Low Frequency Transmission

Final Project Report

Power Systems Engineering Research Center
Empowering Minds to Engineer the Future Electric Energy System
Low Frequency Transmission

Final Project Report

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Power Systems Engineering Research Center

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- Dongbo Zhao, GRA
- Anupama Keeli, GRA
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Executive Summary

The goal of this project is to evaluate alternative transmission systems from remote wind farms to the main grid using low-frequency AC technology. Low frequency means a frequency lower than nominal frequency (60/50Hz). To minimize costs, cyclo-converter technology is utilized resulting in systems of 20/16.66 Hz (for 60/50Hz systems respectively). The technical and economic performance of low-frequency AC transmission technology is compared to HVDC transmission and conventional AC transmission in different configurations. The issue is quite important since wind potential exists in remote and off-shore locations and the transmission system required to bring wind energy to the main power grid represents a substantial expenditure of the overall wind energy projects. The end result of this study is a comprehensive method for evaluating and selecting the design parameters for alternative configurations of wind projects and typical results of these evaluations for selected example systems.

In this project we have identified a number of possible configurations that are mainly based on the three main options: (a) interconnection of a wind farm to the main power grid via AC transmission, (b) interconnection of the wind farm to the main power grid via DC transmission, and (c) interconnection of the wind farm to the main power grid via low frequency AC transmission (LFAC). Using these three distinct transmission options, eight alternative configurations were developed that include the above three options. These alternative configurations were analyzed from several points of view. Specifically, the following evaluations were performed: (a) optimal kV levels for each specific alternative configuration, (b) reliability performance of each one of the alternative configurations, (c) transfer capability of each one of the configurations, and (d) transient stability analysis of each one of the configurations. For each one of these evaluations, a parametric study has been performed when warranted. A summary for the final report is provided below.

Chapter 1 provides an overview of the project and the reasons that the project was initiated.

Chapter 2 provides an overview of the overall approach to the stated objectives for the proposal. Specifically, the approach is based on developing comprehensive models for the proposed technologies and to use these models to evaluate their performance and compare them to competing technologies. The models developed are described in more detail in the Appendices B and C.

Chapter 3 provides a literature survey for alternate connection methods of wind farm to the main power grid using HVDC, conventional AC and LFAC technologies. Based on the survey, eight alternate wind farm configurations have been proposed in Chapter 4 of the report, including different combinations of in-farm technologies and out-farm transmission technologies (HVDC, conventional AC or LFAC).

Chapter 4 describes alternative topologies for low-frequency transmission. Chapter 5 provides a methodology for determining the optimal kV level selection and equipment rating. The selection methods are formulated based on the minimization of the total cost,
which contains the operational cost and the acquisition cost. Specific analysis of the
selection of optimal kV level and equipment ratings based on the formulation of the total
cost for each of the eight proposed configurations has been performed. Examples of these
computations are provided in the section for each one of the eight alternative
configurations. The example results are summarized at the end of the chapter and
presented here. It should be emphasized that the values of the table below are valid only
for the considered example systems.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>kV Level Selection</th>
<th>Minimum Annualized Total Cost (M$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>0.48</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1.05</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>1.20</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>0.82</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>0.75</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>1.25</td>
</tr>
</tbody>
</table>

In Chapter 6, the operational study presents the comparison of maximum power transfer
capability between nominal-frequency systems and LFAC transmission systems. The
maximum power transfer capability is computed by gradually increasing the power
transfer until one of the operating constraints or static stability limits are violated. The
operational constraints are voltage limits, loading limits and electric current limits. The
stability constraints are the static stability limits. Example results are also presented for
specific example systems. For convenience we present one example of transmission at 76
kV below. The much higher power transfer capability of the low frequency AC system is
clearly apparent.

