural gas in Nigeria is PHCN and it accounts for about 70% used to operate electricity generating gas plants in Afam, Ughelli, Sapele and Egbin.

4. Energy Demand and Supply Scenario

Electricity plays a very important role in the socio-economic and technological development of every nation. The electricity demand in Nigeria far outstrips the supply and the supply is epileptic in nature. The country is faced with acute electricity problems, which is hindering its development notwithstanding the availability of vast natural resources in the country. It is widely accepted that there is a strong correlation between socio-economic development and the availability of electricity.

The ECN (Energy Commission of Nigeria) was established by Act No. 62 of 1979, as amended by Act No. 32 of 1988 and Act No. 19 of 1989, with the statutory mandate for the strategic planning and co-ordination of national policies in the field of energy in all its ramifications. By this mandate, the commission which is the apex government organ empowered to carry out overall energy sector planning and policy co-ordination. As part of its contribution to the resolution of the problems of the electricity sector along the line of its mandate, the ECN has been collaborating with the IAEA (International Atomic Energy Agency) under an IAEA regional project titled “Sustainable Energy Development for Sub-Saharan Africa (RAF/0/016)".
The project entails capacity building for energy planning and the determination of the actual energy demand and the strategies for supply for each participating country over a 30-year time horizon. The implementation of the project requires the establishment of a WT (working team) and a CST (country study team) both of which include the major public and private stakeholders in the energy sector of the country. The working team consists of technical experts that directly implement the project and reports to the CST, which serves as the steering committee for the project on a regular basis. Members of the WT were trained on the use of the IAEA models and have computed the Nigeria energy demand and supply projections covering the 2005-2030. The project involves the use of the following IAEA energy modelling tools [2]:

- MAED (model for the analysis of energy demand);
- MESSAGE (model for the energy supply strategy alternatives and their general environmental impact).

4.1 Energy Demand Projection

The energy demand projections were computed using MAED with the key drivers of energy demand, namely demography, socio-economy and technology. The application of MAED requires detailed information on demography, economy, energy intensities and energy efficiencies. This information is first assembled for a base year which is used as the reference year for perceiving the evolution of the energy system in the future. Selection of the base year is made on the basis of availability of data, assessment that the data are representative of the economic and energy situation of the country [2].

MAED allows the breakdown of the country’s final energy consumption into various sectors and within a sector into individual categories of end-uses in a consistent manner. The breakdown helps in the identification of the social, economic and technical factors influencing each category of final energy demand. In modelling the Nigeria’s energy case, four economic scenarios were developed and used as follows:

- Reference scenario—7% GDP growth;
- High growth scenario—10% GDP growth;
- Optimistic scenario I—11.5% GDP growth;
- Optimistic scenario II—13% GDP growth (based on Presidential Pronouncement for the desire to be among the first 20 economies by 2020) [2].

Economic growth and structure of the economy are the major driving parameters in the four scenarios. Projected electricity demand has been translated into demand for grid electricity and peak demand on the bases of assumptions made for T&D losses, auxiliary consumption, load factor and declining non-grid generation. Table 1 shows the electricity demand projections for the scenarios. It must be emphasized that the demand indicated for 2005 represents suppressed demand, due to inadequate generation, transmission, distribution and retail facilities. Suppressed demand is expected to be non-existent by 2010.

For the 13% GDP growth rate, the demand projections rose from 5,746 MW in the base year of 2005 to 297,900 MW in the year 2030 which translates to construction of 11,686 MW every year to meet the demand. The corresponding cumulative investment (investment & operations) cost for the 25-year period is US$484.62 billion, which means investing US$80.77 billion every five years within the period. In conducting the studies, all the available energy resources in the country were considered in order to broaden the nation’s energy supply mix and enhance its energy security.

4.2 Energy Supply Projection

The total energy supply were computed using MES-SAGE and utilizes the projected energy demand as an input to produce a supply strategy. MES-SAGE is an energy supply model, representing energy conversion and utilization processes of the energy system (or its part) and their environmental impacts for an exogenously given demand of final energy. It is used
for development of medium-term strategies, the planning horizon being in the order of 30 years. The time scope is limited due to uncertainties associated with future technological development. The energy system dynamics are modelled by a multi period approach. It is an optimization model which from the set of existing and possible new technologies selects the optimal in terms of selected criterion mix of technologies able to cover a country’s demand for various energy forms during the whole study period [3].

MESSAGE takes into account demand variations of various final energy forms during the day, week and year, as well as different technological and political constrains of energy supply. It is an energy and environmental impact model, enabling the user to carry out integrated analysis of the energy sector development and its environmental impacts. The application of the MESSAGE model results in a least-cost inter-temporal mix of primary energy, energy conversion and emission control technologies for each scenario. For the computation of Nigeria’s energy supply the same scenario that was used in MAED is used. The result for the electricity supply projections is shown in Table 2.

5. Key Sector Indicator

Nigeria currently has 14 generating plant which supply electric energy to the national grid. Of the 14 generating plants, three are hydro and 11 are thermal (gas/steam). The national grid is made up of 4,889.2 km of 330 kV line, 6,319.33 km of 132 kV line, 6,098 MVA transformer capacity at 330/132 kV and 8,090 MVA transformer capacity at 132/33 kV [4].

Due to the importance of the sector, President Umaru Musa Yar’Adua, immediately after he was sworn in May 29, 2007, recognized the urgency of the emergency on the sector by specifically addressing the problems of the sector in an urgent and immediate basis and eliminating the usual bureaucratic time wasting procedures of treating issues of the sector, while ensuring that due process is not compromised.

Accordingly, a program of action is currently being formulated to address the problems of the sector in the short term, medium term and long term. In the next nine months in the short term (2005), it may be realistic to concentrate mainly on the effective and efficient utilization of the existing generation and transmission infrastructures as well as completing the NIPP. The following should be achieved:

- Maintaining and sustaining a minimum generation of the available capacity of 5,800 MW;
- Reduce Transmission and Distribution power outages by at least 75%;
- Reducing transmission and distribution technical losses;
- Increasing revenue collection in PHCN by 50%;
- Improving on customer service delivery in the distribution and marketing section of PHCN;
- Improving on health, safety and environmental measures in generation, transmission and distribution of electricity.

To achieve these, the issues that must be addressed in generation, transmission, distribution and marketing are as follows.

5.1 Generation

The total installed capacity of the currently generating plants is 7,876 MW (Table 3), but the
Electricity Generation and the Present Challenges in the Nigerian Power Sector

Table 2  Electricity supply projections per scenario, MW.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (7%)</td>
<td>6,440</td>
<td>16,668</td>
<td>28,356</td>
<td>50,817</td>
<td>77,450</td>
<td>136,879</td>
</tr>
<tr>
<td>High growth (10%)</td>
<td>6,440</td>
<td>15,861</td>
<td>30,531</td>
<td>54,275</td>
<td>107,217</td>
<td>192,079</td>
</tr>
<tr>
<td>Optimistic I (11.5%)</td>
<td>6,440</td>
<td>15,998</td>
<td>31,235</td>
<td>71,964</td>
<td>177,371</td>
<td>276,229</td>
</tr>
</tbody>
</table>

Table 3  Existing power generation capacity in Nigeria.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Plant</th>
<th>Plant type</th>
<th>Location state</th>
<th>Age (years)</th>
<th>Installed units</th>
<th>Installed capacity (MW)</th>
<th>Units available</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Egbin</td>
<td>Thermal</td>
<td>Lagos</td>
<td>22</td>
<td>6</td>
<td>1,320</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Egbin AES</td>
<td>Thermal</td>
<td>Lagos</td>
<td>6</td>
<td>9</td>
<td>270</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Sapele</td>
<td>Thermal</td>
<td>Delta</td>
<td>25-29</td>
<td>10</td>
<td>1,020</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Okapi</td>
<td>Thermal</td>
<td>Cross River</td>
<td>2</td>
<td>3</td>
<td>480</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Afam</td>
<td>Thermal</td>
<td>Rivers</td>
<td>25</td>
<td>20</td>
<td>702</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Delta</td>
<td>Thermal</td>
<td>Delta</td>
<td>17</td>
<td>18</td>
<td>840</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>Omoku</td>
<td>Thermal</td>
<td>Rivers</td>
<td>2</td>
<td>6</td>
<td>150</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Ajaokuta</td>
<td>Thermal</td>
<td>Kogi</td>
<td>Na</td>
<td>2</td>
<td>110</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>Geregu</td>
<td>Thermal</td>
<td>Kogi</td>
<td>1</td>
<td>3</td>
<td>414</td>
<td>3</td>
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<td>10</td>
<td>Omotosho</td>
<td>Thermal</td>
<td>Ondo</td>
<td>New</td>
<td>8</td>
<td>335</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>Olorunsogo/Papalanto</td>
<td>Thermal</td>
<td>Ogun</td>
<td>New</td>
<td>8</td>
<td>335</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Sub-total (thermal)</td>
<td></td>
<td></td>
<td></td>
<td>93</td>
<td>5,976</td>
<td>44</td>
</tr>
<tr>
<td>12</td>
<td>Kainji</td>
<td>Hydro</td>
<td>Niger</td>
<td>38-40</td>
<td>8</td>
<td>760</td>
<td>6</td>
</tr>
<tr>
<td>13</td>
<td>Jebba</td>
<td>Thermal</td>
<td>Niger</td>
<td>24</td>
<td>6</td>
<td>540</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>Shiororo</td>
<td>Thermal</td>
<td>Niger</td>
<td>22</td>
<td>4</td>
<td>600</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Sub-total (hydro)</td>
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<td></td>
<td></td>
<td>18</td>
<td>1,900</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Grand total</td>
<td></td>
<td></td>
<td></td>
<td>111</td>
<td>7,876</td>
<td>58</td>
</tr>
</tbody>
</table>

Summary

<table>
<thead>
<tr>
<th></th>
<th>% Thermal</th>
<th>% Hydro</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>84</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>76</td>
<td>24</td>
</tr>
</tbody>
</table>

installed available capacity is less than 4,000 MW as at December 2009. Seven of the fourteen generation stations are over 20 years old and the average daily power generation is below 2,700 MW, which is far below the peak load forecast of 8,900 MW for the currently existing infrastructure. As a result, the nation experiences massive load shedding.

Through the planned generation capacity projects for a brighter future (Table 4), the current status of power generation in Nigeria presents the following challenges:

(i) Inadequate generation availability;
(ii) Inadequate and delayed maintenance of facilities;
(iii) Insufficient funding of power stations;
(iv) Obsolete equipment, tools, safety facilities and operational vehicles;
(v) Inadequate and obsolete communication equipment;
(vi) Lack of exploration to tap all sources of energy form the available resources;
(vii) Low staff morale.

5.2 Transmission

The transmission system in Nigeria system does not cover every part of the country. It currently has the capacity to transmit a maximum of about 4,000 MW [5] and it is technically weak thus very sensitive to major disturbances. In summary, the major problems identified are:

(i) It is funded solely by the Federal government whose resource allocation cannot adequately meet all the requirements;
(ii) It is yet to cover many parts of the country;
(iii) It is current maximum electricity wheeling capacity is 4,000 MW which is awfully below the required national needs;
### Table 4  Planned total present and future electricity generation infrastructure in Nigeria.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Power station</th>
<th>Type</th>
<th>State</th>
<th>Capacity (MW)</th>
<th>Status</th>
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<tr>
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</tr>
<tr>
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<td>6</td>
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<td>7</td>
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<tr>
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</tbody>
</table>

(iv) Some sections of the grid are outdated with inadequate redundancies as opposed to the required mesh arrangement;  
(v) The Federal government lack the required fund to regular expand, update, modernize and maintain the network;
(vi) There is regular vandalization of the lines, associated with low level of surveillance and security on all electrical infrastructure;

(vii) The technologies used generally deliver very poor voltage stability and profiles;

(viii) There is a high prevalence of inadequate working tools and vehicles for operating and maintaining the network;

(ix) There is a serious lack of required modern technologies for communication and monitoring;

(x) The transformers deployed are overloaded in most service areas;

(xi) In adequate of spare-parts for urgent maintenance;

(xii) Poor technical staff recruitment, capacity building and training programme.

5.3 Distribution & Marketing

In most locations in Nigeria, the distribution network is poor, the voltage profile is poor and the billing is inaccurate. As the department, which inter-faces with the public, the need to ensure adequate network coverage and provision of quality power supply in addition to efficient marketing and customer service delivery can not be over emphasize. In summary some of the major problems identified are:

(i) Weak and inadequate network coverage;

(ii) Overloaded transformers and bad feeder pillars;

(iii) Substandard distribution lines;

(iv) Poor billing system;

(v) Unwholesome practices by staff and very poor Customer relations;

(vi) Inadequate logistic facilities such as tools and working vehicles;

(vii) Poor and obsolete communication equipment;

(viii) Low staff morale and lack of regular training;

(ix) Insufficient funds for maintenance activities.

6. Power Sector National Policy

The PHCN was set up to coordinate the privatization process to ensure successful privatization of the power sector [6]. Presently, a chief executive officer can operate independent of any other unbundled company heads each unbundled company. They all, including the coordinator in the liaison office, receive funds for their day-to-day operations from the market operator who disburses the funds according to certain laid down criteria. Each company is also empowered, through with limitations to operate as a commercial company. It is currently planned that each of the successor companies shall operate as a fully commercialized company. The PHCN structure shall also be retained to oversee the activities of the Managing Director/CEOs of the successor companies. This structure should operate for a limited period of five years this will make companies privatized [7].

In addition, to restructuring NEPA government through the NIPP and PHCN also made attempts to develop the infrastructure in generation, transmission and distribution on fast track basis. The aim was to improve power supply to consumers. In order to achieve that, the federal government in collaboration with state government embarked on the implementation of new generation, new gas pipelines, a new transmission and new distribution networks in 2005, using the excess crude account. The projects were estimated to cost N1.23 trillion out of which about N361 billion was released [8].

7. Major Challenges

From the above brief presentation, the following are some of the most critical challenges of the power sector responsible for the generation short falls, transmission bottlenecks, and distribution problems in Nigeria:

(i) Poor utilization of existing assets and deferred maintenance;

(ii) Delays in the implementation of new projects;

(iii) Lack of sustained, sound and practicable relationship between the federal government and other stakeholders particularly the JV international oil companies and the IPP (independent power producers);
(iv) Inadequate power evacuation at newly completed and fictionalized power plants;
(v) Erratic supply of gas domestic resources for power generation;
(vi) The national grid is yet to cover many parts of the country;
(vii) Vulnerable and overloaded existing transmission system;
(viii) Poor voltage profile to the tail-end consumer;
(ix) Current maximum electricity wheeling capacity is 4,000 MW which is awfully below the required national needs;
(x) Some sections of the National Grid are outdated with equipments in a state of poor and inadequate maintenance;
(xi) The federal government being the only provider of funds to expand to the national grid did not commit the required funds to regularly expand, update, modernize and maintain the sector;
(xii) Regular vandalism of the gas lines, and cable lines, associated with low level of the surveillance and security on all electrical infrastructure;
(xiii) High prevalence of inadequate working tools, vehicles and spare-parts for operating and maintaining the power system;
(xiv) There is a serious lack of required modern technologies or communication and monitoring of the generation, transmission and distribution infrastructure;
(xv) Low customer satisfaction (load shedding, poor voltage profile, inaccurate billing, difficulties in paying bills, no-notice disconnections, etc.);
(xvi) Poor technical staff recruitment, capacity building and training programme;
(xvii) Inappropriate tariff that would enable the utility to get adequate funds to maintain and expand the infrastructure.

8. Way Forward

To address the challenges listed above, a drastic and innovative strategy is required, most especially as energy generation, transmission and distribution in Nigeria for appropriate development is a priority issue of government.

8.1 Planning and Operations

A comprehensive review of the operation and management of Power Sector targeted at efficiency and effectiveness is required. In that respect, the following should be undertaken:

(i) A detailed national load demand study should be carried out with a view to providing reliable information on the current practical and detailed power requirements and a futuristic forecast for the next 25 years (The World Bank is currently supporting some work on this);
(ii) A detailed and practicable power generation, transmission and distribution master plan for Nigeria for today and the next 25 years should be produced;
(iii) A detailed cost implication on a phased development and operating the power supply system on state-by-state basis is required;
(iv) Strategic roles of the States and local governments in the implication of the national masterplan must be explicitly stated;
(v) A cost sharing formula for all tiers of government to fully participate in the development of national power supply must evolve;
(vi) The institutional arrangement on how the power sector will function with the federal government as the central implementation organ, working in tandem with the states and local governments should evolve;
(vii) The clear roles of the states in the energy sector, specifically required to serve as the state monitoring facility on resource contributions, utilization and system efficiency should be strategize.

8.2 Funding

To demonstrate the urgency and resource requirements on power supply which give the additional power and resources required in countries that could be defined as less fortunate with resources
compared with Nigeria. While the per capita power generation ranges from 3 kW to 6.6 kW in those countries, the corresponding figure for Nigeria is 0.05. This is literally shameful and unacceptable.

It can be estimated that the average cost for adding a mega watt of electricity is US$1.5 million. This demonstrates the resources required in power supply to develop and particularly industrialized any country on a sustainable manner, are large. Based on this index, it therefore can be estimated that from the staggering current generation capacity of about 3,000 MW in the country, Nigeria would have to invest a whopping US$150 billion (N18 trillion) to generate additional 100,000 MW, to attain the required for full industrialization of our economy by 2020 which was computed by the Energy Commission of Nigeria using a growth rate of 13%. The financial requirement is phenomenal.

The combined determination of Mr. President to declare a state of emergency on power supply in the country, and the administration’s firm commitments of industrializing Nigeria by 2020 must be taken very seriously. However, it is worth nothing closely that the federal government has, since independence, remained the major financier of power supply in Nigeria. This might have followed a political history of the country since independence, where the Military Governments that dominated the administration, institutionalized the concept of establishing and developing the power sector as the sole responsibility of the Federal Government. Furthermore, under the military traditions, the Military Head of State (federal government) had always directly appointed the State Governors and had dictated resource allocations to the States from the Federation Accounts and literally also tele-guided the implementation of most capital projects executed in the States. This scenario under a democratic system of government as currently practiced in Nigeria is not feasible. A deliberate and proactive strategy is required to ensure that all tiers of government fully participate in this National Priority sector.

It is therefore opined that, in view of the vision for power to be provided on a sustained stable basis to the entire nation, all tiers of government, similar to the strategy deployed on the provision of roads/highways network that we currently operate in the country.

The concept being proposed is that, in view of the large investment required for the development of the generation, transmission and distribution networks, states and local government should contribute a certain percentage of the total cost similar to the concept on road-network where all tiers of government participate in development, maintenance and repairs.

References

Design of a Photovoltaic Panel Orientation System

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Abstract: This work highlights the design and the realization of an automatic solar-panel orientation system in order to achieve high-performances. The solar panel sensor constitutes the main part of the system, since it ensures the pursuit of the sunbeam. The management of the system, depending on the movements, the presence of sun, and the regular checkup of the system evolution, is ensured by an electronic unit executed around a microcontroller.

Key words: Solar energy, photovoltaic panel, sensor, microcontroller.

1. Introduction

Nowadays, a great interest to the renewable energy exploitation (geothermic, wind, solar…) is noticed in many countries of the world. This interest is a result of economical and ecological problems generated by the massive use of fossil energies (oil, coal, gas…). Moreover, the reserve of these energies does not cease decreasing and the prices do not cease fluctuating enormously according to the economic situation. An attempt to better exploit these energies then, becomes a shared objective of several communities of the world.

Solar energy is very promising. It may play an important role in the replacement of fossil energies. It is known that the earth receives approximately 10,000 times from the sun the total quantity of the power consumed by the entire humanity, this explain why an increasing importance is given to solar energy these last years.

The aim of this work is to design and realize an automatic sun-position following system. The main objective is to increase the output of a photovoltaic panel by maintaining its position suitably towards the sun.

Compared to the work presented in Refs. [1, 2], this paper presents a system that is indicated to follow the position of the sun with an intelligent way. It takes into account the various disturbances which can influence the good work of the system (clouds, night…). The system also makes possible to catering the load with the maximum of energy provided by the panel, thus it makes the real consumption of the whole system directly be taken out from the panel as long as there is sun. In the absence of this latter, the system makes it possible to take its needs of energy out from a refillable battery.

This work is achieved within the framework of an end of studies project at the national school of engineering of Gabes (laboratory RCCPI). In this article, the project will be described starting first of all, with the study of the whole problem, in order to implement the basic contributions of the work. Then, the recommended solution and the functionality of the system components will be presented. The last part describes the practical realization and the exhibition of the trials carried out on the system within the laboratory.

2. Issue

Once it is exposed to sun, a photovoltaic panel produces an electric power. The produced energy is
related to several factors (altitude, temperature, angle of incidence...) that influence its output.

The purpose of this work consists in improving the solar panel effectiveness by acting on the angle of incidence which has a huge importance on the output of the photovoltaic module.

As shown in Fig. 1, the angle of incidence is the sunbeam projection angle on the plane of the solar panel.

It can be defined according to the following equation [3]:

\[ R = 100 \sin(\beta) \]

With: \( R \) is the output of the panel in \%, \( \beta \) the angle of incidence. Fig. 2 shows the output variation function of \( \beta \).

Thus, it is clear that the output is indeed influenced by the orientation of the solar panel and it is at its peak when the sun rays arrive upright to the panel:

\[ R = 100 \sin\left(\frac{\pi}{2}\right) = 100\% \]

In fact, the position of the sun varies perpetually, not only during daylight but also during the year as indicated in Fig. 3.

Then the sun does not follow the same trajectory each day, the fact that put us face ward a complicated problem of sun-position following. In addition, disorders can appear from time to time such as the night, the clouds and the intervention of the user facts that increase the complexity of the problem [5, 6].

3. Solution

The suggested solution consists in the design of a system allowing the solar panel to follow the position of the sun in order to maintain an angle of incidence \( \beta = \pi/2 \).

To guarantee a fast and prompt movement of the panel, a mechanical system device containing two articulations in pivot connection is recommended. This system makes possible to point the normal panel surface exactly towards each point of the space swept by the sun. The movement is then, ensured by two actuators allowing the panel to turn around its horizontal and vertical axes.

Fig. 1  Angle of incidence.

Fig. 2  A graphic showing the variation of the output according to the angle of incidence.

Fig. 3  Various positions of the sun.

To follow the sun position, two sensors are used: one to detect the presence of the sun and another to detect the angle of incidence \( \beta \).

The control unit receives the information sent by the sensors and emits the suitable control signals towards the actuators via a power unit. In the case of sun absence, the control unit sets the system in alert. A graphic interface is made to allow the user supervising and following the evolution of the system. The diagram in Fig. 4 presents the various interactions between the basic equipments of the system [7].
4. Functionality and Mechanism of the System

To understand the principle of operation of the system, a description of the diagram is presented in Fig. 4.

4.1 Sensors

Sun presence sensor

This sensor is performed basically by photo-resistance. It is placed at the highest point of the system device that is not to be bothered by any other component and not to undergo any shade either. The signal received by the sensor passes through a conditioning circuit and resent to the control unit. This latter may start the process once the level of tension received (0 or +5 V) correspond to the level affected with the presence or absence of the sun.

Sun position sensor

This sensor is also performed by photo-resistance. It gives a plain idea about the sun position according to the surface of the panel. This sensor sends a signal of (0 or +5 V) throughout the conditioning circuit towards the control unit which launches the correct order of movement that would be realized by the operative part.

4.2 Control Unit

The control unit is the intelligent part of the system. It consists of a mother card containing a microcontroller 16F877A programmed out of C language. The system can communicate with the computer through the serial standard RS232. Fig. 5 describes in short the cycle of the system control.

The control unit receives data sent by the sensors in the form of a binary word coded on 10 bits. This binary word describes the sun presence sensors status, sun position sensors’ and butted of race end status. The treatment of the data by the control unit lets the latter send the suitable control signals towards the operative part.

4.3 Operating Unit

This unit is composed of two engines with direct current of low power. An engine M1 allows the adjustment of the vertical slant angle of the panel. An engine M2 ensures the rotation of the axis to adjust the horizontal angle. Each engine is accompanied by a reducer aiming to decrease the speed of revolution and to multiply the torque. Fig. 6 gives an outline on the assembly of the system.

5. Realization and Check

The solution suggested is characterized by two strong points of operation that prove the effectiveness and the intelligence of the sun-following system:

- The first point consists in a process of sun research which is launched out once the sensor detects the presence of sun after a period of absence (night, cloud or maintenance...);
The second point consists in a process of training which makes the system be able to adapt with the place where it was placed. After the design and the realization of the system, practical tests have been carried out in order to assess its performance.

A test comparison between a fixed panel (has a fixed position) and directed panel (sun follower) is realized. Each 15 minutes the tension and the current of the system connected to a fixed load is mentioned. Power \( P = U \times I \) is calculated then. Fig. 7 describes the evolution of the power according to time (measurements made on April 19, 2011 at temperature: 11-23 °C, moisture: 60%, wind: 26 km/h, and visibility: 10 km).

Two operative modes are available in the system:
- Manual mode;
- Automatic mode.

To select the operating mode the user has just to press one of the two buttons placed in a tight metal box.

5.1 Manual Mode

This mode ensures the manual orientation of the panel in the four directions (right/left and up/down). It allows controlling the panel manually and in a permanent way what is neither practical nor advised and is not the purpose of this work once more. Where as, this mode determines the starting point of the operation cycle. Then the switch to the automatic mode corrects the manual adjustment and starts the automatic cycle. The system, default start mode is always manual.

Even if the user starts in automatic mode without taking the sun position in consideration, the system waits 16 minutes and launches the research process. If the sun is unavailable (the night for example), the system awaits its appearance to start the process. The system is then autonomous, which makes the mode manual usable either in the case of system starting or in other particular cases.

5.2 Automatic Mode

To over go the bothersome conditions (clouds, night, user intervention…) some precautions should be taken.

When clouds pass in a slower or faster speed, the sun sensor remains sensitive to the sooner return of the solar rays. The system is shut down once sunbeams are absent and restarts automatically to their return.

In a prolonged absence of the solar rays (more than three hours), the system adopts an awaiting position by positioning the panel to a slope of 45° (operation of the M1 engine).

The engine M2 reacts carrying out a circular sweeping setting the sensor on when it comes across the solar rays. An adjustment of the position is then led. In the research process, the engine M2 turns on until it stops when contacting the race end butted. After a short temporization, an opposite wise rotation is started and M2 stops when the sensor receives sunrays. To shorten
the searching time for the sun, in order to reduce power loss, the system records the most frequent way of movement and adopts it as favorite.

6. Conclusions

The work presented in this paper concerns the design and the realization of a solar panel orientation system in the purpose of having the best performance. This requires that the plane of the panel be continuously perpendicular to the solar rays. Following the movement of the sun is the only solution to ensure this circumstance. The solar ray sensor makes up the essential element of the system since it is the only one that ensures sun-position detection.

The management of the whole tasks of the system such as the movements, the incidences of sun presence, the management of energy and the follow-up of the system evolution, is ensured by an electronic circuit carried out around a microcontroller. The designed system tests are in a perfect conformity with the objectives laid down for this work. Fig. 8 presents a photo of the realized system.

However, other improvements to increase the system effectiveness are possible such as the addition of an inverter, the integration of a dependability system or even the improvement of the driving mechanical system.

References

Use of Renewable Energy Sources in Saudi Arabia through Smart Grid

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Abstract: Even though Saudi Arabia is the world's largest producer and exporter of petroleum and petroleum based products, it is also blessed with high potential of renewable energy sources like solar and wind. Untapped wind and solar energy sources, which are abundant throughout the kingdom, can be connected and optimally integrated into the grid through the use of smart grid technologies and the expansion of transmission facilities. Smart grid is an auto-balancing, self-monitoring power grid that accepts power from any source of fuel like oil, sun or wind and delivers electricity from suppliers to consumers. It helps to control the use of appliances in order to save energy, reduces cost and increase reliability. This paper describes the attributes of a smart grid and how these act as driving force to modernize the electrical power grid. The necessity of conservation of oil in Saudi Arabia is argued. Moreover, the vast availability of renewable energy sources like solar and wind in Saudi Arabia and advantages in utilizing these sources through smart grid technologies are advocated in this paper.

Key words: Solar energy, wind energy, smart grid, conserving oil, megawatt.

1. Introduction

According to Hubbert linearization method and other forecasting techniques, it is clear that the world crude oil production is peaked up already and now it is in the decline mode [1, 2]. During the same time, demand is continuously increasing. As oil producing nations consume more and more oil domestically, therefore, they will be able to export less crude oil in future. Due to the increasing demand, once global oil production begins to decline, demand is expected to be higher than the supply and consequently world oil prices will increase [3]. The world oil uncertainty and its influences on the world economy are highlighted in Refs. [4, 5]. Therefore, now it is the time to think seriously about oil conservation and utilization of the alternative energy sources like renewable and nuclear to avoid energy supply gap created by the oil deficiency [6]. Saudi Arabia is a leading oil producer. It also has a high potential for renewable energy sources and is keenly interested in taking an active part in the development of new technologies for exploiting and utilizing these renewable sources of energy. The most natural renewable energy sources which are freely available are wind and solar [7-9]. The power in the earth’s wind and in the solar radiation in Saudi Arabia is sufficient to make significant contribution to the kingdom’s energy supply. Therefore, it is important to explore ways by which this power can be utilized not only for domestic use but for possible export as well. Smart grid technologies can play an important role in this regards.
Smart grid is the convergence of information and operational technologies applied to the electric power grid allowing sustainable options to customers and improved security, reliability and efficiency to utilities [10-12]. Developing smart grid technologies can help countries like Saudi Arabia, where this technology has huge potential, to meet at least part of world’s growing energy demand with available renewable energy sources. The variations in resource availability tend to limit any particular single renewable technology to specific locations and uses. The solution can be obtained by providing distributed and decentralized power to the network by utilizing smart grid systems. These systems do not rely on a single energy source, but on diversified potential sources [13].

The aim of this paper is to assess the role of smart grid technologies in Saudi Arabia and point out the benefit that can be derived by tapping these technologies along with the wide spread use of renewable energy sources. The implementation of these concepts can have significant benefits for the environment as well.

2. Smart Grid and Its Role

A power grid generally transmits power from a few central power generating stations to a large number of loads or users. Smart grid technologies enable this grid to be capable of routing power in more optimal ways and in both directions. The conditions, to which a smart grid could respond, occur anywhere in the power generation, transmission, distribution and demand chain. A conceptual diagram of smart grid is shown in Fig. 1.

Smart grid will likely have a control system that analyzes its performance using autonomous reinforcement learning controllers that have strategies to manage the behavior of the grid for ever changing environment due to some equipment failures [12]. It can easily isolate affected areas and redirect power flows around the damaged facilities, thereby maintaining power availability and increasing reliability.

It encourages the consumers for peak demand shaving or demand sensitive management [10]. By enabling distributed energy resources like residential solar panels, small wind generators and other power sources, smart grid motivates small players like individual homes and small businesses to sell power to their neighbors or back to the grid [13]. It supports traditional loads, moreover they also can easily interconnect micro turbines, renewables, fuel cells and other distributed generation technologies at local, regional, national and even international levels.

Significant increases in bulk transmission capacity will require improvements in the transmission grid management. These improvements are aimed to create an open marketplace where alternative energy sources from geographically distant locations can easily be sold to the customers wherever they may be located. It can optimize capital assets while minimizing operations and maintenance costs. Optimized power flows maximize the use of lowest cost generation resources and thus reduce the waste. The renewable energy resources are for the most part intermittent in nature. Smart grid technologies can enable the power systems to operate with large number of such energy resources in such a manner that both suppliers and consumers are able to compensate for irregularities associated with intermittent nature of most renewable sources.

Smart grid technologies can help to interconnect and control the flow of the plentiful solar energy and wind energy throughout the kingdom with the existing energy sources. The optimal and reliable power supply
of such a system will allow individual consumers to generate power onsite using any suitable method and to adapt their generations to their loads. Therefore, it will make them less affected by the grid’s power failure. It also allows reverse flow of surplus energy generated by a local sub network, after meeting its consumption needs, to the main grid. Smart grid interacts with generators and loads in an automated fashion, in real time and coordinates its performance according to the demand. It manages energy consumption in response to supply conditions or the market price. One advantage of smart grid applications is the time-based pricing that can be applied. Consumer can monitor the changing price in seconds and thereby electrical equipments are given messages to react to such price variation. Smart grid encourages consumers to prefer suitable energy in cooperation with power grid at the most suitable time [10]. It helps load shaving by motivating consumers to operate only the most essential appliances at peak demand periods and to transfer the operation of less critical appliances at off peak hours when electrical energy tariff may be lower.

3. Need of Conserving Oil

The concern about the oil supply and demand is increasing worldwide. For the last decade the world oil demand has become more than the world oil production. Total production of crude oil and natural gas liquids is shown in Fig. 2. It shows that almost 35% to 45% of world oil is produced by OPEC countries. Saudi Arabia is the largest oil producing country among OPEC group and it produces about 30% of total OPEC oil supply [14].

The consumption rate of petroleum products in Saudi Arabia is also increasing. This is due to the fact that, population of the kingdom is increasing, the economy is growing in size, huge number of development projects are being implemented and the electricity generation is mainly petroleum product based. Fig. 3 shows the average growth of energy consumption per capita in the kingdom. It grew by 6.5% from 2000 to 2008 while this growth rate was 4.7% from 1990 to 2000 [15]. The current top five net oil exporters are Saudi Arabia, Russia, Norway, Iran and the UAE. These countries export about half of world net oil from 2000 to 2005, the combined increase in domestic consumption of these countries was 3.7% per year whereas, from 2005 to 2006 these was an accelerating rate of increase in the consumption of 5.3% per year. Moreover, from 2005 to 2006, these countries showed reduction in the export rate of 3.3% per year [1]. Based on Hubbert Linearization method, the ultimate recoverable oil reserves of Saudi Arabia would be 185 giga barrels [1]. Fig. 4 shows the Saudi Arabia’s crude oil production rate and future forecast for it. It peaked to 9.5 million barrels per day (mbd) in 2005. In 2008 and 2009 the crude oil production was 9.3 mbd and 8.1 mbd, respectively. After 2010 a steady decline is forecasted [2]. Thus, the above discussions clearly point out that the conservation of petroleum products is essential to meet world’s demand in the future.
Adapting smart grid technologies to utilize renewable energy sources for electric power generation will lead to conserve oil. The additional benefit is that the clean renewable sources do not produce green house gases thereby reducing global warming and improving the environment.

