Commissioning and Testing of the KangJin UPFC in Korea

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Abstract
KEPRI, the research institute of Korean Electric Power Corporation (KEPCO), has been investigating the feasibility of applying inverter type FACTS equipment into the local power system through a series of research projects. Based on the results, KEPCO has completed a 80MVA UPFC pilot plant project applied to the 154KV system with a consortium formed with Hyosung Corporation, Siemens, and local research institutes in 2003. This paper presents the installation, commissioning, and test results of the 80MVA UPFC installed at Kangjin substation, located in the southern region of the Koran peninsula. The distinct features of the Korean power system, characteristics of the surrounding power system near the pilot plant installation site, system configuration, construction and installation status for application and operation of FACTS equipment to the local power system are also described in this paper.

Keywords: FACTS, STATCOM, SSSC, GIS, Flexible-AC-Transmission Systems, Unified- Power-Flow-Controller, Static-Synchronous-Series-Compensator, Gas-Insulated-Switchgear

1. Introduction
The current Korean power system is subject to the following problems. First, the short circuit capacity of the system has increased due to the continuous reinforcement of the transmission lines and loop configuration. This increases the system reliability, but has the side effect of existing switch gears not being able to break the circuit at the required moment due to the increase in short circuit current. Thus 154KV system configuration has been modified to a radial system, and the ratings of the circuit breakers on the 345KV system have been increased. Second, the generated power amount of existing power plant complexes is increasing each year, thus increasing the possibility of loss of synchronism in generators when there is a fault on a surrounding feeder. This problem can be solved easily by reinforcing the system with additional lines, but plans for constructing new lines may be delayed or even cancelled, due to oppositions from environment protection activists and other legal matters such as compensating landowners. Through a series of planning projects[10], KEPCO has investigated several different equipment as possible solutions to under voltage and overload during system faults [6, 9]. The results show that installation of a UPFC showed the best system performance and proved to be the most economical solution. To derive detailed technical specifications and establish operation strategies, the UPFC installed in AEP’s Inez [1, 2] and the CSC [7, 8] installed at NYPA’s Marcy substation have been reviewed.

2. 80MVA UPFC Project
Power generation complexes in Korea are concentrated in coastal areas and loads are concentrated in inland metropolitan areas far away from the generated power source. Increase in short circuit capacity due to the loop configuration of the system, voltage drop due to long transmission lines, and system instabilities due to the concentration of large generators have contributed to the need for power flow control to the north. Solutions to these problems have been addressed in several engineering projects. Prior to applying FACTS technology to the 345KV system, which is the backbone of the Korean power system, the need for a pilot plant project was acknowledged to verify reliability and operational performance through actual installation and operation of an inverter type FACTS equipment.

As shown in Figure 1, the KEPCO UPFC pilot plant is installed at the Kangjin substation, which is located in Kangjin on the southern part of Korea near the southern seashore within the Chunlanamdo province to support the 154KV system at SinKangjin during faults. The Kangjin substation where the

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UPFC is installed consists of open type outdoor equipment, which takes up a lot of equipment space thus leaving little installation space for the UPFC. To make efficient use of the given space, the UPFC connection to the grid was established using a GIS. Figure 3 shows the single line diagram of the 154KV Kangjin-Jangheung line where the UPFC is installed. The connection between Kangjin-Jangheung has a double bus structure, and the buses are operated alternately. To increase the reliability of the transmission system, KEPCO normally uses a double bus system and this structure must be taken into account when designing the grid connect system.

3. System configuration
The KEPCO UPFC system consists of series and parallel inverters that make up the SSSC and STATCOM. Equipment such as series and parallel transformers for inverter connection, GIS and switchgears for grid connection are also included. Two inverter stacks make up a single module, and the auxiliary and main transformers at the inverter output are configured to reduce the harmonic content of the inverter output. For the circuit breaking part, a GIS (Gas Insulated Substation), where a VCB, DS, CT, and PT are packaged into a single system is used. This reduces installation space and has excellent reliability and stability characteristics. The characteristics of each individual equipment, configuring the KEPCO UPFC system is shown.

1) Inverters
The UPFC consists of two inverters. Each inverter makes up the STATCOM and SSSC. The rating of a single inverter is ±40MVA, and each GTO device used in the inverter stack is rated for 4500V, 4000A. The GTO module consists of a GTO device, anti-parallel diode, snubber components, and heat sinks. A single pole consists of 4 valves, each valve consisting of five GTO modules connected in series. The total DC voltage is distributed evenly between each GTO module under dynamic and steady state switching conditions. The dc connections on the inverter pole occur at one end of the pole and ac connection occurs at the opposite end. This configuration minimizes circuit inductance, maintains proper distances for insulation, and minimizes the distance of cooling runs. The pole is liquid cooled with a single inlet and a single outlet cooling manifolds to distribute coolant to the various pole components in parallel.