Maximum Transmission Capability at the Operation Voltage 76kV

<table>
<thead>
<tr>
<th>Distance (miles)</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer Capacity (MW) at 60Hz</td>
<td>180.3</td>
<td>82.8</td>
<td>57.54</td>
<td>44.17</td>
<td>36.78</td>
<td>34.31</td>
<td>30.56</td>
<td>27.98</td>
<td>26.19</td>
<td>24.84</td>
<td>23.38</td>
</tr>
<tr>
<td>Transfer Capacity (MW) at 20Hz</td>
<td>225.3</td>
<td>141.3</td>
<td>106.1</td>
<td>86.28</td>
<td>73.49</td>
<td>68.29</td>
<td>60.19</td>
<td>54.27</td>
<td>49.22</td>
<td>45.21</td>
<td>41.96</td>
</tr>
</tbody>
</table>
Chapter 7 describes the overall approach for performing transient analysis of wind farm systems and provides case studies for voltage stability.

Chapters 8 and 9 describe the requirements for transient stability studies to determine the suitability and operational robustness of these systems. These studies are important for better understanding the dynamic behavior of these systems that include complex power electronic systems. These studies also provide the generation of harmonics by these systems. They are critical for understanding the harmonic content generated by wind farms and LFAC transmission systems. The methods can be used to determine the need for harmonic filters and if filters are needed, the method can be also used for the design of these filters. Also, the power transient study allows the close observation of control performance of power transients. Chapter 8 presents the overall approach for transient analysis of the proposed low frequency AC transmission systems and presents the controls of the power electronic subsystems for this operation. Design details for these systems are also addressed, such as harmonic filter design, etc. Chapter 9 describes a numerical integration of the basic models using the advanced quadratic integration. Details of the simulation method are presented and results for specific systems are presented. The ability of the proposed systems to control the power transferred and to control the operation of these systems is demonstrated.

Chapter 10 provides an analysis of the eight alternative configurations from the reliability point of view. Reliability analysis methods have been proposed for the alternative wind farm configurations. Both the structural reliability model and the wind variability model are considered in the reliability study. Monte Carlo models of the components and probabilistic approaches of the topologies are utilized to formulate the reliability analysis and reliability indices calculation. Case studies for each of the eight configurations are provided and the reliability indices results are compared. Specifically, the reliability of the wind farms is assessed in terms of the following reliability indices: EGWE (Expected Generated Wind Energy) and CF (Capacity Factor). Results for example systems (one example per proposed alternative configurations) are provided. A summary of these results is given below for convenience.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>EGWE</th>
<th>IWP</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.98</td>
<td>60</td>
<td>0.383</td>
</tr>
<tr>
<td>2</td>
<td>22.42</td>
<td>60</td>
<td>0.374</td>
</tr>
<tr>
<td>3</td>
<td>20.82</td>
<td>60</td>
<td>0.347</td>
</tr>
<tr>
<td>4</td>
<td>26.22</td>
<td>60</td>
<td>0.437</td>
</tr>
<tr>
<td>5</td>
<td>12.31</td>
<td>60</td>
<td>0.205</td>
</tr>
<tr>
<td>6</td>
<td>25.86</td>
<td>60</td>
<td>0.431</td>
</tr>
<tr>
<td>7</td>
<td>20.54</td>
<td>60</td>
<td>0.342</td>
</tr>
<tr>
<td>8</td>
<td>26.27</td>
<td>60</td>
<td>0.438</td>
</tr>
</tbody>
</table>
Conclusions and future work is discussed in Chapter 11. Since wind energy is the most rapidly developed generating systems from all renewable resources and the forecast is that they may be forming a large percentage of the generation system, their performance is of paramount importance to the reliability of the power system of the near and far future. The models developed in this research project can be utilized to study other very important operational characteristics and capabilities of these systems. One main concern is that as the percentage of wind generating systems become very large (even 100% in some systems) what will be the operational challenges of these new systems from the stability, control, operation and protection point of view. Suggestions are provided in Chapter 11.

A total of four students contributed to this project (three at Georgia Tech and one at Iowa State University. One Master’s thesis was written on the subject and two PhD theses were written on the subject. In addition, nine publications were generated that describe the work of this project. These publications and the three Theses (Dissertations) compliment this main report.

**Project Publications:**


**Student Theses and Dissertations:**