4. Saudi Arabia and Solar Energy

Saudi Arabia is the most potentially productive region for harvesting power from the sun. From Fig. 5, it can be noted that the Arab states are the best areas to take advantage of solar energy. In Europe, most countries in North America, most Latin American countries, and the countries of Western Asia, the average annual rate of solar radiation is between 100-200 W/m², while in the Arab countries, including the GCC (Gulf Cooperation Council) countries, it reaches to about 250 W/m².

By geographical considerations, from the western edge of North Africa to the eastern edge of Central Asia, there is a vast, rainless region that receives about 6-7 kWh/m²/day [7]. While it is technically possible to convert sunlight into electricity anywhere, it costs far less to do so in the areas that receive the most powerful form of sunlight.

The increasing price of oil and its expected deficiency in the future can attract many of the European countries to import solar energy for their nations from Saudi Arabia. Thus, there is a great potential that the solar energy from Saudi Arabia can be harvested, not only for supplying increasing demand of power in Saudi Arabia, but also such power can be exported to other countries where potential of solar energy is less, but which have high energy demand and can afford to pay for the energy. In 1980 Saudi Arabia started “solar village” program to develop the use of the solar energy technologies for application in remote regions. The Energy Research Institute, KACST (King Abdul Aziz City for Science and Technology) conducted several solar energy related research projects [9]. These studies showed good potential for solar energy use in Saudi Arabia.

Another area where Saudi Arabia can utilize the solar energy is the desalination of water. According to Saudi Arabia’s national science agency (KACST), the Kingdom is now planning to build solar energy based desalination plants in order to save energy of fossil fuels. A tremendous amount of oil is currently being used to provide power for the country’s desalination plants; around 1.5 million barrels per day [16]. This causes the price of desalinated water to rise with any rise in the oil price. Along with powering its desalination plants, the country also aims to use solar power to add generating capacity to its electricity grid. Solar energy will be integrated to the power network by using smart grid technologies.
5. Wind Energy of Saudi Arabia

The wind map of Saudi Arabia indicates that the kingdom is characterized by the existence of two vast windy regions along the Arabian Gulf and the Red Sea coastal areas [9]. Fig. 6 shows the wind speed map of Saudi Arabia [17]. There are many regions which have a high wind speed that offer potential of building wind farms. Thus, there are a lot of regions that have a high average wind speed such as Dhahran, Jouf, Turaif, Yanbu and Alwajh.

The mean annual wind speed in these two windy regions exceeds 16.7 km/h and ranges from about 14 to 22 km/h and 16 to 19 km/h over the Arabian Gulf and Red Sea coastal areas, respectively. The mean annual wind energy density lies between 250 and 500 kWh/m² on the Red Sea coastal sites and drops to about 50 kWh/m² in the inland areas. Wind energy can be harvested and connected to power network and smart grid technologies can help in this as well.

6. Discussion and Conclusions

It is argued that smart grid technologies can play an important role in integration of renewable technologies in the electric power network. As a result, it can help to conserve oil which is commonly being used for generation of electric power in the kingdom of Saudi Arabia.

The solar desalination of water using solar is expected to help Saudi Arabia to reduce its dependence on fossil fuels since it uses 1.5 million barrels of oil per day for this purpose [16]. Construction of solar plant with capacity of 20 MW will generate about 200-300 GWh/year, with estimated power plant area of 1.25 km². It will save 500,000 barrels of oil and avoid 200,000 tons of carbon dioxide per year [8]. The use of AC (air conditioner) units increase in the summer period (April-September) in the kingdom due to high solar radiation and temperature rise. The average solar radiation for 12 hours in these months is about 540 W/m². Considering a building has 100 AC units, the average operating power for these units will be about 50 kW. Installing a PV panel at the roof of the building with an area 650 m² will be enough to compensate for this power consumption. The excess power with the increase in area can be supplied back power network through smart grid technologies.

Wind does not stop blowing everywhere at same time but it aggregates wide geometrical area. Single wind turbine produces large variable output while installing and integrating a number of wind turbines at different sites decreases this variability. In the kingdom, the wind over a wide geometrical area can thus be effectively used to generate power. Moreover, integration cost of wind for larger balancing area will be less than that of the smaller balancing area [18]. Installing and interconnecting about 100 wind based generators with turbine diameter of 120 m at high density wind energy area will generate about 400-500 GWh/year. The large-scale wind generation through smart grid will also reduce per-unit variability and will increase predictability of wind generation.

The effort to build smart grid will help to interconnect solar and wind power plants with the power lines. Considering the potential of solar energy in Saudi Arabia, such a power grid will have potential to simultaneously provide energy to seawater desalination plants and other purposes in the Middle East and North Africa [19]. After commissioning of GCC power grid, Saudi Arabia can export excess energy to the other GCC countries. Moreover, a planned power grid will allow interconnection including GCC and other pool such as Egypt, Jordan,
Iraq, Lebanon, Syria, Turkey and Europe [20]. The effective use of renewable sources in the Kingdom through smart grid technologies will reduce the amount of oil used for producing electricity, thereby dependence on crude oil will be reduced and it will help to conserve oil for future. The conserved oil can be exported or turned into value added products in future.

Saudi Arabia is blessed with plenty of crude oil, solar energy and wind power. Smart grid technologies can transfer these blessings throughout the world. Smart grid improves the communications between the electricity producers and consumers and decisions about when and how to generate and consume electric energy are optimized. Smart grid is not a vision to future, but rather a solution to the energy and environmental challenges facing the world today. To utilize the renewable energy sources in the remote area, major expansions of transmission and distribution facilities are required. The time taken to commission these facilities is about 10 years. So if it starts now, the Kingdom becomes a MW exporter in the coming years. Lot of research work is essential to implement smart grid in the Kingdom. Successful efforts to implement such technologies will make Saudi Arabia a major megawatt exporter of electric power and will produce economic and environmental benefits for the mankind.

References

Side-on Ignition Compared with Ignition by Laser Driven Compression

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Abstract: Recent results for side-on ignition of uncompressed proton-boron (HB11) fusion that use the Chu-Bobin side-on ignition with petawatt-picosecond laser pulses is extended to the reaction of helium 3-helium 3 (He₃). The HB11 reaction resulted in radioactivity is lower values than from burning coal per generated energy. This was based on the very rare experiments with extreme suppression of pre-pulses in order to suppress relativistic self-focusing. Subsequently, acceleration of highly directed plasma blocks of modest temperature and ultra-high ion current densities above 10¹¹ Amps/cm² were measured in agreement with earlier derived theory. This permits the conditions of the Chu-Bobin for side-on ignition of solid density fusion. Results for similar neutron lean He₃ are reported. A detailed comparison with the usual spherical laser compression and ignition of fusion is given for clarifying the basic differences of the ignition process.

Key words: Laser, fusion, helium-3, radioactivity, plasma blocks, self-focusing.

1. Introduction

Fusion energy generation by laser driven ignition of high compression DT (deuterium-tritium) fuel achieved a significant milestone by commissioning of the largest laser in the world of the NIF (national ignition facility) in 2009, producing laser pulses of more than MJ (megajoule) energy of about nanosecond (ns) duration [1]. The solid state density nₛ is aiming to achieve spark ignition [2] by means of indirect drive and by conversion of the laser radiation into x-rays within capsules DT for heating and compression to more than 1,000 times. This highly sophisticated process is to reach gains G of 50 up to 100 of generated fusion energy per input laser energy producing 10¹⁸ or more fusion neutrons per shot [3]. The difficulties to achieve conditions of spark ignition (central ignition) are well known and the applied techniques are extremely well developed to achieve this goal. Confidence is given by comparing earlier results, Fig. 1 indicates an increase of the fusion neutrons on nearly the square of the laser energy Eₐ such that the 10¹² fusion neutrons with kJ laser energy may reach 10¹⁸ neutrons at MJ laser pulses.

The confidence to reach such neutron numbers may be estimated also from the alternative compression scheme of volume ignition [4] which scheme was confirmed [5] by evaluation of the Wheeler modes and applied with inclusion of self-heating by the generated neutrons [6, 7] and clarified as a rather uncomplicated “robust” method [8]. It was rather surprising that the highest measured laser produced yields [9] were exactly following this volume reaction process, measured 1986 in Livermore [10], in Osaka [11] and with the ever highest reported values of 2 × 10¹⁴ neutrons in Rochester [12]. According to Fig. 2 which drawn from the experiments, a compression to 1,000 nₛ would arrive at 10²⁰ neutrons if such linear extension would be permitted. The line in Fig. 2 was drawn in
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Fig. 1 Measured and projected neutron gains at DT fusion using ignition by spherical laser compression depending on the energy of the laser pulse following Hora and Ray [3].

Fig. 2 Measured DT neutron gains from spherical laser compression for direct and indirect drive with single and double shell targets depending on the measured maximum compression, summarized in 1998 [9].

1991 [13], before the Rochester results in 1995 [12] with the remarkable coincidence of these measurements with the earlier drawn line.

If the verification of the expected reactions using the complex spark ignition [2] may need a longer time with the experiments, a faster solution for fusion energy may use volume ignition of pellets with ingeniously improvement [14] of double shell compression of targets (see Fig. 2). Even at room temperature this may lead to the gains of 50 or more and to the $10^{19}$ neutrons with NIF. This may at least lead in principle to the conditions for building LIFE (laser driven inertial fusion energy) [15, 16] as prototype of a fusion power station by 2020 where the solid state laser drivers are diode pumped with more than 15 times higher efficiency for a much more compact laser than NIF. This would be a highly serious and reliable contribution in the fight against the climatic catastrophe using fusion energy.

2. Question of Very High Fusion Gains

The gains $G = 100$ and $10^{20}$ fusion neutrons from spherical laser compression of DT is close to the absolute limit due to exhaustion of the fuel in the reacting pellets. If there would be no other options, the LIFE project could at least lead to a solution of energy production by nuclear fusion with the end product of stable helium as the ash is in difference to the radioactive waste problem of nuclear fission reactors. The nuclear radiation problems in the material of the reactor are still remaining but the handling of generation and handling of radioactive tritium in the power station are of a lower grade than in fission reactors and may well be manageable. The possibility of gains above 100 up to 10,000 for laser driven fusion energy was studied on the basis of a modified scheme of fast ignition [17, 18] by Nuckolls and Wood [18, 19] using the new development of laser pulses with several petawatt (PW) laser pulses of picoseconds (ps) duration [20]. First results of the interaction of such pulses with targets led to unexpected nonlinear relativistic effects with extreme gamma ray emission resulting in nuclear transmutations, in acceleration of electrons and the highest charged ions to GeV energy, positrons from pair production [21], to the possibility to analyze numerous details of B-meson generation and annihilation in the interaction area for the LHC (large hadron collider) [22] and several new aspects [23].

The scheme of Nuckolls and Wood is a two step mechanism. First, plasma has to be compressed to densities of about $1,000 \ n_0$ by usual spherical irradiation methods with ns laser pulses. As a second step, a laser pulse of about 10 PW-ps had to be irradiated to produce an extremely intense 5 MeV electron beam which ignites a large volume of DT of
modest density, e.g. produced by chemical implosion to about 10^4 n to about 10^4 n only. This is a controlled reaction for energy production with a repetition rate in the range of Hertz (Hz) in a power station. Several involved problems including volume interaction processes distinguishing from the process discussed in the following section were considered [18]. All these details need to be clarified as well as those in the following considerations where indeed the aim of the very high gains is of extreme attraction. But whatever may be in the future, the LIFE system using laser fusion by high compression of NIF is a matured solution on which carbon-free energy production may be based as one option to avoid the climatic catastrophe.

3. One-Step Side-on Laser Ignition

The desire was postulated by Dean [24], that lasers should ignite fusion reactions in one step. This may be a way for plasma compression with ns laser pulses for the limited gains in the range of 100 [25], but the most attractive aim for gains of 10,000 [19] still involved the two steps of (a) ns compression of high plasma densities from which (b) the second ps laser pulse could produce the necessary ultra-high electron beam for ignition. The way to both the high gains and a one step laser interaction may be opened by using a rather unexpected anomalous interaction phenomenon with laser pulses in the PW-ps range [20, 21].

The question was studied using hydrodynamics by generating a shock-like fusion flame whether a laser pulse can ignite solid state DT fuel without compression side-on by Chu [26] and Bobin [27]. The result was very disappointing, because laser pulses of ps duration needed an energy flux density \( E^* \) with the threshold \( E^{*\text{t}} \):

\[
E^* > E^{*\text{t}} = 4 \times 10^8 J/cm^2 \text{ for DT} 
\]  

Eq. (1)

This was far beyond the then available capacity and this side-on scheme was dropped in favor of the spherical laser compression. The situation changed after 2 PW laser pulses of half ps duration were available [21], where any application is prevented by the numerous complex relativistic effects. Only after an anomaly of interaction was discovered [28] and subsequently clarified [29], this worked only by suppression of pre-pulses by contrast ratio better than 10^5, all other effects from relativistic self focusing could be excluded and a plane-wave wave interaction was possible as confirmed experimentally in many details [30]. Plane-geometry interaction of ps neodymium glass laser pulses of 10^{18} W/cm^2 were dominated by nonlinear (ponderomotive) acceleration and the Doppler measurements of the accelerated plane fronts [28] arrived exactly at earlier theoretically and numerically predicted values [30].

The highly directed plasma front moving perpendicular to the irradiated target and another moving into the target were confirmed [31]. Their origin was from dielectrically strongly increased skin layers [32]. The generated plasma blocks to modest temperature consisted in space-charge quasi-neutral direct ion beams of up to:

\[
j > j^* = 10^{11} \text{ Amps/cm}^2
\]  

Eq. (2)

or even higher current densities \( j \). This permitted a come-back of the side-on ignition of the fusion flame in solid density DT [30] from the Chu-Bobin theory which had to be modified with respect to later discovered effects of thermal inhibition [3] and collective (Gabor) stopping power [32, 34]. The application of the ultra-intense ion beams for nuclear fusion was formulated before [32] using ps laser pulses in the range of 10 PW. Similar to the electron driven laser ignition by Nuckolls and Wood [18, 19], gains up to 10,000 may be possible. A pre-compression of the DT fuel by chemical explosives [18] to about ten times the solid state is possible similar to electron beams also for the side-on driving by the here considered nonlinear force driven plasma blocks with the ultra-high ion current densities of Eq. (2). A difference between the electron and the ion driving with respect to two or three-dimensional properties will be discussed below.
4. Fusion of He$_3$-He$_3$: Nuclear Energy with Negligible Radioactivity

When extending the hydrodynamic computations of laser driven side-on ignition from DT to HB11, the very surprising results was received, that this is only less than about ten times more difficult than the fusion of DT. This is in strong contrast to the fusion ignition of by spherical compression where HB11 is about 100,000 times more difficult than DT [35-37]. It seems that then the very simplified laser fusion of HB11 by using ps laser pulses of few dozens of PW power may lead to remarkably low cost generation of nuclear energy without all the difficulties of radioactive radiation of all other known nuclear power stations. Nuclear radiation is then less per generated energy than burning coal [38] with respect to the fuel, the reactor and the final ash, helium.

It is then interesting to consider another case of fusion energy with no primary neutron production. Such a case is to burn helium-3 following the reaction [39]:

$$^{3}\text{He} + ^{3}\text{He} = ^{4}\text{He}(1.429 \text{ MeV}) + ^{1}\text{H}(5.716 \text{ MeV}) + ^{1}\text{H}(5.716 \text{ MeV})$$  

(3)

The fuel He-3 can be harvested from the surface of the moon as known from the scheme to produce fusion of deuterium with He-3 [40] where the load of one space shuttle with He-3 could produce all energy in the USA for half of a year.

Eq. (3) is primary without any neutrons as the HB11 reaction. Only secondary reactions of the 5.716 MeV protons with the helium will lead to radioactive nuclei. Whether these consist in much more or less radioactivity than burning coal per generated energy needs to be evaluated but should not differ by orders of magnitudes from the case of HB11. Results in the characteristic plots shown in Fig. 3 are deduced with performing the hydrodynamic computations at the same conditions as before by Chu [26]. To find the threshold driver energy flux density one notes that $2 \times 10^9 \text{ J/cm}^2$ does not lead to ignition while $3 \times 10^9 \text{ J/cm}^2$ does ignite. By interpolation, the threshold of laser side-on ignition of solid state density $^3\text{He}$ has a threshold energy flux density and threshold temperature:

$$E_t^* = 2.7 \times 10^9 \text{ J/cm}^2$$
$$T_t^* = 88 \text{ keV}, \text{ for } ^3\text{He}-^3\text{He}$$  

(4)

Where as before, the emission of bremsstrahlung is just compensated by the generated fusion energy.

In order to appreciate the result of Eq. (4) we are listing here—under the same simplified conditions of Chu [26] the results [35]:

$$E_t^* = 4 \times 10^9 \text{ J/cm}^2$$
$$T_t^* = 87 \text{ keV}, \text{ for HB11}$$  

(5)

and [34]:

$$E_t^* = 4 \times 10^8 \text{ J/cm}^2$$
$$T_t^* = 7.2 \text{ keV}, \text{ for DT}$$  

(6)

This indicates that both neutron-free Eqs. (4) and (5) for laser side-on ignition of solid state density are not very much more difficult than DT in very drastic contrast to the ignition by the spherical laser compression scheme.

5. Discussion

It should be realized that the new direction for laser driven fusion energy by side-on ignition with nonlinear...
force driven plasma blocks is just at the beginning to be explored and general difficulties may appear at further studies when other methods than hydrodynamics are used. To focus the main stream of research and obtaining the highly matured spherical compression from the now biggest laser on earth [1, 16] is most important with the subsequent LIFE [15] power station. But it will be necessary not to miss the chance to arrive at fusion gains up to 10,000 with the new scheme while the classical compression scheme will not exceed gains in the range of 100 or little more with DT only.

One point for comparison of the side-on ignition with electron beams [18] and the here elaborated ion beam approach direction [30, 35] is of conceptual nature. Chu [26] and Bobin [27] method is based on the two-dimensional process of a shock wave to generate the fusion flame. This includes the result of a basic difference between a chemical detonation flame and the nuclear flame as studied in a very detailed way before [26]. In contrast, the electron beam interaction [18] needed the three dimensional application of the $\rho R$ criterion where the ignition within a plasma sphere of radius $R$ and the plasma density $\rho$ is essential [18].

This criterion was derived from the numerically calculated optimum fusion gains $G$ ([12, 41] for calculating the fusion energy per input laser energy $E_o$ into a spherical volume with radius $R$ of fusion fuel of density $\rho$ per solid state density $\rho_s$:

$$G = \left(\frac{E_o}{EBE}\right)^{1/3}(\rho/\rho_s)^{2/3} = const \times \rho R \quad (7)$$

where $EBE$ is the break even energy with the value 6 MJ for DT. The first Eq. (7) was formulated in 1970 [41] and the second, resulting from $E_o \sim \rho R^3$, was first published by Kidder [43]. This is the result of volume burn at spherical uniform compression according to the self-similarity model ([12], see Section 5) only at optimum temperatures (of 11.5 keV for DT) and is valid up to gains $G < 8$ for DT only [44]. For higher gains, volume ignition was discovered [3], confirmed by Wheeler modes [4], where other gain formulas were derived for higher gains [8, 25, 44]. Under these special restrictions, the $\rho R$ Eq. (7) can be used for three dimensional geometry only. The side-on ignition by nonlinear force driven plasma blocks with the generation of shock fronts as fusion flames [26, 27] is a two dimensional problem. Gain formulas for more general three dimensional conditions were derived by Betti [45].

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Natural Ionizing System of Electrical Protection and Energies against Atmospheric Discharges (Lightning)

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Abstract: This is the new highest technology, 100% Venezuelan and unique in the world, technological innovation, world patent for maximum protection, security and zero risk (0) to all electrical and power generation systems: hydroelectric and thermolectric power plants, wind, nuclear and solar power plants, etc.; it is the only technology around the world that has the potential to disperse and propagate to land mass the enormous energies associated to the atmospheric discharges (lightning), which are in the order: 200,000 to 500,000 Amperes; 1,000 million kilowatts and high-level transient voltage of 100 million volts. This new high technology is the solution to the paradigm of Benjamin Franklin and it is the mechanism to end “blackouts” that produces so many damages and losses of billions of dollars to both generators and users of electrical service, throughout the world.

Key words: Atmospheric discharges, lightning, electrical substations, grounding protection.

1. Introduction

The electrical faults, interruptions and “blackouts” generated by atmospheric discharges (lightning) in transmission lines, electrical substations (high voltage), power equipment and electronic equipment of high sensitivity are the main problem in today’s electrical engineering in the world.

The biggest problem and the greatest challenge currently facing power generation and all humanity are breakdowns and power failures, destruction of industrial equipment and installations and huge “blackouts” generated by the destructive effects of atmospheric discharges (lightning) that cause losses of billions of dollars (US$ MM) to both power generation companies as people and users of electrical energy.

For each 100 power failures, breakdowns and “blackouts” around the world, 85 are generated by atmospheric discharges (lightning).

The calculation and design of protection systems for transmission lines and electrical substations (reticular mesh of grounding, bars, etc.) that are currently used in electrical engineering are inefficient, because those calculations (reticular mesh of grounding) are made by taking only the electrophysical characteristics of power transformers and other items, such as: transformers capacity, reactance, capacitance, inductance, secondary current, short circuit current symmetrical and asymmetrical, land resistivity, mesh geometry and others. In other words, reticular mesh of grounding are not designed or calculated to counteract the destructive effects of lightning.

The dispersion capacity of a reticular mesh of grounding would be in the order of 10,000, 20,000 or 30,000 Amperes [1, 2]. In that sense, the energy values associated to lightning are in the order of 500,000 Amperes, 1,000 million of Kilowatt and high-level transient voltage of 100 million Volts that no reticular mesh of grounding would be able to disperse.
Currently the world does not exist (or existed) any device or technology that has the ability to disperse and spread the huge energy of an atmospheric discharge (lightning) to the land mass without causing damages to buildings, equipment or people.

Eight years ago and 15 years of research after, Luis Cabareda invented, the only technology existing in the world that has the capacity and efficiency to avoid damages and destructive effects of lightning, it is the new highest technology, 100% Venezuelan and unique in the world: natural ionizing system of electrical protection (Cabareda, 2006, Science, Technology and Innovation Award, FUNDACITE, Science and Technology Ministry of the Bolivarian Republic of Venezuela) is conformed by: natural ionizing lightningrod ionca and active trimetallic ionic electrode triac of grounding, definitive and total solution against “blackouts”, power failures and breakdowns, losses of energy generated by atmospheric discharges (lightning) in hydroelectric and thermoelectric centrals, transmission towers and lines of high voltage (800 kV, 400 kV, 230 kV, 115 kV) and electrical substations, towers and centrals of radio-telecommunication, drills and oil refineries, equipment of tomography (CT), magnetic resonators, X-rays, cellphones, ports and airports and buildings.

This new invention, technological innovation: new highest technology, 100% Venezuelan and unique in the world, will contribute significantly to sustainability and saving of energy and for a better and more efficiency of generating and distributors systems of electrical energy and fuel. It will avoid losses of thousands of human lives, and its implantation and installation will generate billions of indirect and direct jobs, it will also avoid losses of energy and losses of billions of dollars (US$ MM) around the world. Every day our world loses 4.8 million barrels of oil by the destructive effects of atmospheric discharges (lightning) because lightning attacks and destroy all monitoring, measurement and control systems of drills, oil refineries, gas plants, etc..

At the same time, “blackouts” that cover large regions generate losses of thousands of gigawatts, invoiced and consumed.

This new highest technology offers 20 years of guarantee, maximum security and zero risk.

### 2. Natural Ionizing Lightningrod Ionca

It bases its operation on (Fig. 1) its electrophysical structure and the enormous differences of existing potential and the electrical field in the atmosphere in conditions of storm that allow to generate “crown effect” or “ionizing effect” that produce billions of high ion conductivity, because it has electrodes to atmospheric potential (atmospheric excitatory) and electrodes to grounding potential isolated to each other [3, 4]. This “ionizing effect” is increased by “hit effect” between air molecules and particles (ion) accelerated by the enormous existing electric fields during the storm. This natural ionization generates a “grounding direct discharge” which is the precursory current of lightning and that jointly with the stepped currents that derive from the interaction of the microparticles in the clouds, indicates the way and the trajectory for the atmospheric discharge (lightning), which will be lead through natural ionizing lightningrod ionca and the active trimetallic ionic electrode triac of grounding to the land mass; dispersing and spreading the enormous energies associated, without causing damages (Fig. 2). Electrophysical characteristics: height: 620 mm, diameter: 470 mm, weight: 6.4 kg, material: stainless steel 304, polytetrafluoroethylene (400 °C), vertical penetration: 50 y 100 m, warranty: 20 years.

### 3. Active Trimetallic Ionic Electrode Triac of Grounding

It bases its operation and highest efficiency on (Fig. 3) its electrophysical characteristics that allow the total and complete adhesion to the land mass, whose land has been dealt chemically with high-electrical conductivity electrolytes that decrease the enormous
Natural Ionizing System of Electrical Protection and Energies against Atmospheric Discharges (Lightning)

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Fig. 1 Natural ionizing lightning rod ionca. Electrophysical basis.

Fig. 2 Natural ionizing lightning rod ionca.

One natural ionizing lightning rod ionca can protect an area of 10,000 m² (1 Hectare)

Fig. 3 Active trimetallic ionic electrode triac of grounding. Electrophysical basis.

resistivity and allow water saturation and humidity retention, total adhesion to the land mass and high indices of alkalinity [5, 6]. The volume of the treated ground is from (Fig. 4) 18 m³ to 27 m³ approximately and is united to the land mass by the electrolytic and not mechanic adhesion, facilitating the way of dispersion and propagation of the enormous energies associated to the atmospheric discharges (lightning) and electrical faults, generally (Fig. 5). Energy dispersal capacity to land mass: 500,000 Amperes, 1,000 million kilowatts, lowest electrical resistance $R = 0.86-3 \ \Omega$ (ohm). Land characteristics: lowest land resistivity, porosity and compaction, maximum humidity, temperature, station of the year, electrolytes, PH.

4. Energy of Lightning

Lightning, it is an interaction and transmission of elevated electrical charges between the atmosphere and the earth in conditions of storm or atmospheric disturbances. On the earth it happens 4,000 storms daily and 9,000,000 lightning daily. The energy of lightning is in this order: 200,000 to 500,000 Amperes; 1,000 million KW; 1 million MW = 1,000,000 MW; 100 million Volts.

The energy generated by the biggest hydroelectric’s dams around the world would only reach 10% of the energy of a single lightning: Hydro Québec (Canada) 36,810 MW, Guri (Venezuela) 10,000 MW, Macagua (Venezuela) 3.140 MW, Caruachi.
Natural Ionizing System of Electrical Protection and Energies against Atmospheric Discharges (Lightning)

5. Consequences of Atmospheric Discharges (Lightning)

Damages to constructions and electricals equipment, electronic, communications, computation and cybernetic, generally: inductive and conductive effects that produce high levels of transitory overvoltages (100 million Volts). Damages to people: cardiac and respiratory arrest, cerebral injuries, burns, plow of the eardrum, pulmonary and bony injuries, post-traumatic stress. Losses of billions of dollars to both: generators and users of electrical service around the world [7].

6. Characteristics of the Atmospheric Discharges (Lightning)

30-100 million Volts. 200,000-500,000 Amperes. 100-1,000 million Kilowatts. Electric field: 30 Volt/m. Potential gradient: 15 KV. Air impedance: 5 KΩ. Atmospheric pressure: 100 atmosphere. Duration time: 10-30 μseg. Energy: $3 \times 10^9$ J/m. Temperature: 15,000 to 30,000 °C. Acoustic energy: 25% (thunder). Caloric energy: 75% (electrical discharged) [8].

7. The Lightning Rod

The lightningrod (Fig. 6) is a device conformed by one or several metallic bars with certain geometric disposition united to an grounding electrode by a downpipe conductor, that facilitates the way of the lightning from the cloud to the earth, allowing the dispersion and propagation of the enormous energies associated, without causing damages to people and/or equipment [9, 10].

8. Grounding Systems

It is a set of metallic elements directly buried that allow and facilitate the dispersion and propagation of energy associated to a lightning and electrical faults, without causing damage. The adhesion to land mass of (Fig. 7) traditional systems of grounding like bars and reticular mesh of grounding is mechanical. The adhesion to land mass of the active trimetallic ionic electrode triac of grounding is electrolytic [9, 10].

- It protects people and/or equipment (electrical, electronic, communication, computation);
- It protects against: lightning, transitory overvoltages of discharge and low level, accidental contact with lines of HT (high tension) and LW (low tension);
- It stabilizes the voltage of normal operation;
- It facilitates the switch operations;
- Equipotentiality: touch voltage and step voltage;
- It allows the dispersion and propagation to land of the associated energy (lightning) to electrical faults, leakage currents and atmospheric discharges.

9. Electrical Substation, Today (Fig. 8)

Nowadays, this is how engineers build electrical substations, and this is wrong.
11. Results and Conclusions

Power generation is vital and very important, but providing protection and security to the energy generated is perhaps even more important. The world must avoid the energy losses with an efficient and effective protection. The 85% of major “blackouts” and electrical faults in power generation, power equipment and electronic equipment of high sensitivity in the world are produced by the destructive effects of atmospheric discharges (lightning). This results in loss of lives and billions of dollars each year.

The new highest technology, 100% Venezuelan, unique in the world, natural ionizing system of electrical protection conformed by the lightning rod ionizing natural ionca and the active trimetallic ionic electrode triac of grounding of world-wide standard whose operation and electrophysical basis are based on phenomenon and events scientifically verified like: atmospheric discharges (lightning), “crown effect”, “hit effect”, “grounding direct discharge”, metallic and atmospheric ionization, electromagnetic and electric fields, ionizing potential and electronic affinity, electrical potential presented in the atmosphere in conditions of electrical storm, resistance and atmospheric pressure, tripole in the cloud, cosmic rays, physical state of the water (liquid, solid and gaseous), electrolytes, resistivity of the ground and resistance of dispersion, effects to improve...
Natural Ionizing System of Electrical Protection and Energies against Atmospheric Discharges (Lightning)

the ground resistivity to give high degree of alkalinity), principle water humidity and retention (properties of the charcoal, copper sulphate, sodium chloride and the bentonite), substances, equipotential lines and equipotentiality of a system (properties of the steel, receives and aluminum like good electrical conductors), exothermic weld.

This new high technology, 100% Venezuelan is the definitive and total solution against electrical faults and interruptions generated by atmospheric discharges (lightning) and affect electrical substations, power equipment and electronic equipment of high sensitivity, oil exploration, drills, tanks and stations of fuel provision; avoids “the burning” of electronics cards in electronics equipment of high sensitivity (Rx, CT, MRI). It is the mechanism to end the “blackouts” that produces so many damages and losses of billions of dollars around the world.

It is scientifically proved and globally accepted that the existing electrical systems of protection at the moment like: reticular mesh of grounding and cooperweld bars do not have capacity to disperse and propagate to land mass the enormous energies associated to the atmospheric discharges (lightning), which are in the order: 500,000 Amperes, 1,000 million Kilowatts and high-level transient voltage of 100 million Volts, enormous energies that can not be dispersed by reticular mesh of grounding, which has a maximum capacity between 20,000 and 30,000 Amperes. This is the principal cause of major blackouts and electrical faults around the world.

The lightning rod ionizing natural ionca and the ionic electrode active trimetallic triac of grounding are ecological, natural, do not contaminate the environment and fulfill all electrical codes and norms international and national such as: IEEE (The Institute of Electrical and Electronics Engineers), NFPA (National Fire Protection Association), ANSI (American National Standards Institute), BSCP (British Standard Code Practice), WMO (World Meteorological Organization), NFC, NEC (National Electrical Code), COVENIN (Venezuelan Commission of Industrial Standards); and it has received the certification and recognition from IEEE. The Institute of Electrical and Electronics Engineers, Latin America and the Caribbean Region: (1) World Renewable Energy Congress, WREC 2011, Sweden, Linköping University, Author, Presenter, Venezuela Delegate; (2) XXI World Energy Congress, WEC 2010, Canada, Author, Presenter, Venezuela Delegate; (3) The New Highest Technology Paper: The International Energy Technology Data Exchange (www.etde.org); US Department of Energy Office of Scientific and Technical Information, OSTI, Library and Archives Canada and Scientific Libraries Worldwide; (4) IEEE, XV International Congress of Electrical, Electronic and Systems Engineer, INTERCON 2008, Peru, Author, Presenter, Venezuela Delegate; (5) Polytechnic Experimental National University “Antonio Jose de Sucre” (UNEXPO), Arbitrated University, Venezuela; (6) Antenor Orrego Private University (UPAO), Peru; (7) Science, Technology and Innovation Award granted by Foundation for the Development of Science and Technology (FUNDACITE), Ministry of Science, Technology and Intermediate Industries, 2006, Venezuela; (8) General Department of Science and Technology Research, Ministry of Science, Technology and Intermediate Industries, Venezuela; (9) National Center of Technological Innovation; (10) CVG MINERVEN; (11) National and Internationals Publics and Private Companies; (12) Projects and Construction built: Church La Chiquinquira, CVG MINERVEN (Gold Mining), Promotora Minera Guayana (PMG), AGAPOV Group (Russian)—Gold Mining, Corporación 80.000, C.A., AGAPOV Group (Russian)—Gold Mining, CVG ALCASA (Aluminum), CVG VENALUM (Aluminum), Clinics: Medical Specialty Center, La Floresta, Chilemex, Maracay Medical Center; FIOR Venezuela (Iron Briquettes), CVG CARBONORCA (Anodes); (13) Project: Toyota Venezuela (Toyomaya), Engineering Projects:
Petróleos de Venezuela (PDVSA), PDVSA Boquerón, ENELBAR (Electrical Substations: Bárbara, Morón, Valle Seco, Chivacoa, Nirgua, Yaritagua), CADAFE (Electrical Substations: Tucupita, Temblador).