2) Power transformer
Each inverter is connected to the grid through a transformer. There are a total of four transformers used in the grid connection. The shunt and parallel transformers are 40MVA each and two auxiliary
transformers are each rated 22.2MVA. As the transformer is connected to inverter, dc components may be injected. When dc components of the inverter output are mixed into each transformer they can be the cause of saturation. The transformer was designed to operate, under normal operating conditions, with a DC current of 5 amperes flowing. Due to the constant flow of current on the primary side of the serial transformer, special skills and consideration are required for thermal, mechanical, insulation design, and manufacturing. As shown in Figure 2 two identical twelve pulse, three level inverters are connected to a common DC capacitor bank, the combining the output through an auxiliary transformer, a twenty four pulse harmonic neutralized inverter can be configured. By combining the output waveforms of the two inverters with this configuration, harmonic components can be reduced. The combined output is connected to the grid through the series and shunt transformers.

![Figure 2. Magnetics Configuration Diagram](image)

3) Coupling circuits
Figure 3 shows the grid connection scheme of the UPFC equipment. The GCB output of the Jangheung 154KV line is cut and a double circuit is configured using a GIB. The output terminals of the inverters which are located inside a building are connected to each auxiliary transformer with power cables. The outputs of the auxiliary transformers are connected to the shunt and series transformers which are then connected to one of the newly constructed double circuit lines. The output of each equipment is connected to the existing 154kV Jangheung line through a newly installed GIS.

![Figure 3. System layout of Kangjin UPFC](image)

4. Commissioning of the Pilot Plant
Before the commissioning was initiated, the representatives from KEPCO, KEPRI, Hyosung, Siemens have been appointed Test Coordinators for coordination within their respective organizations and

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prompt decision making. The Commissioning was done in three stages: pre-commissioning, off-line commissioning and on-line commissioning.

1) Pre-commissioning
Pre-commissioning is the stage where the installation and individual operation status of each equipment are checked prior to system commissioning. Two different types of tests were performed during the UPFC pre-commissioning. The first test was a de-energized test where the equipment was checked before applying station service power. The second test was the auxiliary system test where individual operation tests were performed with the station service power applied.

2) Off-line Commissioning
In this stage, various operational tests are performed prior to connecting the shunt/series inverter to the system bus. The test items of the offline test are almost identical for the shunt and series inverter. A separate commissioning power supply was used to supply DC power to each inverter in the offline state. The main purpose of this test is to confirm that various system analog signals are correctly fed back to the controller, and check if the voltage waveform is correctly formed through the inverter output voltage and the auxiliary transformer. During the test, the charged DC voltage is slowly increased from the low voltage level to the rated voltage level while testing the general operation performance of each inverter. The voltage waveforms of each pole and both sides of the intermediate and main transformers have to be monitored to check the switching pattern and the ratio of transformers as is shown in the Figure 4 and 5. Phase difference can be confirmed in this test.

3) On-line Commissioning

The primary side of the shunt transformer is shorted to ground and disconnected from the power system for the short circuit current test. The purpose of this test is to check the impedance of the transformers and polarity of the CTs. The typical current waveform is shown in the Figure 6. These tests are repeated for the series inverter with different switch configuration.

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The UPFC has 3 different operation modes: STATCOM, SSSC and UPFC. Each mode is tested step by step.

- **STATCOM mode**

(1) **VAR control mode**
The line voltage variations were measured when the UPFC shunt inverter (STATCOM) was operated in the full capacitive/inductive range and the results are shown in the Table 1. The maximum voltage variation was about 2,400V when the STATCOM operates from full inductive mode to full capacitive mode.

<table>
<thead>
<tr>
<th>VAR ref (MVAR)</th>
<th>MVAR</th>
<th>Bus Voltage (kV)</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>-9.5 → 9.5</td>
<td>19.0</td>
<td>159.3 → 158.7</td>
<td>-600</td>
</tr>
<tr>
<td>-26.1 → 25.9</td>
<td>52.0</td>
<td>159.5 → 158.1</td>
<td>-1,400</td>
</tr>
<tr>
<td>-40.0 → 40.0</td>
<td>80.0</td>
<td>159.0 → 156.9</td>
<td>-2,100</td>
</tr>
<tr>
<td>13.6 → -13.7</td>
<td>-27.3</td>
<td>158.7 → 159.4</td>
<td>700</td>
</tr>
<tr>
<td>30.0 → -33.3</td>
<td>-63.3</td>
<td>158.2 → 159.8</td>
<td>1,600</td>
</tr>
<tr>
<td>40.2 → -40.7</td>
<td>-80.9</td>
<td>157.7 → 160.1</td>
<td>2,400</td>
</tr>
</tbody>
</table>

(2) **Voltage control mode**
The droop factor of the voltage control mode was set to 3% which was derived from the developer's experience. Comparisons between different reference voltages, calculated voltage and measured voltage are shown in Table 2. The voltage calculated by applying the droop factor is used for STATCOM voltage control mode. STATCOM showed correct voltage control performance.