References

Potential Energy of Crops

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Abstract: This work consists of estimating the energy achieved from all land and water-based vegetations. This real potential is determined by identifying 10 biomass samples taken from vegetable resources which are favored by their aptitude of adaptation to the conditions of Iran. The net energy values of the 10 biomass samples change in the range of 13.65-18.00 MJ/kg using bomb calorimeter. By means of least squares regression method all correlations were found. The results of 10 different biomass materials have been used to develop a linear equation correlation.

Key words: Potential, treated waste water, biome biofuels, crops, biofuel, net heating value, linear equation correlation.

1. Introduction

The usage of biomass, the development of alternative energies, in particular the energy of the biomass, aim at satisfying certain objectives whose principal ones consist in replacing the oil which is considered as a fossil hydrocarbon clearly paid and occasionally available, and fighting against pollution and more global warming. Biomass is non-fossil, and includes solid wastes, agricultural residues, in general, it is all non-fossil organic materials [1]. The oil crises of the too high production cost of the bio-fuels slowed down their development [2]. The usage of biomass as fuel has many environmental and economic advantages. Biomass is a cheap, clean and renewable source of energy. Combustion is the most direct technology for converting biomass into energy. Many countries consider the launching of national programs in favor of the bio-fuels such as China, India, Malaysia and Thailand. These developing countries are quite natural in favorable position for the production of raw materials that are useful for the bio-fuel’s manufacture in particular those whose sugar sector is traditionally significant, which is the case of Iran. This work consists of estimating the heating values of the bio-fuels resulting form the agricultural products in Iran and studying the prospects of this new form of energy. All correlations were developed by means of least squares regression analyses and have high regression coefficients between 0.832-0.870. The new equation has been developed for estimating the net heating values of different biomass samples from their analyses and ash content data.

2. Methodology

The working method is adopted by using bomb calorimeter which consists primarily of the sample, oxygen, the stainless steel bomb, and water. The Dewar prevents heat flow from the calorimeter to the rest of the universe.

The Dewar prevents heat flow from the calorimeter to out site of system. Fig. 1 shows the bomb calorimeter with stirring, a thermometer and combustor [3]. In the experiments of 10 biomass samples favored by their aptitude of adaptation to the Iran conditions. Table 1 shows different types of samples. Samples were ground and sieved into a powder with a particle size of 0.195-0.235 μm.
3. Mathematical Methods

The experimental results of 10 different biomass materials have been used to develop correlations for an estimation of the net heating value from the elemental composition and ash content of the dry biomass. One of the developed correlations is linear as follows:

\[
\text{NHV} = 0.3330 \ [O] - 0.0139 \ [C^2] - 0.1870 \ [H] + 0.1760 \ [\text{ash}] + 0.0117 \ [C] - 35.401
\]

where: [C] is carbon content, [H] is hydrogen content and [O] is oxygen content all in weight percentage.

This equation is as a function of carbon, hydrogen, oxygen and ash content of the dry biomass samples, contents of carbon, hydrogen, nitrogen and ash from the analysis results are given in Table 2.

Carbon, hydrogen and contents of the biomass samples were detected by an elementary analyzer. The oxygen content has been calculated by subtracting from 100 the sum of the other components of the ultimate analysis. The amount of ash of samples has been found according to Refs. [4-7]. Fig. 2 shows the experimental values of samples versus theoretical values from equation, in good accordance.

4. Results and Discussion

The introduction of the industrial crops (10 samples), the recourse to the technique of bomb-calorimeter, the use of the fallow, the re-use of treated worn water and cover only the 1.2% of it. The experimental results of 10 samples are given in Table 1.

### Table 1  The biomass samples and net heating value.

<table>
<thead>
<tr>
<th>Biomass sample</th>
<th>Production in region of Iran (in tons)</th>
<th>NHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice husk</td>
<td>North (2,800,000)</td>
<td>13.65</td>
</tr>
<tr>
<td>Wheat husk</td>
<td>Everywhere (1,500,000)</td>
<td>15.7</td>
</tr>
<tr>
<td>Sunflower stalk</td>
<td>Center (13,000)</td>
<td>16.67</td>
</tr>
<tr>
<td>Sourcheery stalk</td>
<td>Centre &amp; North east (222,000)</td>
<td>18.39</td>
</tr>
<tr>
<td>Walnut shell</td>
<td>West &amp; South (170,000)</td>
<td>19.00</td>
</tr>
<tr>
<td>Pistachios shell</td>
<td>West-South (230,000)</td>
<td>18.38</td>
</tr>
<tr>
<td>Watermelon &amp; cantaloupe peel</td>
<td>North, Centre &amp; South (4,500,000)</td>
<td>18.86</td>
</tr>
<tr>
<td>Pine cone</td>
<td>Everywhere (3,300,000)</td>
<td>18.75</td>
</tr>
<tr>
<td>Olive waste</td>
<td>North (125,000)</td>
<td>16.66</td>
</tr>
<tr>
<td>Potato &amp; onion peel</td>
<td>Centre, South &amp; Northeast (6,200,000)</td>
<td>17.69</td>
</tr>
</tbody>
</table>

### Table 2  C, H, O and ash contents( in percentage).

<table>
<thead>
<tr>
<th>Biomass sample</th>
<th>Ash</th>
<th>N</th>
<th>O</th>
<th>H</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice husk</td>
<td>23.20</td>
<td>0.58</td>
<td>40.04</td>
<td>4.79</td>
<td>31.39</td>
</tr>
<tr>
<td>Wheat stalk</td>
<td>9.09</td>
<td>1.00</td>
<td>49.06</td>
<td>7.66</td>
<td>33.22</td>
</tr>
<tr>
<td>Sunflower stalk</td>
<td>8.96</td>
<td>0.57</td>
<td>50.50</td>
<td>7.67</td>
<td>32.50</td>
</tr>
<tr>
<td>Sourcheery stalk</td>
<td>5.10</td>
<td>0.69</td>
<td>54.31</td>
<td>4.79</td>
<td>35.19</td>
</tr>
<tr>
<td>Walnut shell</td>
<td>3.80</td>
<td>0.09</td>
<td>55.00</td>
<td>4.75</td>
<td>36.40</td>
</tr>
<tr>
<td>Pistachios shell</td>
<td>4.05</td>
<td>0.02</td>
<td>51.83</td>
<td>5.00</td>
<td>39.10</td>
</tr>
<tr>
<td>Watermelon &amp; cantaloupe peel</td>
<td>5.70</td>
<td>0.01</td>
<td>59.38</td>
<td>4.09</td>
<td>30.80</td>
</tr>
<tr>
<td>Pine cone</td>
<td>6.86</td>
<td>0.00</td>
<td>43.08</td>
<td>6.03</td>
<td>44.01</td>
</tr>
<tr>
<td>Olive waste</td>
<td>21.06</td>
<td>1.01</td>
<td>35.00</td>
<td>4.01</td>
<td>38.01</td>
</tr>
<tr>
<td>Potato &amp; onion peel</td>
<td>7.00</td>
<td>1.70</td>
<td>39.60</td>
<td>6.96</td>
<td>45.30</td>
</tr>
</tbody>
</table>
different biomass materials have been used to develop correlations for an estimation of the net heating value from the elemental composition and ash content of the dry biomass. Empirical equation has been used by means of least squares regression analysis [8], the regression coefficient and the standard deviation are 0.8600 and 0.6544, respectively, but empirical equations with the squared content of carbon have not been used due to lower prediction errors. The experimental values of samples versus theoretical values from equation, are in good accordance. This result can be found with relatively uniform composition of the ash-free organic component of biomass.

5. Conclusions

The development of this alternative solution is based on the agricultural management and on the other hand, the synergy between the applied agriculture and desired energetic policies, the coordination between the various services of the state are still essential. 10 biomass samples have been shown by the contents of carbon, hydrogen, oxygen and ash in the dry basis. Experimental analysis showed that the net heating values of biomass samples varied in the range of 13.65-19.00 MJ/kg. An equation has been developed to predict the net heating values of biomass samples from their analysis and ash content values; this indicates that there is a good estimation.

References

Sensorless Predictive Algorithm for Permanent Magnet Brushless DC Drives

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Abstract: A high resolution speed and position identification algorithm, suitable for brushless DC drives, is presented in this paper. In particular, the algorithm is proposed for BLDC (brushless DC) machines that are characterized by an un-ideal trapezoidal emfs shape. The algorithm, which is developed basing upon the MRAS technique (model reference adaptive system) and the Popov’s hyperstability criterion, guarantees the convergence of the estimated rotor speed and position signals to their corresponding actual values. The identification procedure can be performed starting from the knowledge of low resolution rotor position signals, phase currents and the BLDC emfs shape. The identification algorithm is properly tested on a BLDC drive controlled by a predictive algorithm, by performing a simulation study in the Matlab-Simulink environment. The corresponding results have highlighted the effectiveness of the proposed sensorless predictive control system, at both low and high speed operation.

Key words: Permanent magnet machines, parameters estimation, model reference adaptive control, predictive control.

1. Introduction

PM (permanent magnet) brushless drives are nowadays widely used in several applications, mainly due to the simple and inexpensive PM machine, which presents rugged construction, low maintenance and high reliability. Thanks to high energy permanent magnets materials, PM machine presents both high torque to volume and torque to current ratios, together with high efficiency. Hence, PM drives well match the emergent “drive by wire” demands, especially in automotive and aerospace applications, ousting hydraulic and pneumatic actuators and, thus, resulting in a further market expansion.

PM brushless machines are generally classified as BLAC (brushless AC) or BLDC (brushless DC) ones, due to their different emfs shape. In particular, BLAC machine is characterized by sinusoidal emfs, which requires appropriate construction, winding distribution and/or permanent magnets magnetization criteria [1]. Furthermore, high resolution position sensors are generally required by its control system in order to fully exploit machine performances. On the contrary, BLDC machine is characterized by trapezoidal emfs, which can be achieved less expensively than the sinusoidal one. In addition, low resolution position sensors (hall devices) are generally good enough in order to well drive BLDC machine by means of the classical current commutation control strategy. However, this last one generally leads to current ripple and, hence, to torque ripple, especially at high speed operation [2]. All these features have made BLDC drives suitable for low cost/performances applications mainly [3, 4].

In order to improve BLDC performances, several solutions have been proposed in the literature to mitigate the commutation torque ripple. This is generally achieved resorting to proper PWM modulations [5, 6], improved DTC (direct-torque-control) look-up
Sensorless Predictive Algorithm for Permanent Magnet Brushless DC Drives

Tables [7] or by employing DC-DC converter [8]. However, the armature resistance and the emfs variation over the commutation period are generally neglected, thus a torque ripple still occurs.

Hence, some of the authors of the present papers have proposed a novel current control strategy [9] with the aim of fully exploiting the BLDC machine performances. It consists in tracking optimal reference currents in three-phase-on operation mode, providing both minimum Joule losses and torque ripple at the same time. Furthermore, wide speed range operation can also be achieved, as pointed out in Ref. [10]. Although the above mentioned control strategy requires accurate knowledge of rotor speed and position, this can be assured resorting to sensorless algorithm [11], avoiding the employment of high resolution speed and position sensors. Several sensorless techniques have been proposed in the literature for PM machines with either trapezoidal or sinusoidal emfs shape, mainly based on back-EMF detection, flux calculation, observers and other methods. A wide review and future trends of them are summarized and discussed in Refs. [12, 13].

However, in all the above mentioned papers, reference is made to BLDC drives with ideal trapezoidal emfs shape, except Ref. [6], in which un-ideal back emfs are taken into account in order to reduce the torque ripple. This is done by define appropriate emfs shape function basing upon offline measurements of back emfs, performed at constant rotor speed values. However, due to the employment of the traditional current commutation control technique, a torque ripple still occurs. The same emfs identification procedure is adopted in Ref. [14], in which a three-phase-on sensorless DTC technique is suggested too. However, it leads to strong torque ripple, so it does not seem suitable for high performances applications.

In this paper, an optimal sensorless predictive control algorithm is developed for BLDC machines characterized by un-ideal emfs shape [15]. First of all, optimal reference currents are properly achieved basing upon the knowledge of the BLDC emfs shape. Then, this last one is assumed to be made up of the superposition of a trapezoidal shape and an emfs shape deviation. This allows the employment of the sensorless predictive control algorithm previously synthesised in Ref. [11] by means of the MRAS technique (model reference adaptive system) [16], whose stability is guaranteed by satisfying the Popov’s hyperstability criterion [17]. In conclusion, the proposed sensorless predictive control system is computer simulated in the Matlab Simulink environment in order to highlight the effectiveness of both the rotor speed and position identification procedure and the optimal control strategy.

2. Mathematical Model and Control Strategy

The electrical equation of a PM brushless machine can be expressed, in terms of chain quantities, as in:

\[
v_{ch} = r \times i_{ch} + L \times \frac{di_{ch}}{dt} + e_{ch}
\]

where \( r \) and \( L \) represent the phase resistance and the equivalent inductance respectively, \( i_{ch} \) and \( v_{ch} \) are the chain current and voltage vectors, whereas \( e_{ch} \) is the chain emfs vector due to permanent magnets. All these ones can easily be computed basing upon their corresponding phase quantities by means of:

\[
\begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
u_a \\
u_b \\
u_c
\end{bmatrix}
= \begin{bmatrix}
u_{ch} \\
u_{ch} \\
u_{ch}
\end{bmatrix}, \quad u = \{v, i, e\}
\]

where \{a, b, c\} denote the motor phases indexes. Hence, a BLDC characterized by un-ideal trapezoidal emfs shape is considered, whose chain emfs are depicted in Fig. 1 [15]. Due to the symmetrical shape of the emfs, the indexes \{x, y, z\} and \( \sigma \) are introduced as shown in Table 1.

Furthermore, the per-unit rotor position \( \theta_{pu} \) is defined as in:

\[
\theta_{pu} = \left( \frac{3}{\pi} \times \theta_m - \frac{1}{2} \right) \% 1
\]
Sensorless Predictive Algorithm for Permanent Magnet Brushless DC Drives

Fig. 1  The chain emfs shape of an un-ideal BLDC machine.

Table 1  Three-phase indexes and signs.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>x</td>
<td>y</td>
<td>z</td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>b</td>
<td>y</td>
<td>z</td>
<td>x</td>
<td>y</td>
<td>z</td>
<td>x</td>
</tr>
<tr>
<td>c</td>
<td>x</td>
<td>y</td>
<td>z</td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>σ</td>
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<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
</tr>
</tbody>
</table>

being % the mod operator, \( p \): the pole pairs and \( θ_m \): the rotor position.

In this way, assuming \( pΛ \) as the voltage constant of the motor, the chain emfs vector can be expressed as:

\[
e_{ch} = σ \times 2Λ \times ω \times ϵ_{ch}
\]  

where:

\[
ω = p \times ω_m
\]

being \( ω_m \) the rotor speed. Moreover, always referring to Eq. (4), the vector \( ϵ_{ch} \) defines the emfs shape of the drive, so it can be expressed as:

\[
ϵ_{ch} = e_{ch} + δ_{ch}
\]

In particular, the \( δ_{ch} \) vector represents the chain emfs shape deviation with respect to the ideal trapezoidal shape, which is represented by the \( ϵ_{ch} \) vector:

\[
e_{ch} = \begin{bmatrix} 1 \\ -(1 - \theta_{pu}) \\ -\theta_{pu} \end{bmatrix}
\]

As a result, the electromagnetic torque can be expressed as:

\[
T_e = σ \times \frac{2pΛ}{3} (ζ_{xy} \times i_{xy} + ζ_{yx} \times i_{yx} + ζ_{zx} \times i_{zx})
\]

In order to optimize the PM machine operations, it is possible to choose the reference chain currents such that they satisfy both the minimum torque ripple and the minimum Joule losses constraints [9]. These ones are expressed by Eqs. (9) and (10) respectively:

\[
ζ_{xy} \times i^{(ref)}_{xy} + ζ_{yx} \times i^{(ref)}_{yx} + ζ_{zx} \times i^{(ref)}_{zx} = σ \times 3f^{(ref)}
\]

\[
\frac{r}{3} (i^{(ref)}_{xy})^2 + (i^{(ref)}_{yx})^2 + (i^{(ref)}_{zx})^2 = p^{(ref)}
\]

being \( f^{(ref)} \): the reference equivalent torque current, whereas \( P^{(ref)} \) is the minimum Joule losses achievable at the reference torque value \( T_e^{(ref)} \), as shown in Eqs. (11) and (12) respectively:

\[
f^{(ref)} = \frac{T^{(ref)}}{2pΛ}
\]

\[
p^{(ref)} = \frac{r}{3} \times \min \left( i^{(ref)}_{xy} + i^{(ref)}_{yx} + i^{(ref)}_{zx} \right)
\]

Moreover, the reference chain currents must satisfy the following constraint:

\[
i^{(ref)}_{xy} + i^{(ref)}_{yx} + i^{(ref)}_{zx} = 0
\]

As a result, by properly combining Eqs. (9), (10) and (13), the optimal reference chain currents vector can be obtained, as in:

\[
i^{(ref)}_{ch} = σ \times 3f^{(ref)} \times \frac{ζ_{ch}}{\|ζ_{ch}\|}
\]

Therefore, the knowledge of the chain emfs shape deviation vector \( δ_{ch} \) is necessary in order to determine the optimal reference chain currents, like those depicted in Fig. 2.

3. Predictive Control Algorithm

In order to synthesized the predictive control algorithm, the discrete time model of the PM brushless machine is necessary. Hence, the substitution of Eqs. (4) and (6) in (1) leads to:

\[
\frac{di_{ch}}{dt} = -\frac{r}{L} i_{ch} + \frac{1}{L} V_{ch} - \frac{2Λ}{L} ω (ε_{ch} + δ_{ch})
\]

In this way, assuming the rotor speed constant in each \([kT_s,(k+1)T_s]\) sampling time interval, the discretization procedure can be successfully carried out, leading to:

\[
i_{ch,k+1} = f \times i_{ch,k} + h \times Δε_{ch,k} + σ_k \omega_k (μ \times Ξ_{ch,k} + Δ_{h,k})
\]

In particular, \( Δε_{ch,k} \) is the chain voltage pulse widths vector, whereas the coefficients \( f, h \) and \( μ \) are:

\[
f = e \times \frac{T_s}{T_e}, \quad h = \frac{V}{e} \times \frac{T_s}{T_e}, \quad μ = \frac{2Λ}{r} \times (1 - f)
\]
being $T_s$ the sampling time interval and $V$ the DC bus voltage of the inverter. Moreover, referring to Eq. (16), $\Xi_{ch,k}$ represents the effect of the trapezoidal emf components on $i_{ch,k+1}$ and it can be expressed as:

$$\Xi_{ch,k} = \left[ \begin{array}{c} -1 \\ 1 - \xi_k \end{array} \right]$$

being:

$$\xi_k = 3 \left( \frac{L}{r} - \frac{T_s}{1 - f} \right)$$

Finally, always referring to Eq. (16), $\Delta_{ch,k}$ represents the effect of the chain emfs shape deviations on $i_{ch,k+1}$:

$$\Delta_{ch,k} = -2 \sum_{k=1}^{(k-1)/T_s} \int_{t_k}^{t_{k+1}} e^{-\frac{t}{T_s}} \delta_{ch}(t) \, dt$$

Now, if the chain currents vector on the left side of Eq. (16) is imposed equal to its reference value, given by Eq. (14), the voltage pulse widths vector can be deduced as:

$$\Delta_{ch,k} = \frac{1}{h} \left( \frac{|i_{ch,k}|}{|i_{ch,k-1}|} - f \times i_{ch,k} - \sigma_k \omega_k \left( \mu \times \Xi_{ch,k} + \Delta_{ch,k} \right) \right)$$

In fact, this last equation allows the computation of the voltage pulse widths vector which must be applied over the $[kT_s, (k+1)T_s]$ sampling time interval with the aim of achieving the reference current values at $(k + 1)T_s$.

4. Position and Speed Identification Algorithm

The above predictive algorithm implementation requires the knowledge of both $\omega$ and $\theta_{pw}$ values at starting of each sampling time interval. Referring to the BLDC drive, an identification algorithm, based upon both the MRAS (model reference adaptive system) [16] technique and the Popov hyperstability criterion [17], was already proposed in Ref. [11] considering ideal trapezoidal shape of emfs. That is like the case considered in this paper but neglecting the chain emfs shape deviation vector $\delta_{ch}$. Nevertheless, the same algorithm can be used, but properly taking into account the effect of the chain emfs shape deviation vector $\delta_{ch}$. This can be done by compensating $\Delta_{ch,k}$ in Eq. (16) by means of the voltage pulse widths vector $\Delta A I_{ch,k}$. This last one can be expressed as:

$$\Delta A I_{ch,k} = \Delta T_{ch,k} \times \frac{\sigma_k \times \omega_k}{h} \Delta_{ch,k}$$

By substituting Eq. (22) in Eq. (16), the following Eq. (23) is achieved.

$$i_{ch,k} = f \times i_{ch,k-1} + h \times \Delta T_{ch,k} + \sigma_k \times \omega_k \times \mu \times \Xi_{ch,k}$$

Therefore, Eq. (23) represents the discrete time model of a BLDC drive with ideal trapezoidal emfs shape, equivalent to the un-ideal BLDC drive affected by emfs shape deviation. In particular, if the equivalent BLDC drive is supplied by the voltage pulse widths vector $\Delta T_{ch,k}$, its chain currents are the same of the un-ideal BLDC one supplied by the $\Delta A I_{ch,k}$ pulse widths vector. Hence, since $\Delta A I_{ch,k}$ is directly synthesizable by means of Eq. (21), the voltage pulse widths vector $\Delta T_{ch,k}$ can be easily computed as:

$$\Delta T_{ch,k} = \Delta A I_{ch,k} \times \frac{\sigma_k \times \omega_k}{h} \Delta_{ch,k}$$

Due to the above considerations, the same rotor speed and position identification algorithm introduced in Ref. [11] can be successfully employed basing upon Eq. (23), so it is summarized below.

Referring to the $[(k - 1)T_s, kT_s]$ sampling time interval, the discrete time model expressed by Eq. (23) can be put into the following scalar form:

$$\begin{align*}
i_xk &= f \times i_{x,k-1} + h \times \Delta T_{x,k-1} - \mu \times \sigma_k \times \omega_k \times \Xi_{x,k} \\
i_yk &= f \times i_{y,k-1} + h \times \Delta T_{y,k-1} + \mu \times \sigma_k \times \omega_k \times \Xi_{y,k} \\
i_zk &= f \times i_{z,k-1} + h \times \Delta T_{z,k-1} + \mu \times \sigma_k \times \omega_k \times \Xi_{z,k}
\end{align*}$$

In particular, the second equation (yz) of Eq. (23) is usefully neglected, since it is not necessary in order to carry out the identification procedure. In this way, the parallel adjustable system can be introduced, as shown.
in Eqs. (26) and (27):
\[
\begin{align*}
\hat{i}_{sy,k} &= f \times \hat{i}_{sy,k-1} + h \times \Delta T_{sy,k-1} - \mu \times \sigma_{k-1} \hat{\omega}_{k-1} \\
\hat{i}_{nx,k} &= f \times \hat{i}_{nx,k-1} + h \times \Delta T_{nx,k-1} + \mu \times \sigma_{k-1} \hat{\omega}_{k-1} + \hat{\rho}_{k-1}
\end{align*}
\]
(26)
\[
\begin{align*}
\hat{\xi}_{sy,k} &= f \times \hat{i}_{sy,k-1} + h \times \Delta T_{sy,k-1} - \mu \times \sigma_{k-1} \hat{\omega}_{k-1} \\
\hat{\xi}_{nx,k} &= f \times \hat{i}_{nx,k-1} + h \times \Delta T_{nx,k-1} + \mu \times \sigma_{k-1} \hat{\omega}_{k-1} + \hat{\rho}_{k-1}
\end{align*}
\]
(27)
where the symbols ~ and ^ denote the “a priori” and “a posteriori” quantities respectively, which are required by the discrete nature of the identification algorithm. Moreover, \( \hat{\rho}_{k-1} \) is a decaying input, which must be zero at the end of the adaptation procedure. Hence, it is possible to define the “a priori” and “a posteriori” current errors as:
\[
\begin{align*}
\hat{\epsilon}_{sy,k} &= i_{sy,k} - \hat{i}_{sy,k} \\
\hat{\epsilon}_{nx,k} &= i_{nx,k} - \hat{i}_{nx,k}
\end{align*}
\]
(28)
The identification algorithm employs the “a priori” current errors in order to update \( \hat{\omega}_{k-1} \) and \( \hat{\xi}_{k-1} \) to their corresponding “a posteriori” values by means of:
\[
\begin{align*}
\hat{\omega}_{k-1} &= \hat{\omega}_{k-1} + \Phi \hat{\epsilon}_{nx,k-1} + \Psi \hat{\epsilon}_{sy,k-1} \\
\hat{\xi}_{k-1} &= \hat{\xi}_{k-1} + \Phi \hat{\epsilon}_{nx,k-1} + \Psi \hat{\epsilon}_{sy,k-1}
\end{align*}
\]
(29)
where \( \Phi \) and \( \Psi \) represent the integral and the proportional adaptation functions respectively. Since these functions must guarantee the asymptotic convergence of the identification procedure, they are chosen in order to satisfy the Popov hyperstability criterion, as in:
\[
\begin{align*}
\Phi_{nx,k-1} &= -\alpha_x \times \mu \times \sigma_{k-1} \hat{\epsilon}_{sy,k-1} \\
\Psi_{nx,k-1} &= -\beta_x \times \mu \times \sigma_{k-1} \hat{\epsilon}_{sy,k-1} \\
\Phi_{nk,k-1} &= \alpha_x \times (f \times \hat{i}_{sy,k-1} + h \times \Delta T_{sy,k-1} - i_{sy,k}) \hat{\epsilon}_{nx,k-1} \\
\Psi_{nk,k-1} &= \beta_x \times (f \times \hat{i}_{sy,k-1} + h \times \Delta T_{sy,k-1} - i_{sy,k}) \hat{\epsilon}_{nx,k-1}
\end{align*}
\]
(30)
In particular, \( \alpha_x \) and \( \beta_x \) are the integral adaptation gains, while \( \beta_n \) and \( \beta_z \) are the proportional ones. However, it is necessary to express the “a posteriori” current errors by means of the “a priori” ones. This can be done by subtracting Eq. (26) from Eq. (27), leading to:
\[
\begin{align*}
\hat{\epsilon}_{sy,k} - \hat{\epsilon}_{sy,k} &= -\mu \times \sigma_{k-1} (\hat{\omega}_{k-1} - \hat{\omega}_{k-1}) \\
\hat{\epsilon}_{nx,k} - \hat{\epsilon}_{nx,k} &= \mu \times \sigma_{k-1} (\hat{\omega}_{k-1} \hat{\xi}_{k-1} - \hat{\omega}_{k-1} \hat{\xi}_{k-1}) + \hat{\rho}_{k-1}
\end{align*}
\]
(32)
Furthermore, if the decaying input is chosen as:
\[
\rho_{k-1} = -\hat{\xi}_{k-1} \hat{\xi}_{k-1}
\]
(33)
the “a posteriori” current errors can be expressed by means of the “a priori” ones:
\[
\begin{align*}
\hat{\epsilon}_{sy,k} &= \frac{1}{1 + \mu^2} (\alpha_x + \beta_x) \\
\hat{\epsilon}_{nx,k} &= \frac{1}{1 + (\alpha_x + \beta_x)} (f \times \hat{i}_{sy,k-1} + h \times \Delta T_{sy,k-1} - i_{sy,k})
\end{align*}
\]
(34)
In conclusion, the “a priori” \( \hat{\omega}_k \) and \( \hat{\xi}_k \) values must be updated as in:
\[
\begin{align*}
\hat{\omega}_k &= \hat{\omega}_{k-1} + \Phi_{nk,k} + \frac{3T}{\pi} \hat{\rho}_{k-1} \\
\hat{\xi}_k &= \hat{\xi}_{k-1} + \Phi_{nk,k} + \frac{3T}{\pi} \hat{\rho}_{k-1}
\end{align*}
\]
(35)
In fact, these last values are needed in order to carry on the identification procedure at \((k + 1)T_s\). In conclusion, both the “a posteriori” and the “a priori” \( \omega_m \) and \( \sigma_m \) values can be easily computed by Eqs. (5) and (19).

The identification procedure applied to the un-ideal BLDC drive is depicted in the block diagram of Fig. 3. Hence, at the \( kT_s \) sampling time instant, the following quantities are available:
- The \( \hat{i}_{ch,k} \) vector, measured at \( kT_s \);
- The \( \Delta T_{ch,k} \) vector, synthesized in the previous sampling time interval;
- The “a priori” \( \hat{\omega}_{ch,k} \) and \( \hat{\xi}_{ch,k} \) values;
- The “a priori” \( \hat{\rho}_{ch,k} \) vector;
- The previous “a posteriori” \( \tilde{i}_{ch,k} \) vector.

Therefore, all these ones are employed in order to compute the “a posteriori” current errors by means of Eq. (34) (block B). Hence, the “a posteriori” \( \hat{\omega}_{ch,k} \) and \( \hat{\xi}_{ch,k} \) values are computed by means of Eq. (29) through Eq. (31), the decaying input \( \rho_{ch,k} \) is obtained by Eq. (33) and the “a priori” \( \hat{\omega}_{ch,k} \) and \( \hat{\xi}_{ch,k} \) values are updated by Eq. (35), being all these operations performed in block C. Then, the “a posteriori” current values are determined by Eq. (27) (block D), whereas \( \hat{\rho}_{pu}, k \) and \( \hat{\rho}_{m}, k \) can be computed by Eqs. (5) and (19) (block E). Then, the “a posteriori” current values \( \hat{i}_{ch,k} \) and the “a priori” \( \hat{\omega}_{ch} \) and \( \hat{\xi}_{ch} \) values are employed, together with the reference torque value \( Te(ref) \), with the aim of synthesizing the control vector \( \Delta Tch, k \) by means of
Sensorless Predictive Algorithm for Permanent Magnet Brushless DC Drives

Fig. 3  Identification algorithm (light gray) and predictive control (light red) equivalent block diagrams.

\[
\Delta T_{ch,k} = \frac{1}{h} \left( i_{ch,k}^{(ref)} - i_{ch,k} \sigma_k \times \omega_k \times \Xi_{ch,k} \right)
\]  (36)

In this way, the current values predicted for (k + 1)Ts can be successfully assumed as the “a priori” values at (k + 1)Ts. In conclusion, the \( \Delta T_{ch,k} \) vector and the “a priori” \( \omega_{pu,k} \) and \( \omega_{m,k} \) values are properly employed in order to determine the \( \Delta T_{ch,k} \) vector which must be applied to the drive over the \([kTs,(k + 1)Ts]\) sampling time interval. This is performed in block G by means of Eqs. (20) and (22).

5. Simulation Results

A simulation study is carried out in the Matlab Simulink environment in order to highlight the performances achievable by the proposed sensorless predictive algorithm. Hence, a BLDC machine affected by a chain emfs shape deviation is considered, whose parameters and rated values are summarized in Table 2. The equivalent block control scheme of the drive is depicted in Fig. 4, in which \{ha, hb, hc\} denote the hall signals, being 10 kHz the inverter switching frequency and 100 \( \mu \)s the sampling time Ts.

First of all, the simulation study refers to the start up of the motor, when a step reference torque of 0.24 Nm is suddenly applied, in order to achieve the steady state speed value of 64 rad/s. Due to the initial rest condition of the motor, the “a priori” \( \omega_m \) initial value is set to zero, equal to its actual value. On the contrary, since the absolute rotor position should be assumed unknown, the “a priori” \( \theta_{pu} \) initial value is assumed zero, being 0.5 its actual value.

The simulations results obtained at the start up of the drive are reported in Figs. 5-8.

In particular, the \( \omega_m \) and \( \theta_{pu} \) evolutions, compared to their corresponding actual values, are depicted in Figs. 5 and 6 respectively. Firstly referring to Fig. 5, it can be seen that it is difficult to distinguish the two speed evolutions, due to the very small rotor speed

<table>
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<th>Parameters</th>
<th>( r )</th>
<th>( L )</th>
<th>( p )</th>
<th>( \Delta )</th>
<th>( V_a )</th>
<th>( I_a )</th>
<th>( \omega_m )</th>
</tr>
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<td>140</td>
<td>1.7</td>
<td>2,000</td>
</tr>
<tr>
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<td>[\Omega]</td>
<td>[mH]</td>
<td>[-]</td>
<td>[Wb]</td>
<td>[V]</td>
<td>[A]</td>
<td>[rpm]</td>
</tr>
</tbody>
</table>

Table 2  BLDC parameters and rated values.

Fig. 4  Equivalent block control scheme of the BLDC drive: (1) symmetrical pulses generator; (2) three-phase inverter.
errors. On the contrary, referring to Fig. 6, the rotor position error is significantly greater, due to the difference between the $\theta_{pu}$ and $\omega_{pu}$ initial values. Nevertheless, it can be seen that the rotor position error is drastically reduced even before the first commutation instant, in correspondence of which both $\dot{\theta}_{pu}$ and $\theta_{pu}$ are reset. Referring to the chain currents and emfs evolutions at the start up of the drive depicted in Fig. 7, they are badly affected especially by the initial errors occurring on $\theta_{pu}$. This prevents the torque from quickly achieving its reference value, as well shown in Fig. 8. However, after the first commutation instant, a good tracking of the reference quantities are obtained, being the subsequent torque and currents ripples due to inverter modulation mostly.

After 1 s, when the steady state speed value is achieved, the reference torque value is increased to 0.75 Nm in order to reach the higher steady state speed value of 200 rad/s. The simulations results are shown in Figs. 9-11. Although the rotor speed variation gives rise to identification errors, they are quite small compared to the respective actual values. Therefore, they do not affect the torque response significantly, as well shown in Fig. 11.

Finally, after 2 s, a step load torque of 0.33 Nm is applied, being the reference torque value unchanged. In this way, the rotor speed decreases to the lower steady state speed value of 112 rad/s, which is achieved in about 1 s. The corresponding simulations results are reported in Figs. 12-14. It can be seen that, in this case, the identification errors are negative, meaning that both $\omega_{m}$ and $\theta_{pu}$ are overestimated. However, since their magnitudes are very small, the torque evolution is not affected significantly, as in the previous case.
Fig. 9  Rotor speed (top) and its identification error (bottom) due to a step reference torque variation (rad/s).

Fig. 10  The $\theta_{pu}$ evolutions (top) and its identification error (bottom) due to step reference torque variation.

Fig. 11  Torque evolution due to a step reference torque variation (in p.u., base torque 0.75 Nm).

Fig. 12  Rotor speed evolutions (top) and its identification error (bottom) due to a step load torque (rad/s).

Fig. 13  The $\theta_{pu}$ evolutions (top) and its identification error (bottom) due to a step load torque.

Fig. 14  Torque evolution due to a step load torque (in p.u., base torque 0.75 Nm).
6. Conclusions

In the paper, a high resolution speed and position identification algorithm suitable for PM brushless DC drives has been presented. The algorithm has been synthesized by means of the model reference adaptive system technique for un-ideal BLDC drives, which are characterized by non trapezoidal emfs shape.

This case has required a proper adaptation and modification of the BLDC control system, consisting in the compensation of the chain emfs shape deviation with respect to the ideal trapezoidal shape. To verify the goodness of the identification algorithm, a PM brushless DC drive, controlled by a predictive optimal algorithm, is considered. The drive has been computer simulated in the Matlab-Simulink environment, at both low and high speed operation. The results have shown that, at starting, the initial position error is quickly reduced, whereas small speed and position errors appear during fast transient only. However, they are quickly reduced thanks to the goodness of the adaptation mechanism of the proposed sensorless algorithm.

References

Mathematical Modelling for Assessing Integrity of Power Systems Grounding Devices

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Abstract: This paper presents the development of a new technique to monitor the operating conditions of a grounding device of high voltage apparatus and systems without any diggings and forced outages. The model is based on the evaluation of the magnetic field distribution along the current-carrying horizontal element when it has been deteriorated or broken. A mathematical model which can be used to analyze and evaluate the integrity of the grounding device has been developed. Computer simulation studies were conducted to validate the effectiveness of the proposed model.

Key words: Grounding devices, horizontal elements, earthing.

1. Introduction

According to world statistics, annually there are 3-10 fatal accidents per million inhabitants in different countries per year. Deaths from electrocution in different countries vary between 9%-10%, which is 10-15 times greater than from other injuries. Annually from 1,000 to 1,200 people die due to electrocution in the US and about 250,000 people throughout the world. Electric shocks are 2%-2.5% among other injuries, 60% of all electrical accidents occur as a result of safety violations, 40% are the result of slack in safety aspects in designing power networks, equipment and installations [1].

Power substation itself is a complex system consisting of high voltage apparatus, switchgear equipments, buildings and auxiliary units. It is necessary to provide normal and safe operating condition for staff and equipment. One reason for increased risk during a short circuit condition is due to ineffective integrity of the grounding devices.

The effectiveness of the grounding devices is influenced by factors such as soil structure, dampness, presence of salts and acids, electric corrosion, freezing process etc.. This is complicated by the inability to carry out visual assessment of the grounding devices’ effectiveness. With time there is a possibility of rise of the grounding devices current spreading resistance, horizontal elements getting ruptured that can lead to failure in operation of secondary commutation circuits during short circuits. In addition, it leads to a high potential affecting electrical equipments’ frames, damages to insulation etc.. There is full inspection including moisture meter readings also a potential of violating electromagnetic compatibility regulation standards.

A grounding device is one of the most important parts of electric power plants. It is not only protection from electrocution of staff and equipment damages but also in some cases a return circuit for load current. Grounding devices apart from providing safety and in some cases a return circuit for load currents also
provides an equipotential distribution of the voltage on the surface of the earth at power plants.

If grounding conductors are damaged, it may cause malfunctions protective relay operation and therefore circuit breaker tripping. It is also may result in failure of the grounding device itself, secondary circuits cables and structural elements such as protection devices and etc.. The circuits may attain unacceptable values when short-circuit fault currents occur in these devices.

As seen from Fig. 1, when an AC transit substation with one common grounding device is bonded together with proper integral conductors there will be no substantial potential different amongst the point of enclosures. But if one of the conductors is damaged, it will increase the value of the current and the voltage in the other. Such overvoltage can create the situation that the second conductor will be damaged due to overheating. Once this happens, the integrity of the grounding is affected.

The most important parameters of electric safety at power plants are touch voltage and step voltage (Fig. 2).

Step voltages are normally less hazardous than touch voltages for two reasons [2]:

1. The human body can tolerate higher voltages across the foot-to-foot current path (step) compared to the hand-to-feet path (touch);
2. For any given position, the step voltage is lower than the prospective touch voltage.

This generality can lead to the step voltage being neglected as a hazard by itself. For example, Electricity Association Technical Specification 41-24 states, “if the earthing system is safe against touch potential it will be inherently safe against step potential” [3].

The location of the worst-case step voltage is accepted by both UK and US standards to be the potential difference across the ground surface one meter diagonally out from the corner of the grid [4].

While a grounding device does not have broken elements, the potential on the surface of the earth will have a uniform value as shown in Fig. 3.

This means that under both normal and abnormal operating conditions all the equipment enclosures and staff will have no potential difference among the perimeter of a power plant (U_{touch1} and U_{touch2} in Fig. 2).

In case of the presence of horizontal elements damages the uneven potential distribution appears on the surface of the earth. The profile of the potential curve in Fig. 3 in such conditions will not have almost uniform distribution in the central part of the figure and this fact can lead to the substantial step voltage appearance. Especially it can be dangerous on the surface above the edge meshes of the grid. Value of the potential difference may exceed the breakdown voltage of the secondary circuits’ cables insulation and in the worst situation may result in the common-mode failure of relay protection and circuit breakers. Such situation can result in the most dangerous consequences for staff and equipment (U_{touch2} in Fig. 2).
Typically, approximately 80%-90% of the whole elements of a grounding device are horizontal elements. It means that integrity of the whole grounding device depends on the integrity of its horizontal elements.

The grounding device’s horizontal elements are to be more susceptible to deterioration in a corrosive environment than the vertical ones. Being in a soil superficial stratum, the horizontal elements are exposed to air oxygen more than vertical elements. As a result, the horizontal elements are more prone to be corroded.

The technical serviceability of the grounding devices can be estimated by a measuring of its current spreading resistance, which according to the current standards should not exceed the limit value. However, the current spreading resistance can satisfy the standard or official limit, even though there are some ruptures or damages in the horizontal elements. This is due to the fact that the horizontal elements’ ruptures are hard to detect because there will be no high voltage distribution even in the crash situation.

Some of the main examples of the elements ruptures are shown in Fig. 4.

A failure of the grounding conductor (1) and damages of the horizontal elements (2) are shown in Fig. 4.

It means that all grounding devices associated with the processes of safe electric energy generation, conversion, transformation, transmission, distribution and consumption and also associated with the lightning protection must satisfy the basic rule of electric safety. All available touch exposed conductive parts of grounding devices, adjacent conductive parts, grounding conductors and also conductive parts of the return circuits, including rails, cable sheathing must be safe for direct contact with them under normal operation, in case of hazardous insulation damages and with an impact of the lightning current as well.

There are several existing publications highlighting proper design, use, maintenance and monitoring of the grounding devices’ characteristics [2-6] which provides information about proper evaluation, installation and connection at the initial part of the grounding devices’ “life”.

Details about the calculation of grid resistance, effect of earth non-uniformity, the highest possible short circuit current and determining the substation GPR (ground potential rise) are available from Refs. [7-9].

The existing technology of grounding devices is currently determined by measuring their parameters as follows: (1) resistance of the grounding device (the dependency of resistance on the distance between the potential and current electrodes in the Wenner method); (2) value of the potential in the most dangerous points of electric power plant and in the grid of the grounding device; and (3) testing the integrity of the ground grid [4, 5, 10]. The integrity test is typically carried out using a variable voltage source capable of delivering currents up to 300 A [7].

According to Ref. [6], the objective is to determine whether the various parts of the ground grid are interconnected with low resistance copper. This copper is shunted by the surrounding earth, which usually has very low impedance.

The ammeter-voltmeter method, using alternating current, can not be used satisfactorily for this test. The reactance of a large copper wire in this case is shunted by the surrounding earth, a path which may have slightly less reactance than the wire. Therefore, a continuity test for buried wire would give indeterminate results if alternating current was used.

The practical integrity test consists of passing about 5 A into the ground grid between two points to be
checked. The voltage drop across these points is measured with a millivoltmeter or portable potentiometer and the effective resistance is calculated from the current and voltage readings.

This method is able to approximately identify the fact of integrity failure but can not identify the location or establish if all elements are fine.

Other methods discussed in literature are summarized as follows: Refs. [11, 12] introduce the method when current with value about 150-200 A and frequency not 60 Hz is injected in a grounding device between two points (pigtails) that are located not far from each other. This method is different from Ref. [13] in that the injected current is required to be around 200 A and its frequency is not 60 Hz or 60 Hz harmonic. Conclusion about the possibility of broken (corroded) element is made when weak magnetic field is fixed above the elements.

However, all experiments were conducted when a substation was under construction and there was no power frequency magnetic field in the substation before injecting the current to the grounding grid. The weak electromagnetic field can also be due to small impedance of the soil.

Ref. [14] describes another method when broken conductors are identified by substantial difference between the theoretical and simulated magnitudes of the leakage currents. In the method a high frequency current (up to 1 MHz) is injected into the ground grid and potential values are measured over the surface of the grid. Ref. [15] highlights a similar approach where faults are not precisely pinpointed, but by isolating a faulty current path, the work of excavation and repair is markedly reduced.

Ref. [16] introduces a device, designed to perform all required voltage measurements under conditions described in standards [4, 6]. It is based on the heavy current method procedure in large substation grounding systems inspections when the measuring current of the main frequency (50 Hz or 60 Hz) is injected into grounding system, providing a source of induced surface potentials. The device consists of two parts, (1) the IMD (intelligent measuring device) and (2) the accompanying IPE (integrated program environment) for a personal computer.

None of these methods determines a possible break indication, especially a point of the horizontal element’s damage.

Most of the mathematical modeling for grounding devices is based on the circuit theory or electromagnetic field theory. The common feature of the models is currents calculation and evaluation of the potentials above the grids conductors.

Ref. [17] describes one of the computer model, based on electromagnetic field theory, for transient analysis of a network of buried and above ground conductors. In this analytical model, the current distribution is determined by the sinusoidal approximating function when current is considered to be zero at the end points of the segments and rises sinusoidally to a maximum at the junction point of the segments.

Assumptions made include (1) the total current in the conductors is filamentary line current in the conductors’ axis; (2) the current on open end points is assumed to be zero; (3) the soil is modeled as linear and homogeneous half-space characterized by conductivity, permittivity and permeability constants; and (4) neglect of the soil ionization.

Ref. [18] focuses on the description of a program support computer visualization model which helps a user to look at the whole ESP (earth surface potentials) map at power substations. In fact, it comes down to work on the image pattern of potential distribution on the surface of the earth with the already pre-measured or calculated potential magnitudes.

Ref. [19], based on Refs. [20, 21], introduces a mathematical model, based on the theory of electromagnetism, combined with the moment method and electrical network model techniques. The model for calculating the magnetic source currents distribution of a grounding system with or without floating metallic
conductors in AC substations is presented. Both leakage currents and their mutual coupling influence are considered in the calculation. The earth is considered as multilayer conductivity media.

There is also a range of research papers regarding the problem of the grounding devices corrosion and its influence on the safety conditions.

In Ref. [22], the authors proposed a new method of corrosion diagnostic of the grounding devices’ elements with a similar approach to that of Ref. [23].

Major engineering project companies and earthing equipment manufacturers now have in-house computer programs to evaluate different substation earthing arrangements [24].

This paper focuses on analysis of the potential changes on the surface of the earth under faults conditions in case of horizontal elements damages. In Refs. [11, 12], the authors have described the possibility to find broken element by the detection of the weak magnetic field over it.

Fig. 5 depicts injection of some current in the grid (for instance, short circuit current) and detection the value of the magnetic field in points 1 to 4. From Fig. 5, one can see that there will be a weak field in the point #3 because of the break of the element. This paper proposes to analyze and describe the processes not only considering the above but also along the different links along the current-carrying conductor.

Fig. 6 shows the evaluation of the magnitude of the magnetic field through the element and observes that the distribution of the field is not even when it is broken.

The main objective of the research is to develop a new technique, for estimation of the grounding devices technical conditions on the surface of the earth without any diggings and tripping of a power plant. As a result, one will be able to evaluate the main electrical characteristics of the grounding devices and safety parameters when the grounding device is integral and has damaged elements as well.

The first step during the finding of the broken element, is moving across the horizontal elements as shown in Fig. 5. When finding the element with the weak field in comparison with the neighboring (surrounding) elements, one can predict that this element is broken. Second part is to come along the length of the marked element and analyze the magnetic field distribution. Finally, if it is observed that the magnetic field distribution is uneven, it can be concluded that the element is broken and one can then proceed to identify the point of the break.

Thus, the main feature of the proposed technique is not only being able to detect that the element is broken (because of uneven distribution of the field) but also able to identify the point of the break (the point with the lowest value of the field and different directions of the currents).

2. Mathematical Model of the Grounding Devices

Modern mathematical models deal with the characteristics in the grounding devices’ grids with respect to electrical safety parameters such as touch and step voltages, ground potential rise and a grounding device resistance.

There are two main theories used to describe the characteristics of the grounding devices: (1) the electromagnetic field theory and (2) the electric circuit theory. Some of their main characteristics are as follows:

(1) Assessment of the electromagnetic field changes
over the integral and damaged horizontal elements (the first principle). It can be important for the description of the characteristics in sensors on the surface of the earth;

(2) Assessment of the changes of the grids’ elements resistance and influence of these changes on the characteristics of current and potential distribution. It is important because it is useful to imply the generator with the frequency that is different from 50-60 Hz (it will allow us not to switch off the electric power plant). In that case it is necessary to know whether currents distribution in the grid will be the same as under the industrial frequency or not;

(3) Assessment of the current distribution in the grounding device grid when there is a broken (damaged) horizontal element and when the grid is integral (the second principle). It is important when it is necessary to evaluate and make some prognosis of electric safety parameters. In the first step of evaluation and analysis, some assumptions are made and they are as follows:

(a) Soil structure. The real structure of the soil is very hard to describe because it is a multilayered structure. It consists of many stratums with different depth and resistivity. It is a common practice to use two-layer model of the soil structure to have enough accuracy. But sometimes it is even difficult to get such two-layer model. Thus, at this stage it is assumed that the soil model is homogeneous;

(b) Elements length. The horizontal and vertical elements length is some meters and cross-section (equivalent diameter) of the element is much smaller than its length. This assumption will allow us to avoid references with respect to wave resistance of the elements. It is for sure if the length of the element is not big its wave resistance can be neglected;

(c) Elements characteristics. Currents flowing in different parts of the horizontal elements are equal. It means that characteristics of the elements are the same throughout their length.

As for the first above-mentioned mathematical description (electromagnetic field spreading over the integral and damaged horizontal elements), the Biot-Savart Law [25, 26] can be used as the main basis for modelling. In accordance to this law, the magnitude of the magnetic field is proportional to the current in the wire and varies as the inverse square of the distance from the source.

\[ dH = \frac{I \times \sin \alpha}{4\pi r^2} \, dx \]  

(1)

where, \( I \)—current that flows through the element;  
\( dx = |dp| \)—length element;  
\( r \)—distance from the element \( dx \) to \( P \);  
\( \alpha \)—angle between the element \( dx \) and \( r \).

A horizontal element of the grounding device’s mesh can be presented as a conductor with the initial current \( I_0 \) and length \( l \) (Fig. 7). The magnetic field magnitude at any point \( P \) can be determined in accordance with Eq. (1).

From the geometry

\[ \sin \alpha = a/r \]  

(2)

Also from the Fig. 7

\[ r = \sqrt{a^2 + x^2} \]  

(3)

Substitute Eqs. (2) and (3) into Eq. (1) gives

\[ dH = \frac{I}{4\pi r^2} \times \frac{a}{r} \, dx = \frac{I}{4\pi \times \sqrt{a^2 + x^2}} \times a \times dx \]  

(4)

But all these equations describe the magnitude of the field created by the current in only a small length element \( dx \) of the conductor. To find the total magnetic field \( H \) created at some point \( P \) by a current of finite value, one must sum up contributions from all current elements \( I \, dx \) that make up the current. That is, to evaluate \( H \) by integrating Eq. (4), one obtains

\[ dH = \left[ \frac{I}{4\pi \times \sqrt{a^2 + x^2}} \right] \times a \times dx = \frac{I_a \times a}{4\pi \times \sqrt{a^2 + x^2}} \, dx \]  

(5)

According to tables of indefinite integrals

![Fig. 7 Scheme for magnetic field evaluation.](image)
Taking the integral of Eq. (5) by using Eq. (6) one obtains

\[
dH = \frac{i}{4\pi} \int a \times dx = \frac{i}{4\pi} \int a \times \frac{dx}{\sqrt{a^2 + x^2}}
\]

Then,

\[
H = \frac{i}{4\pi} \times \frac{1}{a \times \sqrt{a^2 + x^2}} = \frac{i}{4\pi} \frac{1}{a \times \sqrt{a^2 + l^2}}
\]

With the assumptions made it is supposed that the current \( I \) in the element decreases uniformly because of leakage currents from the initial magnitude \( I_0 \). This decrease can be described as follows:

\[
I = I_0 \times (1 - x/l)
\]

Therefore, the final expression can be written as follows:

\[
H = \frac{l_0 \times (1 - x/l)}{4\pi} \times \frac{1}{a \times \sqrt{a^2 + l^2}} = \frac{l_0 \times (l - x)}{4\pi \times a \times \sqrt{a^2 + l^2}} (10)
\]

This Eq. (10) can be written in relative values where:

\[
a* = a/l, x* = x/l, I* = I/l,
\]

Profiles of magnetic field values \( H(x) \), evaluated in accordance with Eq. (11) for some values of \( a* \) when \( I* = 1 \) A, are presented in Fig. 8.

3. Case Studies

By assuming that \( I_0 = 1 \) A, \( a = 0.4 \) m (depth of the horizontal element), \( L = 5 \) m, when the value of \( x \) is changing, in case when the horizontal element is integral, one will obtain the following results of the magnetic field calculation on the surface of the earth as shown in Table 1.

Graphically, these changes are shown in Fig. 9.

If the horizontal element has a break (Fig. 10), it can be presented as two pieces with lengths \( l_1 \) and \( l_2 \) and initial currents \( I_{01} \) and \( I_{02} \) respectively.

Both parts of the element can be described analogically with the above mentioned expression of Eq. (5).

\[
dH_1 = \frac{l_1 \times a}{4\pi} \times \frac{dx}{\sqrt{a^2 + x^2}} \quad dH_2 = \frac{l_2 \times a}{4\pi} \times \frac{dx}{\sqrt{a^2 + x^2}}
\]

The solution on the integrals in Eq. (12) can be represented as:

\[
H_1 = \frac{l_0 \times (l - x)}{4\pi \times a \times \sqrt{a^2 + l_1^2}} \quad H_2 = \frac{l_0 \times (l - x)}{4\pi \times a \times \sqrt{a^2 + l_2^2}}
\]

Then substitute Eq. (9) into Eq. (13), one obtains

\[
H_1 = \frac{l_0 \times (l - x)}{4\pi \times a \times \sqrt{a^2 + l_1^2}} \quad H_2 = \frac{l_0 \times (l - x)}{4\pi \times a \times \sqrt{a^2 + l_2^2}}
\]

For example, if the values of \( I_{01} = 0.7 \) A, \( I_{02} = 0.3 \) A, \( a = 0.4 \) m (depth of the horizontal element), \( l_1 = 2 \) m, \( l_2 = 3 \) m and if directions of the currents in different parts of the broken element are different, the curve of the magnetic field changes is shown in Fig. 11.
But if the directions of the currents before and after the point of break are the same, the curve is shown in Fig. 12.

From Figs. 11 and 12, one can conclude clearly that the direction of the current indicates that there is damage in the horizontal element. Thus the mathematical formulation proposed in this paper is able to clearly assess the overall integrity of the grounding grid.

4. Conclusions

The paper reviews exhaustively the current state of art and publications around assessing integrity of grounding. It thereafter proposes and presents the mathematical modeling for estimating and/or detecting the integrity of the grounding devices on the surface of the earth without any diggings or forced tripping. A numerical example is also presented to illustrate the simplicity and effectiveness of the proposed model.

References


HIL Simulation of a Mixed Islanded Power Network with External DSP Regulator

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Abstract: The present paper deals with the development of a modular, flexible and structured block to block approach for the study of regulators by implementing the different blocks on a DSP (digital signal processor). The proposed low-cost approach has been applied and validated by the implementation of an industrial regulator in a real time hardware-in-the-loop simulation of a mixed islanded power network including precise models of the hydraulic system. The studied network is constituted of three different types of electrical power generation systems and a consumer.

Key words: DSP (digital signal processors), RTS (real time systems), power system simulation, PWM (pulse width modulation), regulators, HIL (hardware-in-the-loop simulation), DLL (dynamic link library).

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>Coeff1</td>
<td>Coefficient 1</td>
</tr>
<tr>
<td>Coeff2</td>
<td>Coefficient 2</td>
</tr>
<tr>
<td>( C_p ) wind</td>
<td>Turbine power coefficient [-]</td>
</tr>
<tr>
<td>( C_{wind} ) wind</td>
<td>Velocity [m/s]</td>
</tr>
<tr>
<td>Ext</td>
<td>External</td>
</tr>
<tr>
<td>GEN</td>
<td>Generator</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Tip speed ratio [-]</td>
</tr>
<tr>
<td>( N )</td>
<td>Generator speed [rpm]</td>
</tr>
<tr>
<td>( P )</td>
<td>Power [W]</td>
</tr>
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<td>( TC )</td>
<td>Computation time [s]</td>
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<td>Read/write time [s]</td>
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<tr>
<td>Theta</td>
<td>Blade pitch angle [deg]</td>
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<tr>
<td>( Ts )</td>
<td>Simulation data exchange period [s]</td>
</tr>
<tr>
<td>( T's )</td>
<td>External device sampling period [s]</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>Step time [s]</td>
</tr>
<tr>
<td>( uc )</td>
<td>Set point voltage [V]</td>
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<tr>
<td>( um )</td>
<td>Measured voltage [V]</td>
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<tr>
<td>( U )</td>
<td>Voltage [V]</td>
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</table>

Indexes

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>hydro</td>
<td>Hydraulic</td>
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<tr>
<td>therm</td>
<td>Thermal</td>
</tr>
<tr>
<td>wind</td>
<td>Wind</td>
</tr>
</tbody>
</table>

1. Introduction

During the last few years, many studies have been dedicated to the development of real-time digital simulators employed in the simulation of power systems and converters. The state-of-the-art in interfacing issues related to such real-time digital simulators as well as HIL (hardware-in-the-loop) interfacing for controller hardware and power apparatus hardware are presented in details in Ref. [1]. HIL simulations are already used in different applications to test critical functionalities. An overview of existing work in different domains is given in Refs. [2-7] (electric ship [2, 3], motor drive systems [4], power electronic converters [5], distributed generation systems [6], test platform for hybrid electric power systems [7]). Real-time HIL testing approaches for power systems modeling and
simulations are presented in Refs. [8-10]. These HIL systems are often based on expensive hardware or operate only for a given hardware device.

A HIL extension, called SIMSEN-RT, of an existing simulation software SIMSEN [11] running on a standard PC has been developed in the laboratory [12]. This HIL system can be used for fine-tuning regulator parameters and for testing of regulators in different operating conditions (islanded network, emergency shutdown...). The main aim of this study is to develop and validate a modular, flexible and structured block to block approach for the study of different regulators by implementing the different blocks on a DSP (digital signal processor). This low-cost approach has been applied and validated by the implementation of an industrial voltage regulator in a DSP (Fig. 1).

An event such as the decrease of wind in a mixed islanded power network described in Ref. [13] has been used as a test case for this development. The interest of this case is to be realistic and to be at the limit of the computing power of a standard personal computer, in real time applications.

The studied power network represented in Fig. 2, is constituted of three different types of electrical power generation and a consumer:

- Hydraulic (300 MW);
- Thermal (1300 MW);
- Wind (200 MW).

This paper is organized as follows: The communication between the simulation software and the external hardware regulator is described in Section 2. Section 3 describes the block structure of the regulators as well as their implementation in DLL (dynamic link library). The studied system is presented in Section 4. The comparison between DSP/DLL and software regulators is given in Section 5. Finally, conclusions are given in Section 6.

2. Description of the HIL Structure

2.1 Signal Path

At each simulation time step a state value is sent by the software (SIMSEN-RT) to the DSP regulator through interface cards needed for AD (analog/digital) translation as well as voltage adaptation. Fig. 3 shows the path of the signal representing a simulation value. The simulation software first sends digital signals to the acquisition card which converts it to an analog voltage through a DAC (digital/analog converter). This analog signal is then sent to an external regulator (a DSP regulator in this case). The DSP regulator performs its computation and outputs a PWM signal (because the used DSP has no analog output). This signal is then converted to an analog voltage through a...
RC filter and sent back to the acquisition card that converts it to a digital simulation value with an AD converter.

2.2 Signal Adaptation

In each step of the signal path there is a need to adapt the signal to the range of values accepted by the different elements. As an example, Fig. 4 shows how to convert a simulation value to an analog voltage. The external voltage range is between zero and 3 V due to the AD converter of the DSP. The RMS (root mean square) line voltage range is between 0 and the double of the nominal voltage (17,500 V in this case).

2.3 HIL Exchange Timing

Fig. 5 represents the communication scheme used to realize a HIL simulation. The simulation and the tested hardware are independent and each one has its own sampling period. The simulation sets its output to a new value every $T_s$ seconds and reads its inputs at the same time. The tested hardware regulator sets its output every $T_s$’s seconds and reads its inputs at the same time.

To perform a HIL simulation, it is required that the simulation runs in real time. This means that each integration step ($\Delta T$) of a simulation has to be computed faster than the real time to let time spared for the communication between the simulation and the tested hardware. This is resumed in the following requirement:

$$T_E + T_C \leq T_s \cdot T_E$$ is the time necessary for reading and writing the data. The computation time ($T_C$) is influenced by the topology of the simulated installation. The computation time of a basic installation is lower than for a complex installation. The integration step has a big influence on the computation time. To get a short computation time, the integration step has to be large. The integration step is constrained by the smallest time constant of the physical phenomena of the simulated installation. A typical integration step is 1 ms for an electrical installation with electrical machines and without power electronics. The simulation software used in this work is able to check whether the real time condition is respected or not. A tolerance value can be chosen so to allow for small discrepancy between real time and simulation time. If the difference is too large, the simulation stops.

3. Regulator Code Structure

In this work the code structure has been designed such as to allow the composition of the regulator in a modular way and an easy transposition in the different implementations (inside the simulation program, in an external program, in a DSP).
3.1 Block Structure of Regulators

In the simulation software a regulation scheme can be built using basic blocks; a C code structure is created to make easy to transpose such a block diagram to a C code. When the block diagram of an industrial regulator is known, it is easy to implement it in the DSP. Each module of a block diagram has its C code equivalent.

Fig. 6 shows some basic blocks used to create a regulator. The code is designed in an object oriented manner with a set of fundamental elements and their copy for each block of a regulator scheme.

The program has two distinct parts, one defining basic block structures and one using these structures to create blocks. These blocks have their parameters filled and are then connected to the other blocks of the regulator scheme. Here is an example of the C code line corresponding to the use of the basic “reg” block.

3.2 Implementation of Regulators in DLL

A DLL is a kind of program that is meant to stay in memory and be called by other programs. In this work it has been taken advantage of so as to be able to develop and test the code of regulator programs on the computer before implementing it on the DSP. The block structure of the regulator code has been put to full use to ease its transfer between the DLL and the DSP.

`f_reg (reg1, setpoint, value);`

The output of the regulator reg1 is then accessible by reading its output parameter: reg1.out.

Fig. 7 shows how to translate a DSP C code for a DLL. The DSP has to be initialized with a specified C code.

This part of C code is no more needed for the DLL. It means that this part of the code has to be removed to generate a DLL file.

The DSP C code used to read an analog voltage through an AD converter has to be modified for the DLL C code as there is no AD converter used by the DLL. The digital simulation value is directly sent to the DLL without any conversion.

Most importantly, the part of the C code used for the regulation can be simply copied from the DSP C code to the DLL C code.

The output DSP C code has to be adapted for the DLL because there is no more PWM signal. The digital output value of the DLL is directly sent to the simulation software without any conversion.

After these modifications, the new C code is compiled by a DLL compiler to generate a DLL file that can be used by the simulation software.

3.3 Implemented Voltage Regulator

In this study an industrial voltage regulator is implemented in C code. The full structure comprises around 150 basic blocks.

4. Simulated Installation

This section describes the mixed islanded power network simulated in this study such as illustrated in Fig. 8. The thermal power plant produces a constant
HIL Simulation of a Mixed Islanded Power Network with External DSP Regulator

electrical power, the wind turbine installation produces variable electrical power depending on wind speed; the hydraulic installation is used to compensate variations in wind and load consumption. The lines voltages of the three generators are set by three voltage regulators. The wind turbine speed is set by a speed regulator that changes the pitch angle of the blades. If the wind is too slow or too fast, the wind turbine stops. The speed of the hydraulic turbine is set by a speed regulator that changes the guide vane opening of the turbine. The speed of the thermal installation is not set by a specified regulator. A constant torque is applied on the rotor of the thermal power plant and the speed is determined by the two previous speed regulators.

The voltage regulator of the hydro-electrical installation is replaced by an external hardware regulator (DSP regulator). The “VReg” block represents the software regulator, the “RTCom” block represents the link to the external DSP regulator and the “Extern” block represents the link to the DLL regulator. These three regulators are represented in Fig. 8. Only one of them is used during a simulation, the two others must be disabled. They are just three equivalent implementations of the same regulator.

5. Tests and Results

The behavior of the mixed islanded power network is tested with wind speed changes. Fig. 9 shows the speed evolution of the wind.

The wind turbine increases its power generation during the wind speed increase. The thermal power and the load power consumption stays at the same value so the variation of wind power is compensated by the hydro-electrical installation.

5.1 Comparison between DSP and Software Regulators

Figs. 10-13 show the comparison of the active power evolution using a software regulator or a DSP regulator. The power evolution is the same in both cases (curves are superimposed).

Table 1 shows the power balance evolution. The wind speed increases between 100 sec and 170 sec with some fluctuations and the power generated by the wind turbine increases too. The increase of wind power (Fig. 12) is compensated by a decrease of hydraulic power generation (Fig. 10). The load power consumption is given in Fig. 13.

Fig. 8  Mixed islanded power network.
Table 1  Power balance.

<table>
<thead>
<tr>
<th>Element</th>
<th>Active power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 100 sec</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>-187</td>
</tr>
<tr>
<td>Thermal</td>
<td>-1,018</td>
</tr>
<tr>
<td>Wind</td>
<td>-30</td>
</tr>
<tr>
<td>Load</td>
<td>1,232</td>
</tr>
<tr>
<td>Losses (lines &amp; transformers)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1 shows that the power consumed by the thermal power (Fig. 11) and the load (Fig. 13) is the same before and after the wind speed increases. The no-load excitation voltage corresponding to the nominal line voltage is equal to 209 V.

Fig. 14 shows a comparison between the excitation voltage given by the software regulator and by the DSP regulator. The two curves follow the same evolution but the DSP output contains noise that is mainly added by the computations performed in the DSP. The nominal RMS line voltage of the synchronous machine of the hydro-electrical installation is 17,500 V.

Fig. 15 represents the evolution of the RMS voltage of the synchronous machine used in the hydraulic installation. The RMS voltage follows the same evolution when it is set by the software regulator or by the DSP regulator. A little offset of 1 V is nevertheless existing due to the AD and DA (digital/analog) conversions.

5.2 Comparison between DLL and Software Regulators

As mentioned before, another part of this project was to generate DLL programs with a slightly modified
version of the DSP code. Figs. 16 and 17 show a comparison between the software regulator and the DLL regulator. The excitation voltage and the line voltage represented in these figures have the same evolution with the software regulator and the DLL regulator, which validates the proposed approach.

For this mixed islanded power network, the frequency remains in an acceptable range of variation (49.85 Hz; 50.55 Hz) for the studied case in both implementations (DLL, DSP).

6. Conclusions

The main aim of this study was to perform a HIL simulation with a voltage regulator implemented in a DSP. The results obtained are convincing. This project has illustrated the usefulness of a modular structure to implement regulators and translated them in different environments. A block diagram of a regulator can be easily translated in C code implemented in DLL files, then tested and in the end transferred to a DSP. Finally this project shows that it is possible to perform HIL simulations of relatively complex systems on a standard computer.

Acknowledgments

The authors would like to thank Dr. Christophe Nicolet for his contribution to the simplification of the hydraulic part of the simulated system to decrease the computation time without any loss of accuracy regarding the physical behavior.