<table>
<thead>
<tr>
<th>Vref (PU)</th>
<th>Vbus (PU)</th>
<th>Vref (kV)</th>
<th>Vbus (kV)</th>
<th>Calculated Vref (kV)</th>
<th>Output (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.030</td>
<td>1.031</td>
<td>158.6</td>
<td>158.8</td>
<td>158.8</td>
<td>1.5</td>
</tr>
<tr>
<td>1.040</td>
<td>1.034</td>
<td>160.2</td>
<td>159.2</td>
<td>159.0</td>
<td>-9.7</td>
</tr>
<tr>
<td>1.050</td>
<td>1.036</td>
<td>161.7</td>
<td>159.5</td>
<td>159.4</td>
<td>-19.6</td>
</tr>
</tbody>
</table>

- **SSSC mode**

Power flow variations were measured when the injected voltage by SSSC changes and the results are shown in Table 3. Power flow was increased when SSSC increased injected voltage in the capacitive mode. Since SSSC should be operated in the condition of minimum line current 0.1 pu, the -Q axis voltage injection (inductive mode) test were restricted as shown in Table 3.

<table>
<thead>
<tr>
<th>Ref. V</th>
<th>Vinj2 (pu)</th>
<th>I line (pu)</th>
<th>P line (MW)</th>
<th>Q line (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.002</td>
<td>0.092</td>
<td>55</td>
<td>-5</td>
</tr>
<tr>
<td>0.600</td>
<td>0.038</td>
<td>0.139</td>
<td>82</td>
<td>-13</td>
</tr>
<tr>
<td>1.000</td>
<td>0.064</td>
<td>0.169</td>
<td>98</td>
<td>-21</td>
</tr>
<tr>
<td>-0.02</td>
<td>0.003</td>
<td>0.087</td>
<td>51</td>
<td>9</td>
</tr>
</tbody>
</table>

- **UPFC mode**
(1) Voltage injection mode
Line voltage and current variations were monitored when the UPFC injected voltage (Vd and Vq) at its full range. Figure 7 shows the voltage injection range of UPFC. Figure 8 shows the power flow variations when UPFC injected voltage as shown in Figure 7. Power flow variations were influenced by the injection of Vd, VAR variations by the injection of Vq.

![Figure 7 Voltage injection range](image1)

![Figure 8 Power flow variation by voltage injection](image2)

(2) Power flow control mode
Line real power and reactive power were measured when UPFC reference was varied in steps. Table 4 shows that transmission line power flow follows the reference perfectly within its capacity limit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vbus (pu)</td>
<td>1.033</td>
<td>0.050</td>
</tr>
<tr>
<td>Iline (pu)</td>
<td>0.033</td>
<td>0.043</td>
</tr>
<tr>
<td>Vinj2 (pu)</td>
<td>0.016</td>
<td>0.032</td>
</tr>
<tr>
<td>Vbus (pu)</td>
<td>0.016</td>
<td>0.000</td>
</tr>
<tr>
<td>Iline (pu)</td>
<td>0.098</td>
<td>0.041</td>
</tr>
<tr>
<td>Vinj2 (pu)</td>
<td>0.132</td>
<td>0.062</td>
</tr>
<tr>
<td>Vbus (pu)</td>
<td>0.140</td>
<td>0.064</td>
</tr>
<tr>
<td>Iline (pu)</td>
<td>0.143</td>
<td>0.680</td>
</tr>
<tr>
<td>Vinj2 (pu)</td>
<td>0.059</td>
<td>0.011</td>
</tr>
<tr>
<td>Vbus (pu)</td>
<td>0.065</td>
<td>0.020</td>
</tr>
<tr>
<td>Iline (pu)</td>
<td>0.074</td>
<td>0.030</td>
</tr>
</tbody>
</table>

5. Operation Test
After the commissioning was completed, various operations were performed to review the results from EMTDC models and PSS/E analysis e.g. the operation effect of the UPFC on the power system near Kangjin S/S, within the maximum operation range in the P, Q domain. During the operation of UPFC, several transmission line faults have occurred. Typical cases are shown in Figures 9 and 10. The first three waveforms from the top correspond to the voltage of the bus where the STATCOM is connected.

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The next three waveforms show the current that flows into the STATCOM. The last three waveforms are the currents flowing into the transmission line. Three phase ground faults have occurred at a substation not far from Kangjin S/S shown in Figure 9. After the fault cleared, the shunt portion experienced over-current twice. However the UPFC rode through the fault successfully, although it stopped gating momentarily twice. It injected full capacitive reactive power into the network to support bus voltage during the fault.

![Figure 9 Three Phase Ground Fault](image1)

On another occasion, double line-to-ground faults occurred twice at a distant substation. The UPFC rode through the first fault, even though it stopped gating three times during the fault. It eventually tripped due to the impact of a second fault shown in Figure 10.

![Figure 10 Double Line to Ground Fault](image2)
6. Conclusion

This project is the first UPFC system introduced into the Korean power system and will serve as a reference model for other FACTS equipment that will be installed in the future. This paper addressed the background of the UPFC project, site information, system configuration and features. Finally typical test items performed during commissioning are described, and operation examples are shown during power system faults. The Kangjin installation will also be a valuable reference to utilities that have limited installation space but are planning to introduce FACTS to their power system.

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References


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