References


Enhancement of Real Power Transfer Capability of Transmission Lines

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Abstract: As power system interconnections become more prevalent, there has been an increase in use of thyristor controlled shunt connected compensation devices for dynamic power compensation and enhancement of real power transmission capacity. In this paper, an enhancement technique of real power transfer capacity of transmission lines is presented. A SVC (static var compensator) is designed and applied to a simple power system for this purpose. Increase in power flow and improvement in bus voltage profile are observed after using the SVC. Stability analysis of the system after experiencing fault as well as consequent fault clearance by time domain analysis has also been performed and satisfactory results are obtained.

Key words: SVC (static var compensator), power transfer capability, minimum susceptance, load flow analysis, fault analysis, stability analysis.

1. Introduction

From the evolution of power system, it is mandatory to transfer power from generation site to the distribution end. There have always been challenges associated with moving large amount of power over a transmission system. With load centers distributed at long distance, there is the need to enhance power transfer capability with the increase in load. If the fuel unavailability constraint is imposed then the necessity of power transfer capability enhancement of transmission lines is acute.

Traditional methods of increasing power transfer capability of transmission lines have been used so far. These include the physical alternation of transmission lines whereas modern practice is to install FACTs (flexible AC transmission system) devices. Due to the problems associated with constructing new overhead lines, it is important to maximize the utilization of the existing transmission systems in a competitive market environment. Growth of different commercial schemes for the electric power industry, particularly deregulation of market, has made this requirement even stronger [1]. A transmission line can be loaded up to its thermal limit but practically if the receiving zones do not have compensating reactive elements, the voltage can drop below the limit fixed by quality criteria [2]. In such occasion, it is advisable to limit the transmission of these lines to prevent excessively low voltages in the receiving end as well as to prevent a possible voltage collapse [3].

The transfer capability of the transmission networks can be limited by various system constraints such as thermal, voltage and stability limits [4]. Over the last several years, the electric power industry has become progressively more concerned with voltage stability and collapse. This concern is based on several voltage collapse phenomena as reported in Ref. [5]. Voltage
collapse can be associated with loss of synchronism for generators if reactive power control is lost at the source [6]. The collapse points are also known as maximum loading point and this voltage collapse can be restated as an optimization problem where the objective is to maximize certain system parameters typically associated with the load levels [7]. Before reaching voltage collapse system may experience oscillatory instability. These voltage collapse and oscillatory instability of power system can be explained with SNB (saddle node bifurcation) and HB (Hopf bifurcation), respectively [8].

Power transmission capacity can be enhanced directly by using series and shunt compensation [9]. The objective of FACTS (flexible AC transmission system) technology is to bring a system under control and to transmit power as premeditated by control centre; it also improves the system stability [10]. The use of FACTS controlled series compensation and shunt compensation, especially TCSC (thyristor controlled series capacitor) and SVC (static var compensator), for stability enhancement has been reported in Ref. [11]. Fast control of active power flow through a transmission line is possible by means of TCSC and SVC [12]. Inter-area stability is improved using TCSC and SVC when the system is subjected to small and large disturbances [13].

In this paper a simple power system with known total load is considered. The range of system susceptance is determined which is used to design a SVC. Designed SVC is then used as shunt compensator in the simple power system. It is observed that real power flow increases in the network with the designed SVC. Bus voltage profiles of the network are also improved. The stability of the system with the designed SVC is also analyzed and satisfactory results are obtained.

2. Basic Theory of Compensation

The real power flow through the line connecting two buses as shown in Fig. 1 is given by:

\[ P = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2) \]  

(1)

\[ \text{Fig. 1 Single line diagram of a two bus power system.} \]

Where,

\[ P = \text{Amount of power flow (W)}; \]

\[ V_1, V_2 = \text{Voltages of bus 1 and bus 2, respectively (V)}; \]

\[ \delta_1, \delta_2 = \text{Voltage angles of bus 1 and 2, respectively (rad)}; \]

\[ X = \text{Reactance of transmission line (}\Omega\text{)} \]

For series compensation line reactance is needed to be modified and for shunt compensation voltage of compensator bus has to be modified.

TSC (thyristor switched capacitor), TCR (thyristor controlled reactor), SVC (static var compensator), STATCOM (static synchronous compensator) can be used as a shunt compensator and FSC (fixed series capacitor), TPSC (thyristor protected series capacitor), TCSC (thyristor controlled series capacitor), SSSC (static synchronous series compensator), UPFC (unified power flow controller), IPFC (interline power flow controller), IPC (interphase power controller) can be used as a series compensator. In this paper SVC is used as a shunt compensator to enhance real power transfer capability of a long transmission line.

3. SVC Characteristics and Operating Range

3.1 Voltage-Current Characteristics of SVC

A typical terminal voltage versus current characteristic of a SVC with specific slope is shown in Fig. 2.

Slope of the V-I curve shown in Fig. 2 is given by:

\[ \text{slope} = \frac{\Delta V_{\text{c max}}}{I_{\text{c max}}} = \frac{\Delta V_{\text{L max}}}{I_{\text{L max}}} \]  

(2)

The voltage at which SVC neither absorbs nor generates reactive power is the reference voltage (V_{ref}) shown in Fig. 2. In practice this voltage can be adjusted within the typical range of ±10%. The slope of the characteristics reflects a change in voltage with compensator current and, therefore can be considered
as slope reactance, resulting the SVC response to the voltage variation. Then terminal voltage is given by:

\[ V_T = V_{ref} + X_{SL} I_{SVC} \]  

Where,
\( V_T \) = terminal voltage (V);
\( X_{SL} \) = slope reactance (\( \Omega \));
\( I_{SVC} \) = current from SVC node (A).

3.2 SVC Operating within Control Range

The control range of a SVC is defined as:

\[ I_{min} < I_{SVC} < I_{max} \text{ and } V_{min} < V < V_{max} \]  

In this range, the SVC is represented as PV-node at an auxiliary bus with \( P = 0 \) and \( V = V_{ref} \). Reactance \( X_{SL} \) equivalent to the slope of the V-I characteristics is added between the auxiliary node and node of coupling to the system as shown in Fig. 3. The node at the point of common coupling is a PQ node with \( P = 0 \) and \( Q = 0 \).

3.3 SVC Operating Outside of Control Range

When a SVC is operating outside the control range, it is represented as shunt element with susceptance \( jB \) as shown in Fig. 4.

Depending upon the operating point, the \( B \) is defining as:

\[ B = \frac{1}{X_C} \text{ if } V < V_{min} \]  

\[ B = \frac{1}{X_L} \text{ if } V > V_{min} \]  

4. Simulation and Results

PSAT tool box of MATLAB is used to simulate the simple power system. The simple power system consists of four buses, two synchronous generators, one PV generator, one slack generator, two transformers, two static loads and a transmission line between bus 2 and 3. SVC is connected in bus 3. Figs. 5 and 6 represent the one line diagram of simple power system with and without SVC, respectively.

An iterative strategy is followed during the SVC design. At first the SVC is designed with assumed value that comes from study of the simple power system. Then it is checked through simulation whether design criteria is fulfilled or not. If not, then redesign and simulation and checking are carried out again. The following of this iterative approach appropriate design of SVC is achieved. The simulation results of the simple power system are presented in what follows.
4.1 Load Flow Analysis

Load flow analysis is performed on the simple power system both by excluding SVC and then including SVC.

Tables 1 and 2 present the bus voltage and real power flow profile of the simple power system, respectively. It is observed that there is a huge change on bus voltages, and nominal change in line flows after connecting the SVC to the simple power system.

4.2 Stability Analysis

Stability analysis of the simple power system, with the designed SVC connected to the system, is performed to ensure that the designed SVC will not move the system to instability during faults. A three phase fault on bus 3 at 1 sec is simulated. The fault is cleared after 0.1 sec. It has been observed that the voltage of bus 3 drops to 0 during fault but pull back after fault is cleared as shown in Fig. 7.

Torque angles of the synchronous generators 1 and 2 are also plotted as shown in Fig. 8. Fig. 8 shows that during fault and its consequent clearing period, torque angles change against time. But this change happens to both of the torque angles. The relative torque angle does not oscillate to out of bounds and the system remains stable after the fault clearing.

5. Conclusions

An enhancement technique of real power transfer capability of transmission lines is represented in this paper. The proposed technique is applied to a simple power system. It is observed that real power flow increases in the network. Bus voltages of the network remain stable.
also improve. Stability analysis of the system after experiencing fault as well as consequent fault clearance by time domain analysis has also been performed and satisfactory results are obtained.

References
FPGA-Based Real-Time Simulation of Modular Multilevel Converter HVDC Systems

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Abstract: AC-HVDC-AC energy conversion systems using MMC (modular multilevel converters) are becoming popular to integrate distributed energy systems to the main grid. Such multilevel converters pose a serious problems for HIL (hardware in the loop) simulators required for control, protection design and testing due to the large number of cells that must be simulated individually using very small time steps. This paper demonstrates the advantages of using a very small time step to simulate a MMC topology. The MMC is implemented on FPGA (fiel-programmable gate array) to simulate fast transient with a time step of 250 ns. The AC network and HVDC bus is simulated on the PC, with a slower time step of 10 µs to 20 µs. The simulator architecture and the components simulated on the FPGA and on the PC will be discussed, as well as the method allowing the interconnection of this slow and fast system.

Key words: FPGA simulation, modular multi-level voltage source converters (MMC), MMC converter real-time simulation, HIL (hardware-in-the-loop).

1. Introduction

The global power system infrastructure is rapidly changing, from concentrated generation centers and EHV (extra high voltage) transmission grids towards increasingly distributed generation/distribution systems. This transformation mandates expanded use of power electronic devices: e.g. HVDC, FACTS and interfacing devices for DC and variable-frequency power sources (photovoltaic, wind generation). Power electronic converters have evolved rapidly, both in terms of available electronic switching devices and converter topologies. The evolution from thyristor-based converters to VSCs (voltage source converters) to MMCs (modular multilevel converters) [1, 2] has placed increasingly onerous demands on simulation technology, in particular real-time digital simulators. The challenge related to the simulation of VSCs, for example, is the very small time-step required to deal with relatively high carrier frequencies, and models have been developed that achieve accurate results using time-steps in the range of 20 to 50 microseconds [3, 4], typical of what may be achieved using standard INTEL/AMD multi-core processors. MMCs add to this challenge because of the large number of I/Os required monitoring the voltages of a large number of cells. In order to study higher frequency electromagnetic transients, the time step should be reduced even more [5].

Demonstration of real-time simulation and HIL (hardware in the loop) simulation for this topology was done in Refs. [1, 3]. At that time, the conclusion was that using a fifth order fixed step solver, with a time step of 20 µs, the model gives good enough results, whether to test the controller or to study system behaviour under certain tests; such as transformer saturation, unbalanced line, ground fault. Simulation was done using a regular Intel PC running Linux Redhat. OP5142 FFGA cards from Opal-RT were used in HIL to manage the analog and digital input/output. To do so, an FPGA card manages
communication between the CPU from the PC and hardware used to acquired physical signals. Since the model was simulated at 20 µs, which is relatively slow, an interpolation on the firing PWM signal was made to increase its resolution. Thought results are satisfying, even better and more accurate results could be obtained by lowering the time step used of the simulation. For instance, the digital-to-analog converter from the OP5142 has a refresh rate of 1.0 µs; using a time step this low would allow studying high speed transient phenomena, up to 50 to 100 kHz with a sampling frequency of 1 MHz (1 µs). Such a low time step value would eliminate the need for interpolation and facilitate the simulation of transients expected across each cell during natural rectification modes. Also, since the FPGA are already required for managing the IOs, they might be used to simulate part of the model as well.

In the system presented in this paper, a high-performance multirate/multiplatform simulation is proposed. The fast simulation will run on three different FPGAs at 250 ns, one FPGA per converter arm, and the slow part, AC and DC network, will run on CPU with a time step between 20 µs.

2. Modelling

2.1 Implementation of the MMC

A MMC is made of many identical cells first connected in series, forming a limb, then in parallel. Fig. 1 shows one cell and Fig. 2 shows the AC/DC converter [6, 7]. If the model is looked at with the standard approach, the size of the matrix to solve increases exponentially with the number of power switches. But by looking at the configuration of the model, certain assumptions can be made to simplify it. The first would be that according to the switching pattern, without considering the cell’s capacitor being short-circuit, one cell can be ON, when capacitor is applied to the output, OFF, when the output is simply short-circuit, or in high impedance mode, when no pulses are sent to the power switches and only input voltage and the capacitor voltage determine the current. Once the current is known and whether or not it runs through the capacitor, the voltage value of each capacitor is computed as well as the output voltage of the limb. Another assumption made is that the current is the same for all cells in a limb.

As illustrated in Fig. 2, in ON and OFF mode, the current is only a function of the total circuit inductance (AC side, the DC side and the limb inductance), the cell output voltages and the source voltage. In the HighZ mode (both IGBT are OFF-mode), the output voltage of the cell is set by the voltage of its RC snubber, note that this snubber is only presented in the HighZ mode. Fig. 3 shows the eight possible modes.

In Ref. [3], a model separated on many CPU allows parallel computing that is required to achieve real-time simulation with a small time step of 20
Fig. 3 Considered behaviour of the cell.

microseconds on standard processors. In order to achieve a time step below one microsecond, one needs an FPGA board capable of handling a large number of I/O signals and enough computing resources to simulate each cell for all possible state. One digital-to-analog converter and two digital inputs are required per cell. It has therefore been decided to implement one MMC arm per FPGA. This way, up to 64 MMC cells could be simulated using all I/O available on the OP5142 FPGA board. The OP5142 FPGA is able to manage 64 analog output converters and 128 digital inputs, which enable the simulation of 64 cells. The number of FPGA boards required is therefore determined by the maximum number of I/O to manage and the capability of each FPGA board in terms of number of I/O channels controllable by one FPGA board.

The next challenge is to optimize the implementation of the FPGA model of each cell to make sure that all the cells could be simulated within the same FPGA chips controlling all I/Os.

One more thing to be considered is the point of connection between the different subsystems simulated on the FPGAs and on standard processors. This is even more crucial considering that both subsystems have different time step. It is common to use inductance or capacitors to separate subsystem in multi-rate real-time simulation if the variation of the inductor current and capacitor voltage is slow as compared to the time step of the simulation. But in this case the inductance has an important impact on the current computation in HighZ mode and the inductor currents and voltages have high-frequency components determined by the cell snubber. Simulation has proved that it is better to simulate this inductance on the FPGA.

This is demonstrated with a simple model, in one case the inductance is simulated with the voltage source at a time step of 20 µs and the MMC with a time step of 1 µs, Model1 in Fig. 4. Then the same model is simulated, but this time the inductance is simulated at 1 µs also, Model2 in Fig. 5.

Fig. 6-8 show the results, to understand them, one must looks at how they are simulated. For model1, the MMC cells receive the current which is determined by the output voltage of the cells, the voltage of the source and the inductance. In this case, the values of the snubber are chosen to reduce the current close to 0, required to simulate the high impedance case when both IGBT are in OFF state. The key here is to choose a snubber value that will have a resonance frequency as high as possible to simulate actual systems but low enough to achieve numerical stability with the selected time step of 20 µs.

Of course, real snubber circuits will have rise time smaller than 20 µs, but one must accept this compromise to achieve real-time simulation required to test controllers in HIL real-time mode. Snubber circuits and fast transients across IGBT or thyristor are therefore analysed with specialized off-line simulation software such as SABER or SPICE.

In Model2, the cells receive the voltage and return the current. The current is computed based on the input voltage of the cell, voltage that would apply the
capacitor and the inductance value. In high impedance mode, snubber time constants can then be computed at
the time step of the FPGA models, which is 20 times faster than the preceding case. This allows smaller snubber values, smaller losses and snubber values closer to the one used on real systems.

Surprisingly, one can also observe in Fig. 6-8 that both models differ by a few percentage points. This increase of accuracy for Model2 is mainly due to a more accurate simulation (solution of 1 µs instead of 20 µs) of each ON-OFF IGBT transition, which affects the charge of cell capacitors.

2.2 FPGA Modelling

When using FPGA, different approaches can be chosen because of its large versatility. This technology is well known for parallel processing enabling the simultaneous computing of many different values. The first implementation demonstrated that each cell could be simulated in less than 100 ns on the SPARTAN 3 FPGA using a 100 MHz clock. However, the number of computational resources available on the FPGA (i.e. number of adder, multipliers...) would not allow simulating up to 64 cells in one FPGA. As mentioned before, one OP5142 FPGA board can handle all the I/O required for 64 cells, but the challenge is now to simulate the 64 cells directly on the FPGA chip. Therefore, a sequential method is used that involves sharing the same FPGA resources for a group of cells. And again because of the I/O limitation, in the number available on one card, each FPGA will only compute the solution of one arm. Fig. 9 shows a block schematic of the architecture that is present on each FPGA.

In accordance with the available I/O, two limbs of 30 cells with their limbs inductance are modelled. As input, there is the AC voltage, coming from the CPU model, and the pulses sent to each cell, this signals could either be coming from an external controller or a controller also simulated on a CPU of the simulator. These gates signals are time multiplexed so the same resource is used to compute all the different capacitors voltage. Then capacitor’s voltages are demultiplexed before being sent to the CPU. The sum of the cell voltage is made and this voltage and the one coming from the source on the CPU are used to determine current in the inductance. As for output, the FPGA returns the current circulating in the limb and the capacitor voltage of each cell; these values need to be sent to the controller to allow regulation of each of them. The capacitor cells voltages are also sent on digital-to-analog converters to enable HIL simulation to use an external controller.

3. Simulation

3.1 Results

The preliminary results obtained by the simplified equivalent circuit were very good; therefore, results just as good are expected for the full model simulated with eMEGAsim [5]. The model used in this simulation is an AC/DC converter, like the one in Fig. 2 with 30 cells per limb for a total of 180 cells. No pulses are sent at the beginning, after 0.3 s pulses are generated by the MMC controller to control the power flow. 180 capacitors voltages are being monitored and individually controlled by the MMC controller to ensure that all capacitor voltages are charged to the same value. Unbalance in cell capacitor voltage will create harmonics and circulating currents. One must note here that the objective of this paper is not to demonstrate the effectiveness of a specific controller implementation but to demonstrate the accuracy of the plan simulation using the same controller.

Considering the large number of capacitor voltage monitored, the next figures only show the minimum and the maximum value of all 180 that is shown with
the value of one of the capacitor. In Fig. 10 these capacitors voltage are shown for the model simulated at 20 µs and the one at 250 ns; both results could be superimposed. The same conclusion can be drawn from the current in Fig. 11.

The main difference is during the natural rectifying mode, when no pulses are sent. During this time, RC snubbers are used; since the value of these snubbers is determined by the time step, reducing the time step reduces the value of snubber time constant and also reduces the error introduced by snubber with large time constant. In Fig. 12, the current for the 20 µs model is much larger than the current observed with the small snubber time constant simulated at 250 ns. The arm current is about 0.02% with a simulation at 20 µs and near to zero with 250 ns. This implies that users may decide to simulate the effect of actual snubber when a simulation time step of 250 ns is used.

3.2 Total Delays for HIL Simulation and Tests

One of the critical parameters when testing actual controller and protection system performance of MMC systems is the total delay measure between IGBT firing signal transition and voltage and current outputs sent to the MMC controller. Using a time step of 20 µs, which is rather small compared to a traditional simulator achieving only 50 µs time step, will lead to a total delay of about 40 µs. A total delay of 50 to 60 µs is considered as the upper range of acceptable delay by several manufacturers. As mentioned before, this simulation with a time step of 20 µs, which yields a delay to 40µs, is good enough to test control systems. But using FPGA based simulation with a time step of 250 ns and a
refresh of all voltage and current at each microsecond decreases the total delay to below 1 µs, which eliminates problems that could be introduced by the use of larger time step.

4. Conclusions

In this paper, results for a 250 ns time step MMC model has been presented. Such a time step is achieved using both parallel processing and time multiplexing on an FPGA.

The key advantages of FPGA-based models with very small time steps are:

(1) Better accuracy for HIL simulation and tests since the resolution of firing pulse accuracy is 250 ns instead of 20 µs;

(2) The total delay measured between the firing pulse transitions issued by the MMC controller and the voltage and current feedback of the simulator is reduced from 40 µs to less than 1 µs, which increases the overall accuracy considering typical MMC controller time steps of 50 µs to 100 µs;

(3) Better simulation of the natural rectification mode and bloc mode (HiZ);

(4) Possibility to simulate the effect of practical snubber with a time constant of 1 to 5 µs, which is impossible with a time step of 20 µs.

Furthermore, since modern simulators, such as eMEGAsim, are already equipped with FPGA boards to manage the large amount of I/O channels required by MMC, the same FPGA boards can also be used to simulate individual cells at 250 ns. Consequently, FPGA processing technology enables more accurate simulation with the same hardware otherwise needed for I/O management.

References


Integration of Power MOSFETs for Synchronous Buck Converters

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Abstract: Efficiency and power loss in the microelectronic devices is a major issue in power electronics applications. The engineers are challenged every year to increase power density and at the same time reduce the amount of power dissipated in the applications to keep the maximum temperatures under specifications. This situation drives a constant demand for better efficiencies in smaller packages. Traditional approaches to improve efficiency in DC/DC synchronous buck converters include reducing conduction losses in the MOSFETs (metal oxide semiconductor field effect transistors) through lower RDS (ON) (resistance drain to source in the ON state) devices and lowering switching losses through low-frequency operation. However, the incremental improvements in RDS (ON) are at a point of diminishing returns and low RDS (ON) devices have large parasitic capacitances that do not facilitate the high-frequency operation required to improve power density. The drive for higher efficiency and increased power in smaller packages is being addressed by advancements in both silicon and packaging technologies. The NexFET power block combines these two technologies to achieve higher levels of performance, and in half the space versus discrete MOSFETs. This article explains these new technologies and highlights their performance advantage.

Key words: MOSFET, synchronous buck converters, integration, DC/DC converters.

1. Introduction

One of the main obstacles for integration in power electronics is the fact that by increasing the power density the junction temperatures of the active devices reaches values that exceed the maximum operating temperature of the devices, affecting the performance and the reliability of the device [1, 2]. On the other hand, integration brings huge benefits like the reduction of the device's size and reduction or virtual elimination of the parasitic of the device [3-5]. This is particularly important in the synchronous buck converters space where there is a constant demand to reduce the space occupied by DC/DC converters in the application boards (especially in computing applications) [6] and the requirements to switch the converters at higher frequencies to reduce the size of the output inductors and capacitors.

In order to solve the thermal problem of integration in power semiconductors two main issues need to be addressed: (1) reduction of the heat dissipated by the active device [7] and (2) improvement of the design and materials used in the package [8] in order to conduct the heat to the external environment as efficiently as possible (lower the thermal resistances).

Several attempts have been made to integrate the low and high side MOSFETs (metal oxide semiconductor field effect transistors) in a package to create a half bridge buck converter but most of them suffer from poor size reduction (in comparison with non integrated solution) and high parasitic values. Most of the problems come from the fact that these solutions have 2D topologies where the transistors are mounted side by side in the package and connected with wire bonds, which have high resistive and inductive parasitic values.
This work presents two innovative technologies in the silicon and package fronts [9, 10], that successfully integrate the low and high side transistors of a Buck converter in a small 5 × 6 mm QFN package with very small footprint and extremely low parasitic values. The next sections will describe the technology and report the thermal and electrical results obtained.

2. Methods

The NexFET power MOSFET (metal oxide semiconductor field effect transistors) [9, 10] takes a step toward creating an ideal switch by reducing the parasitic of the device to dramatically improve its performance. In order to maximize the performance of a typical synchronous buck converter, the parasitic inductances and resistances in the power circuit formed by the two MOSFETs in the power stage have to be minimized. This is accomplished through an innovative packaging approach in the NexFET power block where the MOSFETs are actually stacked on a grounded lead frame with two copper clips (see Fig. 1). The resulting power block package has characteristics that make it unique in the power electronics industry. The package accomplishes four primary functions: small footprint, very low parasitic, excellent electrical and thermal performance, and solid reliability.

To achieve a small footprint and the lowest parasitic possible, a stacking topology is used in the NexFET power block package design. A patented source down silicon technology allows the high-side die to be stacked on top of the low-side transistor to implement a synchronous buck converter topology in a very simple and cost-effective manner.

The low-side die is attached to the main pad of the lead frame, providing the ground connection of the MOSFET pair (see Fig. 2). The low-side drain is connected to the outside through a thick copper clip that constitutes the device’s switching node (VSW pin). The high-side MOSFET die (which also uses a source down technology) is soldered on top of a thick copper clip. Finally, another thick copper clip connects the high-side drain (VIN, input voltage of the buck converter) to the device’s external pins. The gate connections are made using Au wire bonds TG (gate of high side die) and BG (gate of low side die), and TGR (top gate return to the IC driver). TGR is the switching voltage node sense signal that allows the IC driver to properly bias the high-side MOSFET gate.

Fig. 3 shows pictures of two evaluation boards that demonstrate the reduction in board space achieved when using the integrated power block solution. The equivalent discrete solution takes more than two times the board space that the integrated device uses. This is extremely important in most of the applications where several of these synchronous buck converters are connected in parallel to supply the desired voltage and currents to the system.

The saving of real state in the board is especially critical in the computing space where each new generation of microprocessors requires increasing current values with no more space available in the motherboards.

3. Results

This package has an excellent electrical performance, which is critical in achieving high efficiency. Contributions to high efficiency can be summarized as:
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![Discrete Solution](image1)

![Power Block Solution](image2)

Fig. 3  Upper picture: evaluation board using two separate MOSFETs to build half bridge synchronous buck converter. Lower picture: power block, the integrated solution that replaces the function of the separate devices shown above.

1. Using thick copper clips for high-current connections (VIN and VSW), which substantially reduce the device’s RDS (ON) in comparison with wire-bonded solutions. This also reduces conduction losses.

2. Thin silicon dies substantially reduce conduction losses by dropping the contribution of the device’s substrate to RDS (ON).

3. The stacked configuration virtually eliminates the parasitic inductance and resistance between high- and low-side MOSFETs; and using thick copper clips substantially reduce parasitic associated with the VIN and VSW connections when compared to wire-bonded solutions. For a more detailed view of the package parasitic, you can refer to Fig. 4.

![Fig. 4  Schematic of the power block parasitic.](image3)

The main reasons behind these low-thermal resistance values are the reduced silicon thickness and thick copper clips that help to conduct heat generated to the package exterior. One might think that the stacked topology could increase the junction temperatures, especially on the high-side transistor. However, thermal measurements and simulations show that in normal operation the high-side junction temperature is only a fraction of a degree above the low-side die junction temperature. In an experiment with the power block mounted in a typical application board with 2 Watts dissipated in the low-side die and 1 Watt dissipated in the high side, the top-side MOSFET junction is only 0.4 °C higher than the junction of the low-side device. The results are reasonable considering that the thermal resistance between the die is extremely low, and the clips are conducting a substantial part of the heat generated by the stack to the package exterior. Thermal performance combined with its lower power losses allow the power block to operate at similar temperatures to competitive solutions using two discrete MOSFETs. Fig. 5 compares the measured temperatures of the power block versus a pair of MOSFETs. Both circuits operated under similar conditions and the power block’s junction temperature was cooler than the discrete low side MOSFET, and slightly hotter than the high-side device.

Another important characteristic is the package’s impressive reliability performance. Power block has passed the following reliability tests:
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• 1,000 cycles of temperature cycling -40 to 125 °C (three cells of 77 units);
• 10,000 cycles of power cycling, delta junction temperature = 100 °C (three cells of 77 units);
• 96 hours of autoclave, 121 °C/100% RH (three cells of 77 units);
• 1,000 hours of THB, 85 °C/85% RH. Three cells of 77 units);
• 1,000 hours of HTRB, 150 °C/80% rated VDS (voltage drain to source). Three cells of 77 units;
• 1,000 hours of HTGB, 150 °C/80% rated VGS (voltage gate to source). Three cells of 77 units.

The combination of the silicon die thickness, bill of materials and a detailed design of the lead frames and clips results in a very reliable device that can sustain extreme temperature cycles and humidity levels without impacting performance.

Combining the source down NexFET technology and the stacked die packaging technique significantly reduces the associated parasitic and creates a synchronous buck power block capable of outperforming discrete MOSFET transistors. It can be seen in Fig. 6 that the power block solution achieves over two percent higher efficiency at 25 Amps than two discrete NexFETs with similar conduction and switching characteristics. Efficiency peaks at over 93 percent and is 90.7 percent at 25 Amps. The higher efficiency translates into more than a 20 percent reduction in power loss. The reduced power loss improves thermal performance and reduces system operating costs, or can be used to enable higher frequency operation to improve power density.

Beyond improving performance and reducing board space by 50 percent versus discrete MOSFETs, the NexFET power block simplifies the development effort. In discrete implementations, care must be taken in the layout when connecting the two devices to reduce inductance, now this concern is eliminated. The pinout allows easy placement of discrete components. This includes locating input capacitors close to the package, and the output inductor with the noise generating switch node on the opposite side of the package from the input capacitor and PWM controller IC. The NexFET power block also benefits from a grounded lead frame that should improve thermal performance and reduce EMI (electromagnetic interference). These attributes can help designers to achieve first-time success when designing with the NexFET power block.

4. Conclusions

An innovative silicon and package technology that allows the integration of high power MOSFETs transistors to create a buck converter in a QFN 5 × 6 × 1.5 mm package has been developed. The stacking technology of power block package concept virtually eliminates the parasitic between low and high side MOSFETs. The new source down technology plus the power block package technology allows us to have the lowest power loss in this form and factor. The reduced...
parasitic allows power block to work at higher frequencies reducing the real state needed in the application board. The thermal performance is excellent and the product is already qualified and in the market.

**Acknowledgments**

The authors acknowledge the entire engineering team at Texas Instruments Lehigh Valley for their contributions to develop this solution.

**References**


Multilevel Modular DC/DC Converter for Regenerative Braking Using Supercapacitors

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Abstract: Regenerative braking is presented in many electric traction applications such as electric and hybrid vehicles, lifts and railway. The regenerated energy can be stored for future use, increasing the efficiency of the system. This paper outlines the benefits of the MMC (modular multilevel converter) in front of the cascaded or series connection of converters to achieve high voltage from low voltage storage elements such as supercapacitors. The paper compares three different solutions and shows that the MMC can benefit from weight and volume reduction of the output inductance when shifted switching modulation strategy is used. Using this modulation strategy, not only the output frequency is increased, but also the magnitude of the inductor applied voltage is reduced, reducing inductor size and volume.

Key words: Multilevel converters, power converters for EV, power converters for HEV, supercapacitors.

1. Introduction

The main advantage of using electric traction is that the motor that uses the energy is reversible. The braking energy can be stored for future use, instead of being dissipated in heat as in traditional mechanical braking systems. Regenerative braking is presented in many applications, such as battery or hybrid power cars and bikes [1], railway [2], lifts [3, 4] and many others.

Batteries are mainly used in mobile applications as energy storage devices instead of flywheels and superconductive magnetic storage systems because there are no moving components [5], whilst for high energy dynamics (or high power), as in regenerative braking applications, SC (supercapacitors) are preferred to batteries because of their higher power density and reliability [5, 6].

In battery powered applications, hybridization with supercapacitors is a choice in order to not degrade battery life and increase energy efficiency [7, 8]. Supercapacitors provide instant power while batteries provide constant energy. However, direct parallelization of supercapacitor and batteries has many drawbacks. To start with, there is no control on where the energy is being drawn as it depends on the resistance of the cables connecting one storage system to the other and to the regenerative power system. Also, as the batteries have a constant voltage, the supercapacitors will be kept at the same voltage level and, thus, without being able to store neither use the energy stored they have. To achieve higher energy management capabilities, a converter must be interfaced between supercapacitors and batteries in order to control the energy flux [9].

The regenerative system would be connected on the DC bus side before the inverter that drives the electric motor and would store the energy while maintaining the DC voltage constant.
In regenerative braking applications, the connection of SC to the DC bus has to be studied and several possibilities can be taken into consideration.

SC are low voltage devices. To achieve the high voltages needed in traction applications, a large number of elements must be connected in series as depicted in Fig. 1. Moreover, with the direct series connection of SC cells depicted in Fig. 1, constant voltage at input stage of traction inverter is not achieved, and there is no capability of energy management in SC. Direct series connection of SC of different capacitance value can lead to voltage unbalances between cells because of the common series current. These voltage unbalances can produce overvoltage and destruction of cells. Passive and active, power electronics based, devices have been proposed in the literature to balance these voltages [10-13].

To reduce the number of serialized elements and to increase energy management capabilities, a two quadrant, bidirectional in current, converter can be placed between the traction converter and the SC as depicted in Fig. 2. By using this topology, less number of series connected SC is needed, there is control on the charge and discharge of the SC and the voltage at the DC bus can be kept constant [9].

However, this converter needs a big inductor in order to reduce current ripple at the SC side.

Higher efficiency can be obtained using an interleaved converter topology as depicted in Fig. 3 [14, 15]. This solution is widely implemented for low voltage high-current applications, but for traction applications, where high voltages are needed, cascaded DC/DC converters can be used [6, 16, 17].

This paper presents the comparison and design of a MMC (multilevel modular converter) for regenerative applications using supercapacitors. The proposed converter is compared in terms of inductor weight and size with two cascaded converters. Using MMC with shifted switching strategy significantly reduces inductor size and weight.

2. Cascaded and MMC Converters

Cascaded DC/DC converters split the power source in small parts, allowing multiple low voltage inputs and giving high voltage output. The energy management can be improved, because it can be independent for each energy source [7]. Cascaded buck and cascaded boost connection are depicted in Figs. 4 and 5, respectively, for the connection of three cells.

2.1 Cascaded Buck Converter (CBk)

In the cascaded buck the SC are placed on the high voltage side (U11, U12 and U13), while the SC bus is on the low side U2. The operation of this converter is the same as for one of each cells that it holds, a half bridge buck converter, in which its output is controlled by the
duty cycles imposed. The whole converter output is the sum of every cell output voltages, allowing several redundancies that make this topology reliable and robust. However, if it is compared to a one cell converter of the same power, it can be seen that even if the inductance has been split in several inductances, the total weight and volume is the same if the switching frequency and ripple are equal. Thus, the benefits of this topology are the modularity and the high voltage achieved.

### 2.2 Cascaded Boost Converter (CBt)

In the cascaded boost, the SC are placed on the low voltage side (U_{21}, U_{22} and U_{23}), whilst the DC bus is on the high side U_1. Each cell of this converter is a half bridge boost converter that varies its output voltage depending on the duty cycle applied to its transistors. The whole converter output voltage is the sum of each cell output voltage.

To achieve the same DC voltage and power, in this converter double current is needed in contrast to CBk, and half the voltage in the SC. However, if it is compared to a one cell equivalent converter, as done with CBk, the total inductance will be the same, and the benefits of multiple cascaded cells are the same as before.

### 2.3 MMC (Multilevel Modular Converter)

The multilevel buck converter is the series connection of half bridge cells as depicted in Fig. 6. The SC are connected on the high voltage side (U_{11}, U_{12} and U_{13}) while the DC bus is on the low voltage side U_2. The output voltage can be synthesized as the addition of the output voltage of each cell, but in this case a modulation strategy can be used in order to increase the output frequency.

Using shifted switching modulation strategy [18], the frequency of the voltage applied to the inductor is multiplied by the number of series connected converters, reducing inductors’ size.

Every triangular carrier of each one of the comparators is delayed $\frac{360^\circ}{N}$ respect the cell before, where $N$ is the number of cells. Thus, at the output of the converter it can be seen a frequency of $N \times F_s$ ($F_s$ is the switching frequency). Its behaviour can be seen in Fig. 7.

The output inductance can be computed as:

$$ L = \frac{(U_{max} - U_{min})(1 - D_{eqmax})D_{eqmax}}{\Delta I_z \times F_{eq}} \text{(1)} $$
where, $D_{\text{eq max}} = 0.5$ is the equivalent duty cycle where the maximum ripple occurs, $\Delta I_2$ is the output inductor ripple and $F_{\text{eq}} = N \times F_s$. $U_{\text{max}}$ and $U_{\text{min}}$ are defined as:

$$U_{\text{max}} = N \times U_{1N} \left(D - D \text{mod} \frac{1}{N} + \frac{1}{N}\right) \quad (2)$$

$$U_{\text{min}} = N \times U_{1N} \left(D - D \text{mod} \frac{1}{N}\right) \quad (3)$$

$U_{1N} = \frac{U_1}{N}$ is the one converter input voltage and $D$ is the duty cycle.

As seen in these equations and in Fig. 7, increasing the number of series connected converters reduces the voltage across the inductor and increases the frequency, for a fixed switching frequency and inductor ripple.

That reduces the needed inductor value for a fixed inductor current ripple.

2.4 **Converter Input Current Filter**

The cascaded buck and the multilevel buck topologies presented in this paper have the drawback that the input current, i.e. the SC current, has a high frequency harmonic content due to switching.

SC degrade its capacity performance for frequencies above 100 Hz, where the capacity value is near zero, and behaves as a resistor, producing only loses, reducing its lifetime [9]. To reduce these harmonic currents, an input LC (series inductor, parallel capacitor) filter must be added as depicted in Fig. 8. This LC filter reduced voltage and current ripple in SC, but increased the magnetic elements of the topology, increasing weight and size [19].

The size of the capacitor and the inductor of the filter have to be chosen in dependence to the switching frequency. A cut-off frequency five times smaller is a good start. In Fig. 9 the pairs LC for a switching frequency of 20 kHz can be seen. The smaller the frequency, the bigger the value of both elements is.

It has to be noticed that the filter capacitor will have to support the current ripple, so the limitation of this filter may be this element, but in order to set a reference value, a inductance of 1% the value of the equivalent one cell converter will be chosen, and the capacitor to obtain a cut-off frequency below $F_s/5$.

3. **Topology Comparison**

To determine the proper number of series connected cells, the total magnetic energy needed in the inductor for the three topologies can be compared.

The three topologies are compared assuming constant inductor current ripple, constant frequency, and supposing a filter inductor value of 1% of the one cell output inductor.
For the cascaded boost converter (CBr) the total inductance can be computed as:

\[ L_{CBr} \propto \frac{1}{4N} \]  

\[ E_{CBr} \propto 1 \]  

Because the voltage is the half of the buck derived topologies but the current is doubled, and there is no filter needed for the SC. \((U'_1 = 2U'_2\) but now \(U'_1\) is the DC bus that was \(U_2\) in the CBk and \(I'_2 = 2I_2\).)

For the multilevel buck, the inductance can be computed as:

\[ L_{MBk} \propto \frac{1}{N^2} + 0.01N \]  

\[ E_{MBk} \propto \frac{1}{N^2} + 0.01N \]  

Here, the reduction is higher as increasing the number of series connected converters, because the reduction is due to lower voltage, but also higher frequency. Fig. 10 shows the total inductance as a function of the number of series connected converters.

As it can be seen, the total inductance for the cascaded buck converters increases as the number of series connected converters increase because the input filter inductance is increased. On the other hand, the total inductance of the cascaded boost remains constant and its value is the same as for the HB for one channel because there is no need of input filter inductance, and the voltage across the inductors is the half. It must be said that for the boost topology, the current in the inductor will be higher than for the buck derived topologies, thus, considering constant power the amount of copper will be bigger but the amount of ferrite will be smaller. In average, the mass and volume will be approximately the same as in the HB inductance.

As it can be seen in Fig. 10, the minimum for the total inductance is achieved by the multilevel buck topology for a six cell converter.

4. Verification

In order to show the important differences between the size and volume of one inductor in the case of one
cell converter and the inductor needed for a six cell multilevel buck converter, both inductances have been sized and calculated for a converter working between $U_1 = 97.2$ V and $U_2 = 42$ V with a nominal current of $I_2 = 5$ A.

For the one cell, half bridge converter (HB) the inductance value can be computed assuming a ripple of the 15% of the nominal current and a switching frequency of 20 kHz.

$$L = \frac{U_1(1-D)D}{M_{FS}} = 1.26 \text{ mH} \quad (12)$$

On the other hand, for the six cell multilevel buck (MBk) the value needed is depicted by:

$$L = \frac{U_1(1-D)D}{N^2M_{FS}} = 45 \text{ \mu H} \quad (13)$$

The number of turns needed in the inductor with a saturation current of 6 A can be obtained with:

$$N = \frac{L_{sat} I_{sat/A}}{B_{sat/A}} \quad (14)$$

For the HB, 58 turns are needed if E55/28/21 ferrite core is used, but for the MBk eight turns are needed if the RM10/ILP ferrite core is used. Computing the amount of copper wire needed, Table 1 can be obtained.

The mass of copper has been calculated supposing a current density of 5 A/mm² and four wires of 0.25 mm² for each turn, with copper density and the average perimeter stated in the cores datasheet.

The RM10 inductor is 13 times lighter and needs 19 times less volume than the needed for E55. As seen in Fig. 10, the relationship between 1 and 0.088 (which is the value at 6-cell MBk) is kept by the relationship between the two ferrite masses, which is 0.079.

### Table 1 Comparison between inductors.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N$ (turns)</th>
<th>$v$ (mm²)</th>
<th>$m_{Cu}$ (g)</th>
<th>$m_{Fe}$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM10</td>
<td>8</td>
<td>4,247</td>
<td>17</td>
<td>3.72</td>
</tr>
<tr>
<td>E55</td>
<td>58</td>
<td>81,670</td>
<td>216</td>
<td>60.15</td>
</tr>
</tbody>
</table>

### 5. Conclusions

This paper shows that multilevel converters can be used in mobile DC/DC applications not only to increase the efficiency of the power electronics system itself, but to reduce the weight and volume of the system.

The paper presents and compares three topologies in terms of magnetic energy, which is directly related with the volume of the magnetic components. This comparison shows that the best topology is the multilevel buck converters, because it beneficiates not only from voltage reduction, but also from frequency increase if shifted switching strategy is used.

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Multilevel Modular DC/DC Converter for Regenerative Braking Using Supercapacitors


Development and Construction of 345 kV Power-Optical Fiber Composite XLPE 2,500 mm² with Prefabricated Joint

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Abstract: Due to the increasing demand of replacing large capacity overhead lines with underground cables in Korea, KEPCO (Korea Electric Power Corporation) and LS Cable (LS Cable & System) have developed 345 kV optical fiber composite XLPE (cross-linked polyethylene) 2,500 mm² cable system. This system has been installed in Cheongna district of Incheon city. KEPCO and LS Cable are also planning to build the cooling system in a tunnel in order to reduce the ambient temperature caused by currents. In this paper, the process of development, field installation, and final inspection test of the complete system will be described.

Key words: Power cable, underground, tunnel, large capacity, cooling system, distributed temperature, prefabricated joint, optical fiber.

1. Introduction

On March 2011, KEPCO (Korea Electric Power Corporation) has installed 254 c-km of 345 kV and 2,756 c-km of 154 kV underground transmission cables. Among these transmission cables, 952 c-km is oil-filled cable and 2,058 c-km is XLPE (cross-linked polyethylene) cable. In 2011, KEPCO is planning to construct additional 83 c-km of 345 kV and 176 c-km of 154 kV underground transmission cables. Nowadays many local governments are asking for replacing overhead transmission lines with underground cables in a bid to construct new towns in their area.

Particularly, the province on outskirts of Seoul city needs to make it and they are content to pay huge money for removing overhead transmission lines and constructing underground cables.

In this case, KEPCO has no choice but to substitute large capacity cable for meeting the ampacity of existing overhead lines.

Therefore, the large capacity cables, 345 optical fiber composite XLPE 2,500 mm² cables and its prefabricated joint have been developed, some cables have been installed or is under construction.

In this paper, the authors will explain on the development and installation of 345 kV optical fiber composite XLPE 2,500 mm² cables with prefabricated joint, and the monitoring system using various sensors in a tunnel including optic fiber sensor and the cooling system etc. which will be installed in Cheongna FEZ (free economic zone).

2. Status of Development Area

Cheongna FEZ is an important project for building free economic zone where heavy investment was done from abroad. The aim is to construct a global business city of Northeast Asia where 90,000 people can reside.
by December of 2012. So, 4 billion dollars investment in the area of 17,783 km² will be done.

Along with four conventional power plants in the development area, a new private-funded power plant will be additionally constructed.

Regarding transmission lines, 345 kV ACSR 480 mm² (4B) 2 circuits and 2 T/Ls are being operated in the west of Cheongna in the Fig. 1, and 345 kV 1 line and 154 kV 2 lines are installed in the south. In addition, according to the plans of new construction of private-funded power plant interconnecting lines and enlargement of power system, three 345 kV T/Ls and two 154 kV T/Ls are scheduled to be constructed by 2015.

KEPCO has established detailed plans for adding new infrastructure and replacing overhead lines with underground power cables as follows: The underground cable installed in Cheongna FEZ will be concentrated with large capacity cables just like large capacity overhead power lines. Therefore, considering installation space, capacity and economic efficiency, 2,500 mm² was selected as a conductor size and developed and installed in the electric power tunnel. The length of electric power tunnel in the development area is approximately 7.9 km on the west and 8.4 km on the south. Fig. 2 shows a sectional view of the typical electric power tunnel installed in the Cheongna district.

Cables and joints are dispersed, and separated by bulkhead between T/Ls in order to avoid any damage of a joint by electrical failures in adjacent lines. Fig. 3 shows a configuration of joint bay.

### 3. Development of Cables and Accessories

#### 3.1 Development of Cables

KEPCO has reviewed the size of conductor which satisfies the capacity of 3,636 A ( = 909 × 4) which is the continuous current rating of 345 kV overhead power line ACSR 480 mm², 4 bundles. Table 1 shows a comparison between capacities of overhead line and underground cable. Through this comparison, 2,500 mm² was chosen due to the economic reason.

In addition, optical composite cable was developed, where optical fiber is inserted between cable metal sheath and insulator’s external semi-conductive layer for more accurate measurement of distributed temperature of cable. Fig. 4 shows the sectional view of XLPE 2,500 mm² optical composite cable.

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**Fig. 1** Configuration of Cheongna area.
3.2 Development of Joints

KEPCO has adopted the built-in optical fiber joint by PJ method which has a simple structure and relatively short construction period based on operating experience of XLPE 2,000 mm² cable for 345 kV Yeongseo-Yeongdeungpo transmission line in 2002. Fig. 5 shows an intermediate joint with the built-in optical fiber joint.

3.3 Type Test

Type test was carried out in accordance with IEC62067 in KERI (Korea Electrotechnology Research Institute) and KEMA, Netherlands to verify the design of cable system. In addition to the conventional type test, optical loss test was carried out as well.

The cable type test was configured in Figs. 6 and 7 by adding several accessories by the specification of KEPCO. Outdoor termination consisted of total three sets, which are one type of slip-on and two types of condenser-con. Regarding the straight joints, there are prefabricated joint type and premoulded joint type. With two kinds of insulation joint and two kinds of normal joint, total four sets were configured for the straight joints. And lastly, one set of SF6 gas termination was configured. The results of type test are summarized in Table 2.

3.4 Prequalification Test

The PQ test was also conducted to verify the long term reliability. The PQ test was successfully conducted in LS Cable & System, Taihan Electric Wire and Iljin Electric, which are three major cable manufacturers in Korea.

![Fig. 2 Typical configuration of tunnel.](image)

![Fig. 3 Typical configuration of joint bay.](image)

![Fig. 4 Sectional view of optical composite cable.](image)

Table 1 Underground cable’s rated current based on laid in air at 40 °C.

<table>
<thead>
<tr>
<th>Conductor size</th>
<th>Rated current</th>
<th>Number of cable per phase</th>
<th>Remarks (UG* vs OHL**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 mm²</td>
<td>860 A</td>
<td>4 (3,440 A)</td>
<td>95%</td>
</tr>
<tr>
<td>1,200 mm²</td>
<td>1,240 A</td>
<td>3 (3,720 A)</td>
<td>102%</td>
</tr>
<tr>
<td>2,000 mm²</td>
<td>1,520 A</td>
<td>2 (3,040 A)</td>
<td>83.6%</td>
</tr>
<tr>
<td>2,500 mm²</td>
<td>1,650 A</td>
<td>2 (3,300 A)</td>
<td>91%</td>
</tr>
</tbody>
</table>

* Underground cable, ** Overhead line.

![Fig. 5 Prefabricated joint with optical fiber joint.](image)

![Fig. 6 Schematic diagram of test loop for type test.](image)
Table 2  KERI type test results [2].

<table>
<thead>
<tr>
<th>Test item</th>
<th>Requirements</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Optical fiber loss</td>
<td>Less than 1.5 dB/km</td>
<td>pass</td>
</tr>
<tr>
<td>2. Partial discharge</td>
<td>300 kV, ≤ 5 pC</td>
<td>pass</td>
</tr>
<tr>
<td>3. Tanδ measurement</td>
<td>≤ 10^{-3}</td>
<td>pass</td>
</tr>
<tr>
<td>4. Heating cycle voltage</td>
<td>400 kV/20 cycle</td>
<td>pass</td>
</tr>
<tr>
<td>5. Partial discharge</td>
<td>300 kV, ≤ 5 pC</td>
<td>pass</td>
</tr>
<tr>
<td>6. Switching impulse</td>
<td>±1045 kV/10 shot</td>
<td>pass</td>
</tr>
<tr>
<td>7. Lightning impulse</td>
<td>±1300 kV/10 shot</td>
<td>pass</td>
</tr>
<tr>
<td>8. AC voltage</td>
<td>400 kV/15 min</td>
<td>pass</td>
</tr>
<tr>
<td>9. Optical fiber loss</td>
<td>Not exceed 0.3 dB than former value</td>
<td>pass</td>
</tr>
</tbody>
</table>

Like the type tested, the line for PQ test was configured as two sets of outdoor termination and total four sets of insulation joint and normal joint (each two types of PJ, PMJ) and one set of SF6 gas termination. In addition, the linear distance of electric power tunnel was more than 35 m so that the snake is more than 1 pitch for confirming the thermal behavior of the cable touching a large conductor [1]. The thermal behavior was checked by deciding the installation standards of 345 kV cable 2,500 mm² as 1.5 Ds of snake width (average outer diameter of metallic sheath) and 9 m per 1 pitch. The results of PQ test are summarized as shown in Table 3.

4. Cable Installation Work

4.1 Status of Cable Work in the West of Cheongna

The status of cable work in the west of Cheongna is shown in Table 4.

Table 3  Results of the long-term test in LS [2].

<table>
<thead>
<tr>
<th>Item</th>
<th>Test condition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating cycle</td>
<td>345 kV/180 cycle</td>
<td>pass</td>
</tr>
<tr>
<td></td>
<td>90-95 °C 2 hr, 16 on/32 off</td>
<td></td>
</tr>
<tr>
<td>Duration</td>
<td>12 months</td>
<td></td>
</tr>
<tr>
<td>Lightning impulse</td>
<td>±1300 kV/10 shots, 90-95 °C</td>
<td>pass</td>
</tr>
</tbody>
</table>

Table 4  Status of 345 kV cable work in the west of Cheongna.

<table>
<thead>
<tr>
<th>Name of project</th>
<th>Type of conductor</th>
<th>Length</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSCOT/L</td>
<td>XLPE 2500</td>
<td>10.6c-km</td>
<td>Dec. 2010</td>
</tr>
<tr>
<td>Inseo T/L</td>
<td>XLPE 2500</td>
<td>9.0c(D)-km</td>
<td>Dec. 2011</td>
</tr>
<tr>
<td>West Incheon Underground</td>
<td>XLPE 2500</td>
<td>8.4c(D)-km</td>
<td>Dec. 2011</td>
</tr>
</tbody>
</table>

4.2 Installation of Cable Supports

Regarding the cable support, angle support is installed in the straight section and cylinder type support is installed in bent and manhole at an interval of 1.5 m. The verticality shall be within 90 ± 5. A hanger is apart from the bottom by 400 mm and the interval between hangers is 550 mm. Fig. 8 shows the shape that hangers are installed as explained above.

As well, a ladder for fixing the cable axial force of slope part, bent and manhole terminal was developed through sufficient site tests and review and installed as shown in Fig. 8.

4.3 Cable Laying

When laying cables, the laying speed is adjusted through communication by installing telephones at every starting point, ending point and curve.

When laying cables, its minimum bending radius (more than 20 times) shall be maintained. The cable laying speed is set to 5-10 m/min by installing a brake to adjust the drum rotation speed.

In addition, laying in a snake formation is executed in order to protect cables in case of thermal extension of cables. In case of snake laying, the distance per 1 pitch is less than 9 m and the snake width is more than 1.5 Ds.

In case of 345 kV power cable, 1 pitch is 9 m and the movement of thermal extension of cable by snake is
Development and Construction of 345 kV Power-Optical Fiber Composite XLPE 2,500 mm$^2$ with Prefabricated Joint

expected to occur at the point of 2.25 m. Therefore, since the position of hanger is different from the inflection point, the ladder for snake is installed for supporting the axial force of inflection point as shown in Figs. 8-10.

Right after laying the cable, DC 10 kV was applied for one minute between metal sheath and ground in order to check the jacket integrity [2].

4.4 Cable Connection

Fig. 11 shows the parts of prefabricated joint for 345 kV XLPE 2,500 mm$^2$ optical composite cable.

When a cable is laid, the cable status is checked and marked with tape. After offset, the cable is cut, leaving a margin of 500 mm (in case of optical composite cable 2 m) from the node.

For the cable whose metal sheath is removed, a belt heater is wound on the cable and heat of 90 °C is applied for seven hours. Then, after natural cooling, the cable is straightly stretched.

A clean isolated room is installed in order to prevent foreign particles or dust from flowing into the joint during connection work. The humidity is kept less than 70% in the clean room, and a thermo-hygrostat is installed near the connection location to supply fresh air to the clean room.

When finishing works relevant to insulator and semiconductor for connecting cables, keeping straightness is very important and there shall be no scratches as shown in Fig. 12. For the final finishing, glass, a non-conductive material, shall be used as shown in Fig. 13 and it must be cleaned with a cleanser.

At the time of mirror-like treatment as shown in Fig. 14, the specification of the used mirror tube shall be checked. And, after mirror-like treatment, it shall be

---

Fig. 8  Ladder for snake and terminal fixation.

Fig. 9  Cable laying.

Fig. 10  Width of installation of ladder for snake.

Fig. 11  Parts of 345 kV XLPE 2,500 mm$^2$. 

[Spring Unit]  [Stress Cone Pusher]  [Stress Cone]  [Conductor Sleeve]
Development and Construction of 345 kV Power-Optical Fiber Composite XLPE 2,500 mm² with Prefabricated Joint

Fig. 12  Straightness measurement before connection.

Fig. 13  Penciling (removal of semi-conductive layer).

Fig. 14  Mirror-like treatment.

thoroughly checked if there is no foreign substance or damage on the surface of the insulator [4]. In case there are foreign substances on the insulator after mirror-like treatment, they shall be removed with glass flakes and evenly sand-papered.

Fig. 15 shows installing a SRC (stress relief cone) inserter, the insertion direction shall be checked in advance for preventing the long side and short side from being switched. Before inserting epoxy unit and stress relief cone, the manufacturer’s serial number shall be recorded in the construction quality checklist.

The stress cone shall be dried in a box for keeping warm at 60 °C for more than one hour before inserting it. The epoxy unit shall also be dried for more than 30 minutes with a dryer before insertion. In case there is an optical unit in the metal sheath, it shall be inserted carefully not to damage the optical unit when assembling parts as shown in Fig. 16.

When compressing conductors, 700 kgf/cm² pressure is applied and the dimensions before and after compression are recorded in the construction quality checklist for confirming that they correspond to the reference value. As for the measurement of length of the final setting of spring unit, the lengths of L1-A, B of long side and short side of Fig. 17 are measured at four locations (90° direction in each) after inserting the spring unit and in case they are within the reference value, they are kept for more than two hours before measurement of the length of the final setting.

4.5 Final Inspection (AC Withstanding Voltage Test)

1 line of 345 kV POSCO T/L was energized in June 2010 and completed the other line in December 2010. The AC withstanding voltage test as a final acceptance has been chosen.

Conventionally, KEPCO had conducted DC withstanding voltage test as a final acceptance until year 2000. However, DC withstanding voltage test may be a risk factor to XLPE cable through accumulation of space charges. Thus, KEPCO had changed a test method to 24-hour no-load soak test. But, even 24-hour no-load soak test also has the danger of spreading the accident to the system in case of failure. Therefore, AC withstanding voltage test has been applied since 2008.

AC withstanding voltage tester is classified into resonant type and winding type. KEPCO uses a resonant type AC withstanding voltage tester which can be moved in the field and requires low power capacity for the final acceptance (Fig. 18).
For 345 kV AC withstanding voltage test, AC 250 kV is energized for 60 minutes between a conductor and ground to check if there is any abnormality [2].

PD (partial discharge) was measured by a HFCT method and a thin electrode method for securing reliability of POSCO #1 and #2 T/Ls completed in December 2010 [3]. The measurement showed that the size of a signal became gradually larger toward POSCO S/S where a portable withstanding voltage tester was installed, and frequency also became gradually higher in the direction. This implies that the signal source is the GIS device in POSCO S/S. In addition, there was no discharge considered as PD in cables and joints of all lines as shown in Table 5.

Through this test result, field application and operation of XLPE 2,500 mm² cable were successfully accomplished. Total 35 c-km of 345 kV XLPE 2,500 mm² cable including POSCO T/L are now in operation in the west of Cheongna.

5. Cable Cooling System

5.1 Review of Cooling System

For preventing reduction of transmission capacity due to increase of temperature in the electric power tunnel caused from concentration of large capacity underground lines, the installation of cooling system is reviewed as follows:

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Location</th>
<th>Signal frequency</th>
<th>Max. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSCO EB-G</td>
<td>3.5 (MHz)</td>
<td>0.2 (V)</td>
<td></td>
</tr>
<tr>
<td>#2JB</td>
<td>2 (MHz)</td>
<td>0.1 (V)</td>
<td></td>
</tr>
<tr>
<td>#3JB</td>
<td>1 (MHz)</td>
<td>0.04 (V)</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Results of measurement of POSCO #2T/L PD (typical example).

<table>
<thead>
<tr>
<th>Rated current (before cooling)</th>
<th>Rated current (after cooling)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,650 A</td>
<td>1,715 A</td>
<td>Improved by 4%</td>
</tr>
</tbody>
</table>

(1) According to the industrial safety and health standards, the temperature in the tunnel shall be kept less than 37 °C for protecting operators including patroller, repair man etc.;

(2) Temperature in the electric power tunnel should be kept less than 37 °C by preventing reduction of rated current of cable due to increase ambient temperature. The underground power cables’ transmission capacity shall be kept fit for the existing overhead lines and planned lines;

(3) The reduction of transmission capacity should be prevented, by predicting excessive temperature increase caused by soil secular change (generated after construction of the electric power tunnel);

(4) The reduction of transmission capacity should be prevented in advance by predicting the transmission bottleneck in the hot-spot section by considering the temperature change factors of each section of electric power tunnel according to the soil characteristics.

Therefore, a feasibility survey for the cooling system of the electric power tunnel newly constructed in Cheongna district was conducted as follows.
Development and Construction of 345 kV Power-Optical Fiber Composite XLPE 2,500 mm² with Prefabricated Joint

5.2 Selection of Cooling Method

As for cooling methods, indirect water cooling method and wind cooling method were comparatively reviewed. After the comparative review, the indirect water cooling method which can be applied over a long distance and not affected by external factors, having excellent cooling effects, was selected.

In case the internal temperature of the electric power tunnel exceeds 37 °C, coolant flows through a cooling pipe. If the temperature on the low temperature side of cooling basin exceeds 12 °C, or the temperature on the high temperature side exceeds 30 °C, a refrigerator is operated. If ambient air temperature is less than 10 °C, the refrigerator is stopped and bypass to the cooling tower is conducted.

As a result of review, if a cooling system is applied, the internal temperature of electric power tunnel is controlled less than 37 °C and the effect of 4% increase of transmission capacity is additionally expected if the rated current is recalculated by changing the baseline temperature from 40 °C to 37 °C (Table 6).

6. Conclusions

KEPCO determined standards for large capacity cables, such as 345 kV power-optical fiber composite XLPE 2,500 mm², according to the recent demand for placing large capacity lines underground and successfully developed and installed them. In addition, by predicting long-term load prospects for load concentration places and reviewing the cooling system for the electric power tunnel, the temperature increase in the electric power tunnel can be restrained, and about 4% increase of transmission capacity is expected.

The further plan is to configure underground power cables which correspond to large capacity overhead power lines by increasing the transmission capacity through laying of cables of different intervals. In addition, comprehensive real time cable monitoring system and rated current calculation system will be installed by utilizing the optical sensors installed in the cable.

References

[2] IEC 62067, Power Cable with extruded insulation and their accessories for rated voltages above 150 kV (Um = 170 kV) up to 500 kV (Um = 525 kV)—Test methods and requirements, 2006, pp. 33-49.
Influence of Excitation System’s Parameters to the Power System Stability

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Abstract: Excitation system is one of the significant elements affecting the dynamic performance of electric power systems. The power engineering as area of science and industry is subjected to rapid modernization, which is caused by technological progress. However, not all elements of the power system are developing simultaneously. The old type of elements sometimes is sufficient to adapt old system to the new operational conditions. The work developed and proposed in this paper deals with analysis of possible optimization of synchronous generator’s excitation system. Authors examined influence of excitation system’s parameters to the dynamics of transient processes in the power system. Authors investigated optimal parameters of excitation system of the Kegums hydro power plant. For optimization of parameters objective functions were used. The problem of the mutual influence of excitation systems of neighbor power plants was investigated. Investigation of transient processes using developed model proved that optimization of excitation parameters improves efficiency of regulation of excitation system, damping of active power oscillation and in some cases can prevent out-of-step condition.

Key words: Oscillation damping, stabilizer, optimization.

1. Introduction

The quality as well as reliability of electrical energy transmitted to consumers is one of the main parameters for successful operation of the power system. The problem of power oscillation damping in the power system is solved using PSS (power system stabilizer) as additional voltage regulation loops. The optimal PSS settings searching for constantly modernized power system are an important problem of the world power systems.

A lot of work has been dedicated to this problem [1-6]. Kegums HPP (hydro power plant) is one HPP creating cascade of the three HPP at the Daugava River. Modernization of equipment in the Latvian power system takes place during the last decades. Excitation system of the Kegums HPP is an old fashioned AVR+PSS excitation system with different stabilization parameters. Few other power plants are with modernized excitation systems. Hence, parameters of excitation system of the Kegums HPP are no more optimal. This paper deals with analysis of parameters of excitation system of Kegums HPP. Optimal parameters allow to improve power oscillation damping. Possible adaptive approach for more effective oscillation damping is suggested.

The given work presents the next step of investigation of the excitation system’s optimization and adaptation possibility to new Latvian power system operational conditions.

Investigation results of the previous studies showed that use of combinatorial analysis and objective functions’ methods allows to find optimal settings for Kegums HPP excitation system [7, 8].

However, the previous researches were done using simplified mathematical models, where the influence
of only one neighborhood power station was taken into account.

Major goal of the presented work is proof of possibility to select optimal parameters of Kegums HPP excitation system using mathematical model, which simulates real parameters of Latvian power system.

2. Description of Kegums HPP and Excitation System

The construction of Kegums HPP was finished in 1979. Since that time, three generators of 64 MW capacities are in service. Generator voltage is 13.8 kV. Excitation system is AVR+PSS type developed in the former USSR [9].

Transfer function of excitation system is:

\[ U_{reg}(p) = \Delta U(p) \left( K_{U} + pK_{L} \right) + \Delta f(p) \left( \frac{pK_{f}}{T_{p} + 1} + pK_{f} \right) + \Delta f(p) pK_{f} \left( \frac{K}{T_{y}p + 1} \right) \]

(1)

where \( T = 0.5 \) s, \( T_{y} = 0.2 \) s, \( K = 1 \).

Fig. 1 presents block diagram of AVR+PSS excitation system.

3. Influence of PSS Parameters to Dynamic of Control Process

Simplified “machine-system” diagram (Kegums HPP and system) is presented in Fig. 2.

Model is equipped with block, simulating short circuit event. It simulates three-phase to ground short circuit. This type of short circuit is selected as the heaviest case to study transient process.

The dynamic of power system transient investigated for three phase to ground for different duration of short circuit simulation.

In this case duration of short circuit is 0.3 seconds. Increasing the duration causes out-of-step condition.

Maximal short circuit duration depends on the load value in the power system [7, 8].

For considered case load is represented by HPP auxiliaries.

Fig. 1  Block diagram of AVR+PSS excitation.

Increase of the load will increase maximal duration of the short circuit, but it will not influence optimization process of excitation system.

4. Optimization of Excitation System

Results of research conducted by authors showed that existing parameters of excitation system are not optimal from the point of view of the power oscillation damping. The influence of excitation system parameters to power damping was considered.

The following equation as optimization criterion is suggested [3]:

\[ A = \alpha_{1} \int_{0}^{t} \left| P_{G}(t) - P_{ref}(t) \right| dt + \alpha_{2} \int_{0}^{t} \left| V_{G}(t) - V_{ref}(t) \right| dt + \alpha_{3} \int_{0}^{t} \left| f_{G}(t) - f_{ref}(t) \right| dt \]

(2)

where \( P_{G} \) denotes the active power, \( P_{ref} \) is its desired value; \( V_{G} \) and \( V_{ref} \) are the terminal voltage and its desired value, \( f_{G} \) denotes the frequency, \( f_{ref} \) is desired value, \( \alpha_{1}, \alpha_{2}, \alpha_{3} \) denote weighting factor.

The values of quantities used in equation (active power, voltage and frequency) are different. So, deviation of one parameter will always exceed others.

For unbiased estimation of optimization system it is possible to divide multi-objective equation into few simple equations and analyze each taken separately [10].

Comparison of simple equations can develop recommendations for optimization of the system.
Influence of Excitation System's Parameters to the Power System Stability

Fig. 2  Simulation model of Kegums HPP [6, 8].

Optimization criteria can be:

\[
A_1 = \int_0^t (P_G(t) - P_{ref}(t)) \, dt \rightarrow \min
\]

\[
A_2 = \int_0^t (V_G(t) - V_{ref}(t)) \, dt \rightarrow \min
\]

\[
A_3 = \int_0^t (f_G(t) - f_{ref}(t)) \, dt \rightarrow \min
\]

From the transfer Eq. (1) it is seen that for different coefficients character of control is different. The real diapason of coefficients is:

- \( K_{\Delta U} = 15, 25, 50 \) (p.u.);
- \( K_{\Delta U'} = 6 \) to 8.5 (p.u.);
- \( K_{\Delta f} = 11 \) to 14.4 (p.u.);
- \( K_{\Delta f'} = 4 \) to 5.5 (p.u.);
- \( K_{I'} = 2 \) to 3 (p.u.)

Table 1 illustrates combination of coefficients used for the study of optimization the excitation system of Kegums HPP. Figs. 3 and 4 illustrate optimization results for excitation system when optimization criteria are \( A_2 \) and \( A_3 \). When criteria \( A_1 \) and \( A_3 \) are selected the most optimal variant is for parameters of variant 6 and criterion \( A_2 \) gives best result with parameters of variant 10. There is need in selection priority of variant for coefficients \( P \), \( f \) and \( U \) or to select compromise version.

Table 1  Variants of coefficients used for the study of optimization the excitation system of Kegums HPP.

<table>
<thead>
<tr>
<th>Nr</th>
<th>( \Delta U )</th>
<th>( \Delta U' )</th>
<th>( \Delta f )</th>
<th>( \Delta f' )</th>
<th>( \Delta I' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>6</td>
<td>11</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>8.5</td>
<td>11</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>8.5</td>
<td>14.4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>6</td>
<td>11</td>
<td>5.5</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>6</td>
<td>14.4</td>
<td>5.5</td>
<td>2</td>
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<td>6</td>
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<td>11</td>
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<td>8</td>
<td>15</td>
<td>8.5</td>
<td>14.4</td>
<td>4</td>
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<td>9</td>
<td>25</td>
<td>8.5</td>
<td>14.4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>8.5</td>
<td>14.4</td>
<td>5.5</td>
<td>3</td>
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<tr>
<td>11</td>
<td>50</td>
<td>6</td>
<td>14.4</td>
<td>5.5</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>8.5</td>
<td>14.4</td>
<td>5.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 3  Variations of objective function \( A_2 \) for different variants of coefficients during short circuit.
Influence of Excitation System's Parameters to the Power System Stability

Figs. 5 and 6 illustrate results of parameters’ optimization. Transient processes for voltage and frequency variations are shown for different optimization parameters.

Application the coefficients of variant 4 will cause out-of-step condition. The best damping case is observed for application of variant 6.

5. Adaptive Approach for Control of Excitation System

The next step of research was verification of optimal parameters’ selection when influence of a neighbor power plant is investigated. The design diagram of the Latvian power supply system represents the mathematical model which is constructed with PSS/E software.

The excitation system presented in Fig. 1, was integrated into simulation model of the Latvian power system.

Fig. 7 represents investigated network of the Latvian power system. For practical analysis of dynamic behavior during disturbances in the power system each plant is represented by an equivalent generator.

Optimization criteria search was determinated at three-phase to ground short circuit, with duration 0.3 seconds.

The fault location was chosen the same distance to Kegums HPP as represented in Fig. 2. Short circuit’s location is at 110 kV substation (Ķekava).

Variations of objective function $A_2$ for different variants of coefficients are illustrated in Fig. 8.

Fig. 8 shows that parameters of variant 3 are the most optimal. Two worst parameters of transient process are for variants 6 and 11.

Results of voltage investigation on the bus of the Kegums HPP’s synchronous generator at transient process moment (Fig. 9), show that at parameters of variant 6 there is a significant voltage drop.

As it can be observed from Fig. 9a visible overshoot occurs for parameters of variant 11 at the moment of voltage recovery.
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Fig. 7  Simplified diagram of interconnected power plants.

Fig. 8  Variations of objective function $A_2$ for different variants of coefficients during short circuit.

Fig. 9  Variation of Kegums HPP generator's voltage depending on combination of control coefficients.

In turn, comparing voltage raise at parameters of variants 3 and 11, it is possible to reduce overshoot by 5%.

Using objective function $A_1$ (Fig. 10) parameters of variant 10 are most optimal, but the worst is variant 11.

Active power’s characteristics for different variants of coefficients are illustrated in Fig. 11.

Comparing variant 10 with variant 11 is visible that deviations from nominal value can be reduced by 14.7% (the top value) and 27.0% (the bottom value).

Last objective function is shown in Fig. 12. Like the criterion $A_2$, parameters of variant 10 are most optimal, but the worst is variant 11.
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6. Conclusions

In this paper the influence of excitation system’s parameters on the power system stability is observed. The main investigations of the paper are:

(1) Influence of PSS parameters on control process dynamic was investigated;

(2) Optimal parameters for Kegums HPP were selected using objective functions;

The investigations done using simplified scheme Fig. 2 shows that criteria (3), (4), (5) are possible to improve synchronous generator’s output parameters’ damping and in some cases can prevent out-of-step condition in Figs. 4 and 6.

(3) Influence of neighbor operating power plants’ parameters was considered from the point of view of stability of excitation control.

Influence of neighbor power plant’s parameters is significant. The results of investigations which are done using simulation model of the Latvian power supply system, show that optimization of Kegums HPP’s excitation system’s parameters can increase stability and efficiency. Possibility of damping increasing of synchronous generator’s output parameters is illustrated in the paper. For example, active power’s amplitude is reducing by 14.7% and by 27.0% in the first period (Fig. 11).

References


Experimental Investigation of Electric Drive Dynamics

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Abstract: Induction motor is used in many applications to drive an electromechanical system. Transients of the motor torque and speed are outlined by the inertia of rotating rotor. The paper deals with influence of rotor inertia to transients of motor speed. The method of speed control measurement and experimental equipment is discussed. Simulation and experimental results are compared.

Key words: Electromechanical system, simulation, model of induction motor, rotation speed measurement.

1. Introduction

Electromechanical system as an object of investigation comprises electrical and mechanical parts. Electromechanical power converter and its control system depend on electrical part as well as all moving masses coupled between them form mechanical part. Electromechanical system includes various mechanical chains, with infinite or finite stiffness and clearance. Systems with infinite stiffness and without clearance are one-mass system and are quite well analyzed [1-3]. Systems with capable to deform chains and clearance are more complex described [4, 5]. They are described by higher order nonlinear differential equations, and without essential simplifying of problem they can not be solved in analytical way. In these cases computer models of solved program must be developed, using specialized software, and system responses simulated [6-11].

Electromechanical systems are influenced by inertia of moving elements, those change transients of speed and torque. Usually inertia is not defined, in the name plate of a motor, the inertia of load is also unknown, and therefore it can be calculated from simulation results.

The paper presents model of induction motor, results of simulation and dynamic properties of the system with different moments of inertia. A construction of pulse rate speed measuring device is described. The paper presents the method of how the moment of inertia of the drive can be found. This can be done by comparing simulation results with experimental ones.

2. Model of Induction Motor

Dynamic performance of an AC machine is a complex problem taking into account three phase rotor windings moving with respect to three-phase stator windings. The coupling coefficient changes continuously with the change of rotor position $\theta_\text{r}$, and machine model is described by differential equations with time varying mutual inductances. To simplify the problem solution, any three phase induction machine can be represented by an equivalent two phase machine, where $d^\prime - q^\prime$ stator is direct and quadrature axes as well as $d^\prime - q^\prime$ are rotor direct and quadrature axes. The problem becomes simple, but problem of time varying parameters still remains. Park transformation refers the stator variables to a synchronous reference frame, fixed on the rotor. It results in all time varying inductances being eliminated. The other kind of transformation widely used is G. Kron transformation, relating both stator
and rotor variables to a synchronously rotating reference frame that moves with the rotating magnetic field. Time-varying inductances in the voltage equations of an induction machine also can be eliminated by transforming rotor variables to variables associated with fictitious stationary windings. In this case, the rotor variables are transformed to a stationary reference frame fixed on the stator. This method was proposed by Bose [1]. The paper presents mathematical model of induction motor in a stationary reference frame. Mathematical model of induction motor in stationary reference frame, \(dq\) developed for motor is presented in Ref. [3]. For revolving induction motor it can be written as:

\[
\begin{align*}
    u_{ds} &= \left[ \frac{1}{L_s} + \frac{1}{L_s} \right] \psi_{ds} \psi_{ds} R_s + \frac{d\psi_{ds}}{dt}; \\
    u_{qs} &= \left[ \frac{1}{L_s} + \frac{1}{L_s} \right] \psi_{qs} \psi_{qs} R_s + \frac{d\psi_{qs}}{dt}; \\
    u_{id} &= \frac{1}{L_s} \left( \psi_{id} - k_1 \psi_{ds} \right) R_s + \frac{d\psi_{id}}{dt} + \omega_0 \psi_{qs}; \\
    u_{iq} &= \frac{1}{L_s} \left( \psi_{iq} - k_1 \psi_{ds} \right) R_s + \frac{d\psi_{iq}}{dt} + \omega_0 \psi_{qs}.
\end{align*}
\]

(1)

where: \(\psi_{ds}, \psi_{qs}, i_{ds}, i_{qs}\) and \(i_{ds}'\) are stator flux linkages and currents aligned with the direct axis; \(\psi_{ds}', \psi_{qs}', i_{ds}', i_{qs}'\) is stator flux linkages and currents aligned with quadrature axis; \(R_s\) is stator phase resistance, \(R_s\) rotor phase resistance, referred to stator; \(u_{ds}, u_{qs}, u_{id}, u_{iq}\) is stator and rotor voltages.

In the stationary reference frame \(u_{ds} = U_{\text{max}} \cos \omega_0 t\), \(u_{qs} = U_{\text{max}} \sin \omega_0 t\) where \(U_{\text{max}}\) is amplitude of voltage and \(\omega_0 = 2\pi f\) is angular frequency. \(L_m\) is magnetizing inductance, \(L_s = L_{is} + L_m\) is stator inductance, \(L_{is}\) is stator leakage inductance; \(L_r = L_{ir} + L_m\), \(L_{ir}\) is rotor leakage inductance referred to stator and \(k_1 = L_m / L_s\).

Torque delivered by motor, is calculated as:

\[
M = \frac{3}{2} p \cdot (\psi_{ds}' \cdot i_{ds}' - \psi_{qs}' \cdot i_{qs}')
\]

(2)

where: \(p\) is number of pole pairs.

These equations are solved together with the main equation of moment:

\[
M - M_r = J \frac{d\omega}{dt}
\]

(3)

According to Eqs. (1)-(3) the model of induction motor is developed.

3. Simulation of the Induction Motor

Computer model is elaborated for a motor, whose parameters are presented in Table 1. Models parameters are calculated as:

\[
\frac{1}{L_1} \frac{L_m \times k_1}{L_1} = \frac{1}{0.3064} + \frac{0.296 \times 0.9661}{0.3064 \times 0.0277} = 36.96
\]

(4)

where:

\[
k_1 = \frac{L_m}{0.3064} = 0.296
\]

(5)

\[
\frac{L_m}{L_1} \frac{L_m}{L_1} = \frac{0.296}{0.3064 \times 0.0277} = 34.88
\]

(6)

\[
\frac{1}{L_2} \frac{1}{L_2} = \frac{1}{0.0277} = 36.1
\]

(7)

\[
k_1 = \frac{0.9661}{0.3064} = 34.88
\]

(8)

According to calculated coefficients and Eqs. (1)-(3), model of induction motor shown in Fig. 1 is elaborated.

Results of simulation are presented in Fig. 2. The settling time increases with increasing of rotor inertia. At small inertia, the speed exceeds rated that and has oscillating character.

4. Experimental Speed Measuring Device

Experimental model is elaborated for 2.2 kW induction motor, whose parameters are presented in Table 1. Torque was measured by torque sensor of “Lorenz Messtechnik” company, whose parameters are given in Table 2. Both elements were coupled by double-jointed coupling.

Table 1  Parameters of a motor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor power (kW)</td>
<td>2.2</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>2</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>230</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.81</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>5.14</td>
</tr>
<tr>
<td>Magnetizing inductance (Lm), H</td>
<td>0.296</td>
</tr>
<tr>
<td>Stator inductance (L1), H</td>
<td>0.3064</td>
</tr>
<tr>
<td>Rotor leakage inductance (Lr), H</td>
<td>0.0277</td>
</tr>
</tbody>
</table>
Experimental Investigation of Electric Drive Dynamics

Fig. 1 Model of induction motor in d, q reference frame.

![Model of induction motor in d, q reference frame.](image)

Fig. 2 Motor speed response at different inertia moment:
1—curve when inertia is 0.005 kg·m²; 2—inertia is 0.05 kg·m²; 3—inertia is 0.1 kg·m²; 4—inertia is 0.125 kg·m²; 5—inertia is 0.15 kg·m².

![Motor speed response at different inertia moment.](image)

General view of experimental model is presented in Fig. 3.

For speed measurement one of torque measuring device TTL signals is used, who gives information about rotor angle position. This case is signal A. Repeating pulses can be expressed as function of input signals frequency. For speed measurement the converter changing frequency to direct current voltage, should be applied. For this purpose special microchip LM2907N is used. All measuring circuit elements were calculated. According to synchronous speed of motor and number of pulses per revolution, the frequency of pulses at synchronous speed is calculated as:

<table>
<thead>
<tr>
<th>Table 2 Specification of torque sensor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Accuracy class</td>
</tr>
<tr>
<td>Repeatability (DIN 1319)</td>
</tr>
<tr>
<td>Excitation voltage</td>
</tr>
<tr>
<td>Output signal range</td>
</tr>
<tr>
<td>Temperature range</td>
</tr>
<tr>
<td>Measuring range</td>
</tr>
<tr>
<td>Angle impulses output signal</td>
</tr>
<tr>
<td>Angle control 360 impulses, 2 traces, 90° displaced</td>
</tr>
</tbody>
</table>

Fig. 3 Experimental model of induction motor and torque sensor.
\[ f_s = \frac{n_e}{60} \times n_A = \frac{1500}{60} \times 360 = 9000 \text{ Hz} \]  \hspace{1cm} (9)

where:

- \( f_s \) is frequency of pulses at synchronous speed;
- \( n_e \) is speed of rotor, rpm;
- \( n_A \) is number of pulses per revolution in the channel A.

The greatest dimensional frequency is calculated as:

\[ f_{\text{max}} = 1.5 \times f_s = 1.5 \times 9000 = 13500 \text{ Hz} \]  \hspace{1cm} (10)

where: \( f_{\text{max}} \) is maximal dimensional frequency of converter.

Converter is elaborated according to the circuit, shown in Fig. 4.

Elements \( R_3 \) and \( C_3 \) comprise the filter of output signal. Resistance \( R_4 \) and \( R_5 \) are used to set up voltage value at which the input pulse is identified. Microchip is matched for required frequency by choosing capacitor \( C_1 \) and resistance \( R_1 \). According to recommendations, the capacitance value is chosen \( C_1 = 0.1 \text{ nF} \). At this capacitance resistance \( R_1 \) is calculated as:

\[ R_1 = \frac{1}{f_{\text{max}} \times C_1} = \frac{1}{13500 \times 10^{-10}} = 740 \text{ k}\Omega \]  \hspace{1cm} (11)

Designed converter is tested. For this purpose input pulses are generated by standard signal generator with variable frequency; the amplitude of pulses is chosen equal to that of sensor output. According to the test results the output characteristic of converter voltage is measured and plotted in Fig. 5.

Results indicate the output characteristic of converter being linear. Therefore, it fits requirements for measuring devices. Besides that, the maximal frequency, which is input of converter, can be greater than required, i.e. this converter can be used to measure higher speed of other motor.

According to characteristic in Fig. 5, the frequency at any output voltage can be calculated as:

\[ f = 1.2158 \times U_{\text{out}} - 0.0311 \]  \hspace{1cm} (12)

According to the measured frequency, the speed of the motor can be calculated.

Designed and elaborated converter is attached to the sensor. Step response of speed, presented in Fig. 6, is recorded by oscilloscope.

The angular frequency is calculated as:

\[ \omega = \frac{f \times 1000}{360} \times 2 \times \pi \text{ rad/s} \]  \hspace{1cm} (13)

5. Conclusions

Designed and elaborated converter for experimental testing of motor transients has linear characteristic and
can properly operate in the speed range from zero to synchronous.

According to experimentally measured time response the inertia of motor can be determined experimentally. Designed converter for experimental measurement of speed can be used to verify elaborated models of electric drives.

References

General Economic Analysis about the Wind Farms Repowering in Spain

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Abstract: Environmental pollution and emissions from greenhouse gases caused by fossil fuel use are a threat to sustainable development. With renewable energy sources, no polluting emissions are released into the atmosphere. Therefore, using these sources on a large-scale is a key to reducing emissions and meeting the commitments established by Kyoto Protocol. Moreover, EU wants that the 20% of energy consumption is renewable in 2020. This study describes economic aspects, such as net present value and internal profitability rate, of the repowering process for the wind farms. Repowering can generate considerably more power with fewer facilities. This process was the result of a growing demand for renewable energies, facilitated by the great potential of wind energy in the north of Spain. The wind farms studied in this work were set up before 1998 and they had obsolete machinery with low power. There are strong indications that repowering is a profitable endeavour.

Key words: Repowering, viability study, wind farms, sensibility analysis, energy.

1. Introduction

One thing is clear: a lot of tons of CO₂ emissions are saved of being emitted to the atmosphere every time wind power is generated, avoiding coal, fuel, or natural gas combustion in one or several thermal power stations that would be working at a higher rate if there were not wind turbines.

During the last years, sector needs have varied and at this moment new horizons are being opened. Repowering allows increase of the total installed power of the farms, because the efficiency of new wind turbines is bigger. This process is regulated through the RD 661/2007, that it is in charge of controlling the power generation activity in special regime, and the Decreto 138/2010 in Galicia (northwest of Spain), which controls the authorizations.

Repowering a wind farm entails revamping its installations with the aim of extending its service life and/or increasing its power, performance or availability and increasing, modifying and/or updating the equipment for optimum capacity or efficiency.

2. Advantages

Given the constant advances made in wind and generator technology, it is now possible for the same site to have a much higher energy production with new machines [1].

They are quieter, their efficiency is higher (2 or 3 MW), and their start-up speed (winds of 2.5-3 m/s) are much lower when compared with older turbines (0.1-0.65 MW, with start-up wind speed of 5 m/s).

Moreover, higher hubs on the new machines make it easier to exploit the wind at great heights. For this reason, repowering a wind farm leads to a noticeable increase in farm production, although the number of generators installed is reduced [2].
With repowering it is possible to generate considerably more electric current with fewer installations. On the other hand, as the new installations work at lower speeds, their appearance is more calming [3].

This makes their utilisation more feasible. Therefore, repowered sites are [4-6]:
- More productive with fewer machines;
- Less difficult to integrate into the grid;
- Easier on the ear and eye;
- The maintenance costs for air generators with over ten years of service increase by 25%. Replacing machines after ten years, once initial costs have been recovered, makes it possible to have newer and more advanced equipment for a significant number of years;
- The first wind farms used the highest wind measurements; nowadays production can be greater.

3. Disadvantages

However, in Spain there are some disadvantages about repowering a wind farm [4, 7, 8]:
- Excessive regulation (national and regional);
- Conflicts of competition between administrations;
- Problems relating to network access;
- The need for this guarantee in various administrations to pursue the same purpose;
- Lack of certainty as to the remuneration framework applicable.

And this leads to deadlines for authorization too long and difficulty to obtain finance.

4. Repowering the Wind Farms

Wind turbines under study have a similar power because the farms were built as late in the year 1998.

A technical and economic feasibility study on the repowering process is carried out and various alternatives are considered: A, B, C, D, E, F, G, H and I (see Table 1). For the second step, the relevant Spanish legislation [9, 10] must be taken into account; this regulates the activity of energy production within a special regime. It establishes that, for an increase of up to 40%, a new license is not needed, providing that the transmission power cited in the original permit is not exceeded. At first it might be thought that increasing the power by 100% is very profitable, and rightly so.

Nevertheless, with the current system for issuing permits, it is extremely difficult to get a new one, despite the fact that repowering takes precedence.

Consequently, the options are described in Fig. 1.

It is needed to say that the electric power authorised is 17 MW to San Xoán and 26 MW to Bustelo.

Option 3 is not possible in technical terms. The volume of wind generators that would need to be installed for this option is very high; they would not fit on the site given the minimum distances required between wind towers.

Option 4 was chosen instead. As many wind towers as technically possible will be installed, always bearing in mind that the maximum limit of 50 MW can not be exceeded.

On the other hand, three models of wind generators with similar features will be studied: the N80 at 2.5 MW from Nordex; the B80 at 2.3 MW from Bonus and the N90 at 2.3 MW from Nordex, all of which have towers that are 80 m high.

The four options mentioned above will be considered for each model. These options will also condition how many of each model is chosen. Given that the third is not viable, only OPTIONS 1, 2 and 4 will be examined.

There are, therefore, nine possible alternatives, indicated from A to I, as shown in Table 1.
Table 1  Alternatives under study.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N80 2.5 MW</td>
<td>B80 2.3 MW</td>
<td>N90 2.3 MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option 1</td>
<td>Option 2</td>
<td>Option 4</td>
<td>Option 1</td>
<td>Option 2</td>
<td>Option 4</td>
<td>Option 1</td>
<td>Option 2</td>
<td>Option 4</td>
<td>Option 4</td>
</tr>
</tbody>
</table>

5. Wind Resources

One of the main factors for the construction of a wind farm is determining annual energy production. It is already known that the wind farms that have interest in this study are good sites for wind energy; indeed, they were among the first farms in Galicia.

To start with, a comparison was made of various wind generator models with similar features in terms of power, specifically:

- N80 at 2.5 MW from Nordex, with 80 m of rotor diameter and with four possibilities of tower height: 60 m, 80 m, 100 m or 105 m;
- N90 at 2.3 MW from Nordex, with 90 m of rotor diameter and with three possibilities of tower height: 80 m, 100 m and 105 m;
- B80 at 2.3 kW from Bonus, with 82.4 m of rotor diameter and with two possibilities of tower height: 60 m and 80 m.

However, for the calculation was practical, it is necessary to compare models with a tower height of 80 m, the common size of the three models. The highest ones are lattice towers, which mean greater safety for future maintenance work.

As the new height (80 m) differs from the one for which the wind speeds were taken, a new conversion has to be carried out. Thus, the speed for the new height is 10.73 m/s.

One might at first think that model N80 at 2.5 MW would have a higher production. However, this is not the case, as shown in Table 2. The N90 at 2.3 MW has a larger rotor diameter, which would mean a higher annual production.

Taking into account this calculation and using annual production as criteria, it is concluded that the wind generator model chosen will be the N90 2.3 MW from Nordex. Its annual production would be 11,097,610 kWh/year, far above that of the original generators.

With the same programme, energy production is also calculated (kWh/year) for each model. The results are presented in Table 3.

6. Viability Study

To find out which alternative is the most economically viable, it will be necessary to take into account the recovery period for each. In this way, the best alternatives are C and G, whose recovery periods are five years, as well as H and I, at four years, as shown in Table 3.

After the viability study for nine alternatives is done, it can be concluded that, in economic terms, alternative G stands out. C, H and I require a new transmission licence, difficult to obtain. Alternative G has the best recovery period and does not require a transmission licence.

Another factor is project financing, which may or may not be obtained. If financing is not sought, the recovery period would be seven years, whereas it is reduced to five with financing. For a later sensitivity analysis, a financed project will be examined so that a briefer recovery period is needed.

Alternative G, with the lower recovery period (five years), will be studied. Its profitability would be 29.16%, and, moreover, it does not require a new transmission licence. This alternative would entail a total contract cost of 65 M€.

As mentioned earlier, alternative G is the nordex N90 2.3 MW generator.

Although it stands out in the economic viability study, technical results also have to be taken into account, under the heading Wind Energy Resources. Here it is also concluded that the N90 2.3 MW model is the most suitable.
Table 2  Results for the models with a 80 m tower.

<table>
<thead>
<tr>
<th>Model</th>
<th>N80 2.5</th>
<th>B80 2.3</th>
<th>N90 2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower height (m)</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
<td>80</td>
<td>82</td>
<td>90</td>
</tr>
<tr>
<td>Input power (W/m² rotor area)</td>
<td>1.347</td>
<td>1.347</td>
<td>1.347</td>
</tr>
<tr>
<td>Max. speed input power (m/s)</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Av. speed wind at hub height</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Power at output (W/m² rotor area)</td>
<td>240</td>
<td>224</td>
<td>199</td>
</tr>
<tr>
<td>Energy produced (kWh/m²/year)</td>
<td>2,104</td>
<td>1,964</td>
<td>1,744</td>
</tr>
<tr>
<td>Energy produced (kWh/year)</td>
<td>10,575,053</td>
<td>10,471,136</td>
<td>11,097,610</td>
</tr>
<tr>
<td>Load factor (%)</td>
<td>48</td>
<td>52</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 3  Summary of the results.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. w/o financing</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>P. financed</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

The results in relation with payback period, NPV and IRR have been calculated with Oracle Crystall Ball Tool and they are shown in Figs. 2-4.

As it can be seen that the payback period is very short in relation with the amount of money moved, around 60 M€.

7. Sensitivity Analysis

Together, the increase in energy sold, the average rate and the financing percentage make the project more viable. In other words, the NPV (net present value) and internal profitability rate go up, while the recovery period is reduced. Nonetheless, increases in implementation costs, exploitation costs and the interest rate weaken the project’s viability.

The viability analysis indicates that the variables that have the greatest influence on the results are, above all, the quantity of energy sold each year, and, to a lesser extent, variations in the average rate, as shown in Fig. 5. These two variables, therefore, are the ones to take into account when making final decisions.

8. Conclusions

A number of advantages have been determined in this analysis.

Economically, the original generators are sold for scrap or to another country, perhaps in Eastern Europe. The copper content of the cabling can be sold. It is also possible to exploit the original roadways and foundations, which, once broken up, can be used for the farm’s expansion. With the various rates, the productivity and earnings will increase; in the future, repowered farms may receive a premium.
Environmentally, there is a significant reduction in the number of wind generators, so that the visual and acoustic impact are also lessened. This form of energy is cleaner than others.

The change from 124 for 330/325 kW to 18 for 2.3 MW means an annual increase of 82 GWh, 6.6 M€ more a year.

There are strong indications that repowering is a profitable endeavour, whose costs can be recovered in five years. This is mainly due to the sharp increase in the production of each generator or, rather, the more efficient exploitation of the wind at the site.

References

Active Field Canceling System in Next Generation Nano-Fab

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Abstract: ELF (extremely low frequency) magnetic fields from power-line current influence the yield of CMOS foundry. The poor yield happens because of ELF magnetic fields inducing directly the measurement or process equipment for cutting-edge chips below 28 nm process. The equipments of electron microscopes, including SEM (scanning electron microscope), TEM (transmission electron microscopy), STEM (scanning transmission electron microscopy) and EBLS (electron beam lithography system) are very susceptible to ELF magnetic fields emanating from various electrical power sources outside of the building and within next generation CMOS foundry recommends a maximum of 0.3 mG. The active canceling method uses active coils with current sensing field via sensor and inducing man-made electromagnetic field to reduce the stray magnetic field. Unfortunately, the conventional system takes more time to products field because of parasitical capacitance and resistance in long coil. The longer canceling coil the system construct, the more time it takes. Besides, canceling system should spend more time on calibrating non-linear current amplifier through software design. This research designs simpler anti-electro-magnetic system instead of typical frame and develops one turn canceling coil structure to reduce delaying time. Several parallel cells generate field up to 23.81 mG controlled by MPU (micro processor unit). This system decreases the power-line inducing filed below 0.3 mG.

Key words: Extremely low frequency, power-line current, CMOS foundry, passive shielding, actives shielding, hybrid shielding.

1. Introduction

EMI (electromagnetic interference) is the critical influence on EBLS (electron beam lithography system) because of the pattern with very narrow width of a few nanometers scale and complexity of much semiconductor factory equipment that is used for IC (integrated circuit) and mask productions [1]. High performance EBLS are very sensitive to changing ambient magnetic fields (B) because magnetic forces from the power-line affect the electro-beam position on a specimen surface as shown in Fig. 1. The ambient field over 20 mG from power-lines currents moves the beam causing loss of resolution and measurement accuracy as shown in Fig. 2 [2]. Protection for EBLS against magnetic field is necessary as there is pollution in nano-fab and that generated by current flow near power-line frequency within equipments and facilities. The standard of SEMI-E34 defines extremely low frequency about 1 Hz to 1 kHz and the sensitivity levels of equipment whose performance is adversely affected by ELF (extremely low frequency), such as a SEM (scanning electron microscope) or EBLS [3].

Corresponding author: Yu-Lin Song, Ph.D., research fellow, research fields: designed active canceling, passive shielding and hybrid canceling technology to reduce electromagnetic interference. E-mail: d87222007@ntu.edu.tw.
Fig. 1 Outline of electron-beam lithography system.

Fig. 2 EMI noise effect inaccurately dimension on SEM.

Fig. 3 Principle of active shielding.

2. Conventional Magnetic Field Canceling System

Conventional magnetic field canceling system shown in Fig. 4 consists of three steps. They are sensor signal processing step, control step and magnetic field generator step.

Step1: sensor signal processing
The MRS (magnetoresistive sensor) senses the outside magnetic field varies from power-line current. The different B amplitude is amplified by OP (operational amplifier), reduces the noise through LPF (low pass filter) and converts analog into digital signal via ADC (analog-digital converter).

Step2: algorithm and controlling
The controller comprises MPU (micro processor unit) and CA (current amplifier). The algorithm calculates the optimal amplitude of the compensation current from ADC at MPU. The algorithm control adjusts compensation current depended on ambient electromagnet interference sensing from sensor. The current amplifier function is amplified compensation current and drives a current through its coils to generate a field to canceling ambient field at next step.

Step3: magnetic field generator
The strength of magnetic field (B) is generated at a point in space. In the case of the Helmholtz coils [14], the field points of interest are located in the mid-plane between the two coils. As shown in Eq. (1), the strength of the magnetic field is dependent upon three quantities: the compensation current I_{com}, the number of turns N in coils, and the radius a of the coil.
where: $a =$ radius of the coils = separation between the
 coils; $B =$ magnetic field at the mid-plane.

3. Proposed Circuit and Control System

Functional blocks of proposed magnetic field
canceling system shown in Fig. 5, include MRS
readout circuit, field canceling control system and
digital magnetic field generator.

3.1 MRS Readout Circuit

The various resistances ($R_s$) sensing $B$ from MRS is
amplified and filters unnecessary noises from
switches-capacitor circuit. After processing via filter,
the different frequency from VCO (voltage control
oscillator) passes to programmable divider and non-
overlapping block. The feedback frequency $Q^+$ and
$Q^-$ takes from two phases of a non-overlapping circuit.
The dissimilarity from sensor transfers to resistance
$R_{sc}$ depends on frequency taken from SCR
(switches-capacitor resistance) block. This system
stops adjusting oscillator frequency while the
difference of $R_s$ and $R_{sc}$ is zero in frequency
converter voltage block.

(a) Frequency converter voltage circuit

The proposed MRS reads out circuit as shown in Fig.
6. Here variable resistor and DAC (digital to analog
converter) are added at terminals in frequency
converter voltage block. The different frequency from
VCO, divider, and non-overlapping blocks controls
SCR (switches-capacitor resistance) are shown in Figs. 7
and 8.

(b) Subtractor and low pass filter

The difference amplifier formed by OP, it is
associates resistors and capacitors, which senses the
different voltages ($v_1-v_2$) and provides a proportional
output voltage $V_c$, as shown in Fig. 9. The low pass filter parameters, including $R_c$ and $C_c$, are decision factor in this system. The gain of this block is:

$$ A = \frac{1}{S C_c R_c} \left( 1 + \frac{2 R_b}{R_a} \right) $$  \hspace{1cm} (2)

(c) Programmable divider

Frequency divider is an essential component in synthesizer. Usually, the divider is based on dual-modulus prescaler. To achieve wide divide ratio, it needs additional counters, but the power dissipation and complex layout is still a problem. Thus, we use a programmable divide-by-2/3 prescaler [15] as shown in Fig. 10a. As long as Modin = 0, the prescaler divides 2. When Modin turns to 1, it divides 3 as $p = 1$ and divide 2 as $p = 0$. In Fig. 10b, the whole architecture consists of eight divide-by-2/3 prescalers, a 3-to-8 MUX, and 12 OR gates, all of them implement with MCML (MOS current mode logic) because of its better EMC properties (Fig. 10c). The binary control of D0-D8 can determine division from 2 to 300, and the 3-to-8 MUX selects the output $F_{out}$.

$$ \text{Divide ratio} = 256 \times D_8 + 128 \times D_7 + 64 \times D_6 + 32 \times D_5 + 16 \times D_4 + 8 \times D_3 + 4 \times D_2 + 2 \times D_1 + D_0 $$  \hspace{1cm} (3)

This circuit takes programmable divider signal and generates a two-phase non-overlapping clock, $Q+$ and $Q-$. The separation is set by the delay through one inverter as delay cell on the M1 input gate as shown in Fig. 11.

Fig. 9  Subtractor and low pass filter.

Fig. 10  (a) 2/3 cell; (b) wide range frequency divider; (c) MCML and-latch logic circuit and nonoverlapping clock generation circuit.

Fig. 11  Non-overlapping clock generation circuit.
3.2 Magnetic Field Canceling Control System and Digital Field Generator

The input of the MPU is the ambient field strength detected signals orthogonal direction in real time and computes correctly the compensation current Icom. The output of the MPU is the binary control of D0-D6 substitutes as the compensation current Icom, and fed the binary control into seven cells which created opposite field as shown in Fig. 12. The binary control of D0-D6 can generate field from 0 to 23.81 mG counted by Eq. (5) during turning on M1-M7 by binary control of D0-D6 is high. The structure of cell was shown in Fig. 12. They are mos switch M1, resistor R1, R2 and RL, one turn coil to products canceling field and commercial power amplifier which product number is IRF630. During turning on M1, the biasing voltage of power amplifier is obtained by R1, R2 and RL, and carrying a compensation current Icom which generates field. The artificial field changes when altering R1.

\[
\text{Generate field} = 12 \times D6 + 6 \times D5 + 3 \times D4 + 1.5 \times D3 + 0.75 \times D2 + 0.37 \times D1 + 0.19 \times D0 \quad (4)
\]

4. Simulation and Experiment

4.1 Simulation

In Fig. 13, field induces from the power-lines by simulating a 60 Hz sinusoidal wave and the amplitude is 20 mG at the position of sensor. Fig. 14a shows a quarter wave from the Fig. 13. It is now a DC (direct current) forming digital magnetic field in Fig. 14b, and with compensation of the 10 kHz frequency in Fig. 14b detects the change in the field. It finishes the measurement of the points and then continues to find the optimal canceling field. The proposed system decreases the power-line inducing filed below 0.3 mG in Figs. 15 and 16 through SPICE.

4.2 Digital Magnetic Field Generator Experiment

Table 1 shows the experimental result in Eq. (4) for digital magnetic field generator block. The output of the MPU is the binary control of D0-D6 and the experimental result is shown in Table 1. The binary control of D0-D6 set (0 0 0 0 0 0 1), this block generates field 0.19 mG as below shows.

4.3 Canceling System Experiment

This system decreases the power-line inducing filed from 12.65 mG down to 0.4 mG measured via Chauvin Arnoux CA42 Field-meter as shown in Figs. 17a and 17b.

![Fig. 12](image)

(a) Digital field generator; (b) the cell of field generator.

![Fig. 13](image)

Simulate 60 Hz sin wave and the amplitude is 20 mG.
Table 1  Digital magnetic field experimental results.

<table>
<thead>
<tr>
<th>Binary control (D0-D6)</th>
<th>Generated field (mG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0 0 0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 0 0 0 0 1</td>
<td>0.19</td>
</tr>
<tr>
<td>0 0 0 0 0 1 0</td>
<td>0.37</td>
</tr>
<tr>
<td>0 0 0 0 1 0 0</td>
<td>0.75</td>
</tr>
<tr>
<td>0 0 1 0 0 0 0</td>
<td>1.5</td>
</tr>
<tr>
<td>0 0 1 0 0 0 0</td>
<td>3</td>
</tr>
<tr>
<td>0 1 0 0 0 0 0</td>
<td>6</td>
</tr>
<tr>
<td>1 0 0 0 0 0 0</td>
<td>12</td>
</tr>
<tr>
<td>1 1 1 1 1 1 1</td>
<td>23.81</td>
</tr>
</tbody>
</table>

5. Conclusions

The proposed system combines MRS readout circuit, field canceling control system and digital magnetic field generator for power-lines. The software in MCU controlled for active magnetic shielding and the significant results could reduce magnetic field to 0.3 mG for the considered EBLS. The active shielding is very flexible and that can be used completely in closed-loop modes, with input from magnetic field sensors. This research designs simpler anti-electro-magnetic system instead of typical frame and develops one turn canceling coil structure to reduce delaying time.

References


Novel Method for Optimal Location of STATCOM in Distribution Systems Using Sensitivity Analysis by DlgSILENT Software

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Abstract: In this paper a new method has been proposed to decide optimal placement and best sizing of STATCOM (static synchronous compensator). The best place of STATCOM is found using the sensitivity analysis and optimum sizing of STATCOM is managed using the genetic algorithm. The average model can account for the high-frequency effects and power electronic losses, and more accurately predict the active and reactive power outputs of the STATCOM. This paper employs the DlgSILENT simulator and DPL (DlgSILENT programming language) as a programming tool of the DlgSILENT to show the validity of the proposed method. The effectiveness of suggested approach has been tested on part of the distribution network of Iran, Khoramdarreh city in Zanjan province.

Key words: Average model, optimal placement, genetic algorithm, sensitivity analysis, STATCOM.

1. Introduction

In recent years, with increasing development in power networks, the economical operation of power system is more considered. Because deregulation and restructuring of the electricity markets use of FACTS (flexible AC transmission systems) devices is inevitable. The maximum capability of power systems can be exploited by means of FACTS devices. Nowadays, development of power electronics switches causes reduction in the cost of FACTS and therefore, application of FACTS devices especially in distribution networks is more economical.

Because of the economical considerations, installation of FACTS controller in all of the buses is impossible and unnecessary. There are several methods for finding optimal locations of FACTS devices in power systems [1-7]. In Ref. [1], a sensitivity approach based on line loss has been proposed for placement of series capacitors, phase shifters and static VAR compensators. In Ref. [2], a GA (genetic algorithm) based method is used to determine the optimal sitting of FACTS controller in power system. The fitness function is to minimize the generation cost. In Ref. [3], the genetic algorithm is used to seek the optimal location of multi-type FACTS devices in a power system. The optimizations are performed on three parameters: the location of the devices, their types, and their values. In Ref. [4], the TS (tabu search) method is used to solve the combinatorial (i.e. to determine number and location) problem of FACTS device allocation. Ref. [5] compares three heuristic methods (SA (simulated annealing), TS and GA) applied to the optimal location of FACTS devices in order to enhance the system security. The objective function is based on indices quantifying the severity of the contingencies in terms of branch loading and voltage levels. The three methods lead to similar results, but generally TS and
GA converge faster than SA to an optimal solution. In Ref. [6], a real power flow performance sensitivity index has been proposed to decide optimal location of FACTS controllers. In Ref. [7], EVPA (extended voltage phasors approach) is proposed for placement of FACTS controllers in power systems within the voltage stability viewpoint.

Most of the previous works have been done, standard benchmark networks with only a limited number of buses are used for testing their suggested algorithms. Therefore, some special difficulties and problems of these simulations have not been predicted definitely when they are applied in real networks. In addition, transmission systems (high Voltage levels) have been used in former studies and few researches on distribution networks have been accomplished.

In this paper a new method has been proposed for optimal placement of STATCOM in distribution networks. The suggested approach is composed of sensitivity analysis and the genetic algorithm. The search space in optimal placement of compensators problem is very sizable, especially in distribution systems. Use of the approaches like sensitivity analysis can reduce the search space. It is also essential to model STATCOM to be adapted for the power flow program. In previous studies on placement of STATCOM, the STATCOM is traditionally modeled for power flow analysis as a PV or PQ bus depending on its primary application. The active power is either set to zero (neglecting the STATCOM losses) or calculated iteratively. Using average theory, STATCOM can be modeled in power flow analysis carefully and calculation of accurate losses of STATCOM has been provided. Also, a real 20 kV distribution network with a large number of buses has been applied to test the algorithm. DIgSILENT software which contains a powerful programming language called DPL ¹ has been prepared required facilities to execute the proposed algorithms and corresponding simulations.

2. Average Model of STATCOM

Averaging technique is a common approach to the modeling of power converters [8]. Switch-mode converters have a discontinuous behavior which is analytically very complex. There exists a set of SSE (state space equations) that mathematically models the exact system. Thus, the number of switching periods during the synchronous period establishes the number of SSE to be analyzed. Averaging technique approximates the modulation of the converter DC/AC from a periodic discontinuous waveform to a periodic continuous one [9].

The angle $\alpha$ is defined as the phase separation between the fundamental components of output voltage of STATCOM and power system voltage at coupling bus. To provide the required active and reactive powers by STATCOM, $\alpha$ varies in a small nonzero region around zero ($\alpha \in [-1.5^\circ, 1.5^\circ]$). Equivalent circuit average model of STATCOM is shown in Fig. 1, including time-dependent sources [8].

The total power losses of STATCOM is function of the phase shift between the converter output and the power system voltage ($\alpha$) and can be obtained by the average model in steady state. The circuit in Fig. 1 was analyzed at various angles $\alpha$ to obtain the losses of STATCOM. The simulation of this circuit was programmed by MATLAB. Fig. 2 shows STATCOM power losses $(P)$ as a percentage of STSTCOM rating $(Q)$ against the phase shift $(\alpha)$ that is obtained by the average model.

In Fig. 1, functions $f_1$ and $f_2$ represent two linear combination of the three-phase power system phase-neutral voltages $(v_a(t), v_b(t)$ and $v_c(t))$ as follows:

$$f_1(V(t)) = 2v_a(t) - v_b(t) - v_c(t)$$

$$f_2(V(t)) = 2v_b(t) - v_a(t) - v_c(t)$$

Besides, two dependent voltage sources $g_1$ and $g_2$ are defined by:

$$g_1(D(t), V_c) = (2D_a(t) - D_b(t) - D_c(t))V_c$$

$$g_2(D(t), V_c) = (2D_b(t) - D_a(t) - D_c(t))V_c$$

And two dependent current sources $h_1$ and $h_2$ are:

$$h_1(D(t), i_a(t)) = (D_c(t) - D_a(t))i_a(t)$$

1 DlgSILENT programming language.
Novel Method for Optimal Location of STATCOM in Distribution Systems  
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![Equivalent circuit average model of STATCOM.](image1)

**Fig. 1** Equivalent circuit average model of STATCOM.

![Percent of losses (P/Q) of STATCOM.](image2)

**Fig. 2** Percent of losses (P/Q) of STATCOM.

\[ h_{2}(D(t), i_{b}(t)) = (D_{a}(t) - D_{b}(t))i_{b}(t) \]  
where \( D_{a}(t), D_{b}(t), \) and \( D_{c}(t) \) are the three-phase duty ratio functions [9].

Whereas the average model presents a time-dependent circuit, a phasor PQ or PV model is essential for the power flow analysis. Hence, here it is performed adaptive analysis to get the supplied active and reactive powers of STATCOM \( (P_{CON} \text{ and } Q_{CON}) \). A new bus is added for every STATCOM as the converter AC voltage, which is connected to an existing bus \( n \) through the commutation reactance \( (X_{CON}) \) and the AC resistance \( (R) \). Ignoring \( R \) for big \( X_{CON}/R \) ratios, the active and reactive power of the compensator can be obtained by the well-known power relationships for two buses that are connected through a connecting reactance:

\[ P_{CON} = \frac{V_{CON}}{X_{CON}} \sin(\alpha - \frac{\pi}{M}) \]  
\[ Q_{CON} = \frac{V_{CON}}{X_{CON}} (V_{CON} - V_{i} \cos(\alpha - \frac{\pi}{M})) \]

where \( V_{i} \) and \( V_{CON} \) are the magnitude of the fundamental voltages of bus \( n \) and the converter AC bus respectively. Fig. 3 describes the power flow model, including the above parameters. \( P_n \) and \( Q_n \) are active and reactive powers of the power system at bus-\( n \) [9].

### 3. Sensitivity Analysis for Optimal Placement of STATCOM

Many sensitivity performance indices have been proposed for the analysis of power systems. There are two sensitivity indices which have the most attraction for optimal placement of reactive power sources.

#### 3.1 Voltage Sensitivity Index

WNVSI (weighted normalized voltage sensitivity index) at bus-\( i \) is defined as [10]:

\[ WNVSI_{i} = w_i \times \frac{\partial V_{j}}{\partial Q_{j}} \times \frac{Q_{base}}{V_{base}^{2}} \quad i = 1,2,\ldots,N_{Load} \]  

\( V_{i} \): voltage magnitude at bus \( i \);  
\( Q_{i} \): reactive load at bus \( i \).

Where, the superscript base represents the base case. This index includes two components. The BPLW (bus power load weight) is defined as [10]:

\[ w_i = \frac{Q_i}{\sum_{k=1}^{n} Q_k} \quad i = 1,2,\ldots,N_{Load} \]  

And the NLSI (normalized local sensitivity index) is defined as [10]:

\[ SN_{j} = \frac{\partial V_{j}}{\partial Q_{j}} \times \frac{Q_{base}}{V_{base}^{2}} \quad i = 1,2,\ldots,N_{Load} \]  

If weighted factor is not used in voltage sensitivity index, sensitivity analysis will cause to select buses which have low reactive load and exist at the end of minor branches. These buses are not qualified for installing compensators economically. In fact, the weighted factor \( w_i \) causes voltage sensitivity index from a local index out completely.
3.2 Loss Sensitivity Index

Loss sensitivity index can be used for initial choosing the buses of power system which require compensation of the reactive power. A system having \( N \) buses, first \( N_g \) being the generator buses and \( N_g + 1, \ldots, N \) as the load buses is considered. The LSI (loss sensitivity index) with respected to reactive power output of a source placed at a bus-i, has been defined as [11]:

\[
a_i = \frac{\partial P_{Loss}}{\partial Q_i}, \quad i = N_g+1, \ldots, N
\]

where, \( Q_i \) is the reactive power injected at the load bus i, \( P_{Loss} \) is the real power transmission loss of the system. A reactive power source should be placed at a load bus-i, having most negative sensitivity index \( a_i \).

3.3 Introducing a New Combination Sensitivity Index

The use of only loss sensitivity index to find optimal placement of compensators may cause to select the places having low reactive load. Hence, these places are not seemed suitable location for compensation economically. However, WNVSI proposes suitable places apparently, but because reducing of the system losses which is one of the main goals of optimization is not considered, this index is not a complete criterion to choose the optimum locations.

To solve the defects mentioned above, a novel index considering optimization goals in this paper has been introduced. Considering improvement of voltage profile and reduction of system losses are the main goals of optimization in this paper, proposed index which is called compound voltage-loss sensitivity index, has been defined as:

\[
VLSI(j) = \alpha \times VSI(j) + \beta \times LSI(j) \quad j = 1, 2, \ldots, N
\]

where, subscript \( n \) demonstrates normalized values; \( j \): the number of buses; VSI: voltage sensitivity index; LSI: loss sensitivity index; \( \alpha, \beta \): weight factors.

The index calculation is in the way that firstly, voltage sensitivity analysis is executed and VSI is defined for all buses as:

\[
VSI(j) = \frac{Q_j}{Q_i} \frac{\partial V_j}{\partial Q_j}
\]

Where, \( Q_i \) is total reactive loads of system. Then \( VSI_{min} \) and \( VSI_{max} \) are specified by sorting the VSI values, normalized voltage sensitivity index is defined as:

\[
VSI(j) = \frac{VSI(j) - VSI_{min}}{VSI_{max} - VSI_{min}}
\]

In the next stage, loss sensitivity analysis is executed for all buses and normalized loss sensitivity index is calculated as:

\[
LSI(j) = -\frac{\partial P_{Loss}}{\partial Q_j}
\]

\[
LSI_{n}(j) = \frac{LSI(j) - LSI_{min}}{LSI_{max} - LSI_{min}}
\]

The weight factors \( \alpha, \beta \) represent the significance of each one of the goals, improvement of voltage profile and reduction of system losses in optimization problem. It is clear that other important optimization goal, i.e. decrease in reactive power of network has been concealed in \( \frac{Q_j}{Q_i} \) coefficient which is applied in VSI and a separate index is not needed.

3.4 Step-by-Step Sensitivity Analysis for Optimal Location of STATCOM

In suggested approach, first, sensitivity analysis has been performed on the network and compound voltage-loss sensitivity index or VLSI is calculated for all buses. Then based on sensitivity analysis, the most sensitive bus of network has been added to the list of installing places of compensators. After that, the amount of reactive load at the selected bus has been chosen to zero. In fact, compensator has been installed at this bus as much as reactive load. This procedure causes sensitivity of this bus and adjacent buses to be reduced. Therefore they are not chosen again in the next iterations. Then sensitivity analysis on the network (with new conditions) has been executed again and most sensitive bus has been elected to add it to the...
list of installing places of compensators. This procedure will continue in the same way so that the number of places in the list equals the number of compensators which is required.

4. Optimal Sizing of STATCOM Using the Genetic Algorithm

The genetic algorithm has been used to find the optimum sizing of STATCOMs. Genetic algorithms are based on the mechanisms of natural selection. The principles and details of the genetic algorithm have been presented in many references [2, 3].

4.1 Objective Function

The objective function has been made from the three terms by the following relationships:

Minimize:

\[ F = P_{\text{Loss}} \times Q \times VF \]  

where:

- \( P_{\text{Loss}} \): Total real power transmission loss of the system;
- \( Q \): Total input reactive power in the 63/20kV substations;
- \( VF \): Voltage factor.

This objective function is including improvement of voltage stability, reduction of loss and reduction of reactive power of network. The \( VF \) coefficient demonstrates the condition of network from the viewpoint of voltage stability. This coefficient is calculated with the relation:

\[ VF = K_v \cdot \sum_{i=1}^{K_v} |u_{vi} - u_{vi}^*| \]  

\( K_v \): The number of buses out of admissible voltage limit;

\( u_{vi} \): Voltage of buses out of admissible voltage limit in per unit.

The stability of network at viewpoint of voltage is better for the fewer amount of \( VF \). Only the steady state stability in this paper was considered.

4.2 Initial Population

Some responses as chromosomes of initial population must be created for starting algorithm. The length of each chromosome (the number of genes formed a chromosome) is the number of required compensators. In fact, every gene is a number between 0-2 with four decimal places and shows exact size of each STATCOM in per unit.

4.3 Selection Operator

The best solutions in the current population are selected by roulette wheel technique.

4.4 Crossover Operator

Two random chromosomes in the middle generation are selected. Then a random number (n) between 1 to the length of chromosome are selected and pairs of selected chromosomes from n-th gene to later are swapped to each other to produce new chromosomes.

4.5 Mutation Operator

To test each element for fitness and to avoid algorithm stopping at a local optimum some solutions are also randomly modified. Therefore, a chromosome is selected randomly and then some of its genes are replaced with another random numbers.

5. Numerical Results

The proposed algorithm is tested on part of the distribution network of Iran, Khoramdarreh city in Zanjan province. After the implement of algorithm on Khoramdarreh network, 10 optimum places are selected for installing of STATCOM. Fig. 4 shows situation of these places on the network. With consideration of the Fig. 4, the compression of compensators in area-A can be observed. By analyzing the curve of voltage profile, it was clear that these points have the most voltage drop in the network. Therefore, they have been considered to install the compensators.

Table 1 shows the rating of STATCOMs and priority of them to install in the network. In this table, \( Q_{\text{Flow}} \) demonstrates reactive power flow at the corresponding
Novel Method for Optimal Location of STATCOM in Distribution Systems
Using Sensitivity Analysis by DlgSILENT Software

Fig. 4 Proposed locations for installation of STATCOM.

Table 1 The rating of STATCOMs and priority of them to install.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Q_{flow} [kVar]</th>
<th>Q_{STATCOM} [kVar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106.52</td>
<td>146.39</td>
</tr>
<tr>
<td>2</td>
<td>158.70</td>
<td>209.59</td>
</tr>
<tr>
<td>3</td>
<td>154.04</td>
<td>224.83</td>
</tr>
<tr>
<td>4</td>
<td>120.86</td>
<td>132.81</td>
</tr>
<tr>
<td>5</td>
<td>115.79</td>
<td>162.50</td>
</tr>
<tr>
<td>6</td>
<td>116.82</td>
<td>171.36</td>
</tr>
<tr>
<td>7</td>
<td>91.28</td>
<td>70.22</td>
</tr>
<tr>
<td>8</td>
<td>142.15</td>
<td>203.56</td>
</tr>
<tr>
<td>9</td>
<td>111.08</td>
<td>131.74</td>
</tr>
<tr>
<td>10</td>
<td>107.92</td>
<td>160.05</td>
</tr>
</tbody>
</table>

bus and Q_{STATCOM} shows the sizing of STATCOM. Table 2 shows the result of load flow calculation before and after compensation process. A reduction in active and reactive losses of network, improvement of voltage stability and increase in power factor of network represent effectiveness of compensation. The curves of voltage profile before and after compensation process is shown in Fig. 5. It is clear that voltage profile has improved after compensation. This improvement especially in the vicinity of STATCOM locations is more sensible.

6. Conclusions

In this paper a new method has been proposed for optimal placement of STATCOM in distribution networks. The suggested approach composed of sensitivity analysis and genetic algorithm. First, step by step sensitivity analysis approach has been utilized to find optimal placement of compensators. In this process, a compound voltage-losses sensitivity index to cover various aims of optimization requirements has been presented. The selection of buses close to each other in the network is prevented by step-by-step sensitivity analysis. In the next step the amount of reactive power injection of STATCOMs has been defined by GA. The objective function is made of voltage stability, reduction of active losses and reduction of reactive power of network. The average model has been applied to be adapted for the power flow program and to consider the accurate losses of STATCOM in placement study. The result of load flow calculation before and after compensation process shows improvement of voltage stability, reduction of active losses and reduction of reactive power of network.

References


Formation of a Quasi-Stationary Discharge in the Explosive-Emission Electron Sources

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Abstract: Formation of a quasi-stationary discharge or quasi-stationary emission mode in the explosive-emission electron sources is related to the current limitation resulting from the emissive ability saturation of cathode plasma with its expansion. The paper shows that in the process of the discharge current stabilization in the explosive-emission sources with the point- or blade-type emitters the essential role belongs to the electron beam space charge. Availability of the space charge results in limitation of the current growth velocity at the initial discharge phase and, hence, restricts the emissive ability of the cathode plasma and contributes to its saturation. In the vacuum diodes with multiemitter cathodes, the space charge availability increases the cathode operation stability and can provide obtaining of quasi-stationary beam current values or close to them resulting in formation of a plasma emission surface at the cathode close to the continuous one.

Key words: Explosive-emission electron source, point- and blade-type emitters, space charge of the beam, quasi-stationary mode.

1. Introduction

Explosive-emission electron sources are characterized by wide range of electron energies, currents and densities of electron beam current; however, they have limited current pulse duration. The reason of the pulse duration limitation is the rise of the interelectrode gap conductivity resulting from the cathode plasma expansion into the interelectrode gap with velocity of 10^6 cm/s, gas release from electrodes, and anode plasma formation [1-3]. However, there are conditions under which the velocity of the cathode plasma motion to the anode decreases to 10^3-10^4 cm/s and less. In the process, an electron source operates in a quasi-stationary emission mode, and a quasi-stationary high-voltage vacuum discharge is realized in the interelectrode gap. A stable quasi-stationary mode of operation is achieved when current is distributed among a large number of emitters made of the materials supplying a small amount of plasma into the interelectrode gap, the emitters are placed into a hollow electrode limiting the cathode plasma propagation in the transverse to the anode direction, and anode plasma is absent. Under these conditions, the duration of the electron beams which are obtained in the explosive-emission sources can reach 10^{-5}-10^{-4} s and more [4-8].

Availability of a steady-state quasi-stationary discharge in the interelectrode gap is related to the emissive ability saturation of the cathode plasma. The saturation is the result that the emission current becomes equal to the current withdrawn according to the 3/2 degree law, whereupon further propagation of the cathode plasma towards the anode is possible only as a result of increasing its emissive ability. A quasi-stationary current value is achieved when the cathode plasma propagates up to the limiting walls and a plasma emission boundary close to the solid one is formed at the cathode. Small time of the quasi-stationary discharge setting requires, however, high velocity of plasma motion in the transverse to the cathode. The plasma propagation velocity is limited by the cathode emissive ability and, hence, determines the quasi-stationary beam current value.
Formation of a Quasi-Stationary Discharge in the Explosive-Emission Electron Sources

anode direction [9] existence of which under conditions of the electron source is hardly probable.

There are the questions connected with the cathode plasma propagation to the limiting walls. In correspondence with Ref. [10], the cathode plasma disappears at the interaction with the cathode surface. As a result, the propagation of the cathode plasma from the emission center to the limiting walls is complicated.

In this connection, the paper considers a possibility of the e-beam space charge influence on the quasi-stationary discharge setting in the explosive-emission electron source. The space charge alongside with the emissive ability of plasma limits the current value in the interelectrode gap and, respectively, the current rise and thus promotes the discharge transition into the quasi-stationary mode. As opposed to the plasma motion, the process of the space charge formation in the interelectrode gap is characterized by the essentially higher velocity that can provide rapid approaching a quasi-stationary or close to its value of the current; the requirements to the plasma velocity being reduced. At high currents, a definite contribution into the quasi-stationary mode setting can be made as well by the self-magnetic beam field resulting in the space charge density increase and limiting the beam current rise.

2. Current Rise Limitation in the Sources with the Point- and Blade-type Emitters

Results of numerical calculations according to which the beam current value weakly depends on the cathode plasma dimensions testify to the possibility of the current rise limitation by the space charge in the diode with the point- and blade-type emitters. The current value data were obtained at calculations of the e-beam parameters in the diodes with cathodes with the point- and blade-type emitters installed at the plane [11] as well as in the diodes with a 5-blade cathode forming a electron beam with a plane symmetry and 2-blade cathode with a central point forming an axial-symmetric beam [12, 13]. The calculations were carried out using a Poisson-2 application software package.

In case of a single emitter, the cathode was supposed to be an infinite plane with the infinitely thin point or infinitely length blade of the height $h$ installed normally into this plane. Electron emission was realized from the surface of a plasma sphere or cylinder of radius $r$ the center or the axis of that coincide with the point top or blade edge. During calculations, the value of radius $r$, the gap between the point top or blade edge and anode plane $d$ were varied, the voltage at the diode was $U = 600$ kV.

In the diode with a multiply-emitter cathode, the diameter or width of the cathode were equal to 24 cm, periphery blades were installed perpendicularly on the plane at a 6 and 12 cm distance from the central blade or point (Fig. 1). The height of the emitters was equal to 3 cm, and the distances from the emitters to the anode were equal to 4 cm. Current values of the emitters $I_i$ and diode $I$ versus the plasma radius $r$ and diode voltage $U$ were calculated. The sizes of changing $r$ and $U$ were 0.3-1 cm and 600-800 kV, correspondingly.

Tables 1 and 2 present the obtained current values for a case of a point-emitter diode and for both variants of diodes with multiemitter cathodes for a number of parameter values. Here, $r_b$ is the beam radius

Fig. 1 Multiblade cathode diode schematic and electron trajectories for $r = 0.3$ cm and $U = 600$ kV.
Table 1  Electron beam parameters in a point-type cathode diode.

<table>
<thead>
<tr>
<th>h (cm)</th>
<th>d (cm)</th>
<th>r (cm)</th>
<th>I (kA)</th>
<th>r_b (cm)</th>
<th>i (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>0.3</td>
<td>1.8</td>
<td>5.7</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.3</td>
<td>1.3</td>
<td>6.6</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.3</td>
<td>2</td>
<td>6.8</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.6</td>
<td>2</td>
<td>4.8</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 2  Calculated current values in diodes with multiemitter cathodes.

<table>
<thead>
<tr>
<th>Diode</th>
<th>r (cm)</th>
<th>r_b (cm)</th>
<th>I_1 (kA)</th>
<th>I_2 (kA)</th>
<th>I_3 (kA)</th>
<th>I (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial-symmetric</td>
<td>0.3</td>
<td>600</td>
<td>32.7</td>
<td>9.4</td>
<td>0.7</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>800</td>
<td>60.9</td>
<td>17.5</td>
<td>1.4</td>
<td>79.8</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>600</td>
<td>53</td>
<td>14.4</td>
<td>1.2</td>
<td>68.6</td>
</tr>
<tr>
<td>With plane symmetry</td>
<td>0.3</td>
<td>600</td>
<td>42.3</td>
<td>25.6</td>
<td>13.5</td>
<td>149.3</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>800</td>
<td>73.8</td>
<td>35.6</td>
<td>26</td>
<td>244.8</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>600</td>
<td>64</td>
<td>34.6</td>
<td>18.5</td>
<td>215.7</td>
</tr>
</tbody>
</table>

at the anode, i is the point emitter current according to the formula [14]:

\[ i \approx 37 \times 10^{-6} U^3 \frac{v_f}{d - v_f} \]  

(1)

where \( v \) is the plasma velocity, \( d \) is the interelectrode gap, and \( t \) is the time. The values of the current emitted by each blade for multiemitter cathodes are presented here as well: \( I_1, I_2, I_3 \) are the currents from the extreme, medium and central blade or point, respectively (\( \Sigma I_i = I \)). Current values for a diode with 5-blade cathode are presented per 1 m of the cathode length.

The data presented here show that the diode current rise occurs more slowly than the plasma radius increase. Thus, in the diode with a single point-type cathode, the two-fold rise of the plasma radius (from 3 to 6 mm) at the diode voltage of 600 kV, point height of 3 cm and the distance from the point top to the anode of 3 cm results in the 1.7-fold rise of the beam current from 1.8 to 3 kA that is less than the expected 2.3-fold rise according to Eq. (1). In contrast to Eq. (1), the diode current value depends on the point height over the cathode plane: the point height increase from 3 to 4 cm at the same voltage, interelectrode gap and a 3 mm plasma radius results in the current rise up to 2 kA.

When the point operates in a multiemitter cathode, the current rise velocity of the point decreases additionally: the same 1.7-fold current rise is the result of a 3.3-fold increase of the plasma radius (from 3 to 10 mm). The current of the blade emitters increases still slower: depending on the position of the emitters in the cathode, the plasma radius increase from 3 to 10 mm results in the 1.37-1.6-fold current increase. The current of extreme blades increases more rapidly. Ref. [15] also indicated the weak dependence of the current on the plasma radius in the diode with a multiblade cathode.

Increase of operation stability of the emitters when they are joined in a multipoint cathode is observed in real diodes as well. Increase of the number of the operating points in a multipoint cathode, as a rule, results in the decrease of the growth rate of conductivity of the interelectrode gap and increase of the electron beam duration [16]. A possible mechanism of this may be formation of a collective space charge in the interelectrode gap when the current value of each emission center owing to crossing of electron trajectories is determined not only by the self space charge but also by the charge entering from the neighboring emitters. Availability of the space charge created in the diode by a large number of emitters prevents spontaneous current rise of separate points that explains the stabilizing effect of a multipoint-type cathode.

3. Approximate Current Calculation in the Diode with Point- and Blade-Type Emitters

Current rise limitation in the process of cathode plasma expansion under the action of a beam space charge was testified in Ref. [17] when fulfilling an approximate calculation of current in the diode with a cathode that is made in the shape of a single point or a blade on the plane.

The calculation was carried out in the approximation of electron motion along the electric field lines. Fig. 2 presents the diode geometry and the electric field pattern in the absence of the cathode plane and space charge in the interelectrode gap. Electron emission is realized from the plasma surface
with cathode potential. The surface is shaped as a cylinder or sphere of radius $r$ with an axis or center coinciding with the blade edge or point top, respectively. The distance from the emitter to the anode plane is $d$. At $r \ll d$ the arcs of the circles passing through the cylinder axis or sphere center may be considered as the force lines. It was supposed that the space charge distort the shapes of the force lines unessentially. Electron motion occurs in the current tubes along the force lines. Each of the tubes was considered as an element of the diode with electrodes in the shape of coaxial cylinders or concentric spheres with radii of the internal electrode $r_i$ and external $R_i = a_i + r$, respectively, where $a_i$ is the tube length.

Current value in the tube was calculated by means of the ratios for the current of cylindrical and spherical diodes [18]. In the range $r/R_i = 0.015-0.3$, the reverse values of transcendental functions of the formulas were approximated by the expressions (Fig. 3):

1. \[
\frac{1}{\beta^2} \approx 0.92 + 10 \left( \frac{r}{R_i} \right)^2
\] (2)

2. \[
\frac{1}{\alpha^2} \approx 0.27 + 2.9 \frac{r}{R_i}
\] (3)

Taking into account the latter, the expression for the diode current was the following:

1. \[
I \approx \sum_{i=1}^{n} 2.33 \times 10^6 \frac{U_j}{R_i^2} \left[ 0.92 + 10 \left( \frac{r}{R_i} \right)^2 \right] \times S_i
\] (4)

for a cylindrical diode and

1. \[
I \approx \sum_{i=1}^{n} 2.33 \times 10^6 \frac{U_j}{R_i^2} \left[ 0.27 + 2.9 \frac{r}{R_i} \right] \times S_i
\] (5)

for a spherical one. Here, $U$ is the voltage between the electrodes; $S_i$ is the cross section at the anode of a $i$-th current tube; $n$ is the number of the tubes.

**Fig. 2** Diode schematic.

**Fig. 3** Plots (1) and (2) of the approximation dependences (2) and (3), and values of the functions $1/\beta^2$ (3), $1/\alpha^2$ (4) [18].

In case of the point emitter, the beam radius at the anode was determined by the distance $d$ from the point top to the anode and by the point height $h$ [19]:

\[
r_b \approx 2\sqrt{h \times d}
\] (6)

The half-width of the beam in the diode with the blade-type emitter was chosen to be of the same order. The cathode plane influence was taken into account by means of limitation of the beam area at the anode according to Eq. (6) resulting in the decrease of the number of current tubes in Eqs. (4) and (5).

As followed from Eqs. (4) and (5), the diode current is proportional to the voltage in the degree of $3/2$. As opposed to Eq. (1), a direct proportional dependence between the value of the plasma sphere radius $r$ and current value in the diode is absent. Fig. 3 shows that as soon as $r/R_i$ increases, the growth of values of the $1/\alpha^2$ and $1/\beta^2$ functions and, respectively, of the diode perveance, both in case of the point- and blade-type cathodes, occurs with different velocities. Relatively high rise of perveance is observed in the region $0 < r/R_i < (0.015 \div 0.02)$. At further rise of $r/R_i$ the velocity of perveance change is low both in case of the point- and blade-type cathodes. This result indicates that the essential stabilization of the diode perveance is possible under the action of the beam space charge even when the plasma velocity is constant. At the length of the interelectrode gap equal to 5-10 cm, the plasma radius when the current rise decelerates is equal, respectively, to 0.75-2 mm. At the plasma velocity of $2 \times 10^6$ cm/s, the time of the rapid current rise equals to $3 \times 10^{-8}$-10^{-7}$ s, that is in good agreement
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with the experimental data [20]. As soon as this time is achieved, the current rise velocity decelerates sharply and weakly changes at further plasma expansion.

The received data show that the tendency to the current stabilization takes place when using the cathodes in view of emitting points or blades at the plane even in the absence of electrodes limiting the plasma expansion in the direction across the interelectrode gap. However, in practical constructions, current rise without using this type of electrodes is sufficient for increasing the concentration and motion of the cathode plasma that along with the anode plasma formation results in limitation of duration of the quasi-stationary discharge phase and breakdown of the interelectrode gap.

4. Influence of Current Rise Velocity on Plasma Emissive Ability

In accordance with Ref. [2], the cathode plasma emissive ability in an explosive-emission source is determined by the value of thermal current $j_e$:

$$ j_e = \frac{1}{4} Z e n v_e $$ (7)

where $Z$ is the degree of ion charge, $e$ is the electron charge, $n$ is the plasma concentration, $v_e$ is the thermal velocity of electrons.

As it is evident from Eq. (7), the influence of decrease of the current rise velocity on the plasma emissivity under the action of the beam space charge may be very significant. Besides deceleration of the plasma concentration rise, the decrease of the current rise velocity according to Refs. [21, 22] results in decrease of multiplicity of ion charges in the plasma composition that can provide the decrease of the plasma emissive ability even at the rising current. Decrease of the emissive ability results in its saturation. Current values corresponding to the quasi-stationary discharges or close to them can be obtained in the absence of a solid emission plasma boundary at the cathode.

5. Conclusions

The current of diodes with point- and blade-type emitters is calculated. It is shown that the interelectrode gap conductivity increases nonmonotonically: the cathode plasma expansion from emitters results in slowdown of the current rise. The decrease of the current grows velocity results in drop of the value of the cathode material entering the cathode plasma, decrease of the plasma concentration and the ion charge degree in the plasma composition that promotes the emissive ability saturation and quasi stationary discharge realization.

References

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