Series Compensation for fast and cost-effective increase of transmission capacity in power grid

In a contract with ENELVEN, a regional electrical utility in Venezuela, ABB has installed a total of five series capacitors in their power grid to increase the capacity of existing overhead transmission lines serving the petroleum and petrochemicals center of Maracaibo. The total installation of reactive power in the contract amounts to close to 800 Mvar at 400 kV. It was commissioned in 2003. A sixth series capacitor is planned for a future extension of the grid in the same area.

The main purpose of the transmission corridor is to transmit low cost hydroelectric power to western Venezuela. Before, the system lacked the capability to transmit all the power needed, therefore the use of expensive fuel was required for local generation. By series compensating the three 400 kV lines between Yaracuy substation and El Tablazo substation, plus the lines between Yaracuy - Planta Centro and Yaracuy - Arenosa, the total power transmission capacity was increased from 1800 MW to 2125 MW. Three series capacitors are located at El Tablazo and two at Yaracuy.

The project is making additionally 325 MW of power available to help meet growing demand for power in the Maracaibo region, and enables ENELVEN to defer major investment in additional transmission lines or new generating capacity to a later stage.

Thus, conventional solutions to ENELVEN’s anticipated shortfall in power would have been to build additional transmission infrastructure to permit more electricity to be imported into Maracaibo, or to build new generation plants to produce power at the point of demand. But these solutions would have required more complex investments, have had considerable environmental impact and could have taken several years to receive the necessary rights of way and permits.

Instead, with series compensation, ENELVEN has gained a fast and very substantial increase in available power, at around one fifth of the cost of adding new transmission capacity.

Under the terms of the greenfield contract, ABB designed, built, installed and commissioned five series capacitors, one for each of five existing 400 kV transmission lines. A considerable supply of line protection equipment was part of the undertaking, as well.

Main circuit design
For proper functioning, series compensation requires control, protection and supervision to enable it to perform as an integrated part of a power system. Also, since the series capacitor is working at the same voltage level as the rest of the system, it needs to be fully insulated to ground.

The main protective device is a varistor bank of ZnO type, limiting the voltage across the capacitor to safe values in conjunction with system faults giving rise to large short circuit currents flowing through the line. A fast spark gap is furthermore utilized to supplement the function of the varistors during internal faults.

Finally, a bypass switch is incorporated in the scheme to enable bypassing and insertion of the series capacitor as need may be. It is also needed for extinguishing of the spark gap in cases where it has operated.

For external faults, i.e. faults occurring outside of the line segment containing the series capacitor, it is required that the series capacitor stays in operation during and after the fault, i.e. it must not be bypassed. For internal faults, i.e. such malfunctions of the power system that occur in the transmission line containing the series capacitor, the series capacitor may be bypassed.
Control & protection
The series capacitor control and protection system MACH 2 is microprocessor based and uses Optical Current Transducers (OCT) for current measurement, with optical fibres for signal transmission. This system offers several benefits:

- No relay protection equipment is located on the EHV platforms;
- No auxiliary power is required on the platforms;
- The optical current transducers are powered solely by means of light generated at ground level.

Furthermore, maintenance costs are reduced by continuous self monitoring. Maintenance intervals are increased by the use of the self monitoring digital microprocessor based system.

The control and protection system supervises all functions of the series capacitors and provides protective action in the event of faults such as capacitor overload or unbalance, flashover to platform, or varistor overload.

The control and protection system is duplicated in order to form a fully redundant protection concept. This means that not only the measuring path is redundant but also the MACH 2 system. Both systems work in parallel thereby increasing the total security.

The Human-Machine Interface (HMI) is accomplished by means of an Operator Work Station (OWS) which supplies operator and maintenance information. An integrated Sequence of Events Recorder (SER) and a built in Transient Fault Recorder (TFR) are included for diagnostics and analysis. A function is also implemented to monitor the spark gaps. This function provides an indication of the gap status and provides the opportunity to plan maintenance in advance.

SSR assessment
One specific engineering aspect administered within the contract was that of Sub-Synchronous Resonance (SSR). The probability for this low frequency phenomenon to appear in cases where there is a radial connection between a large power station comprising thermal generation, and a series compensated grid, should be assessed. The connection between Yaracuy and the power station Planta Centro was prospectively such a case under a triple contingency scenario.

Extensive computer studies were performed to assess the risk of SSR. The studies were supported by field measurements on the Planta Centro generators, measurements aiming to identify critical torsional parameters of the turbine-generator shafts. Using optical and magnetostrictive transducers that sensed very small speed and torque variations, the torsional modal frequencies and their respective damping could be identified. The confirming measurements were also extended such that the grid was set up in SSR critical radial configuration, this in order to verify the worst case behavior of the system.

The results from the studies and measurements showed that the system could not self-excite into SSR. Consequently it was not necessary to introduce any SSR protection on the generators themselves. However, as a precaution, the series capacitor in the Yaracuy - Planta Centro line is instantly bypassed, should the triple contingency that makes the system radial to Planta Centro occur.

Main technical data (per one series capacitor)

<table>
<thead>
<tr>
<th>Substation</th>
<th>El Tablazo</th>
<th>Yaracuy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of series capacitors</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Nominal system voltage</td>
<td>400 kV</td>
<td>400 kV</td>
</tr>
<tr>
<td>Rated current</td>
<td>1185 A</td>
<td>1481 A</td>
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<tr>
<td>Overload current, 30 minutes</td>
<td>1600 A</td>
<td>2000 A</td>
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<tr>
<td>Rated power</td>
<td>126 Mvar</td>
<td>197 Mvar</td>
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<tr>
<td>Degree of compensation</td>
<td>25%</td>
<td>50%</td>
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<tr>
<td>Series capacitor reactance</td>
<td>30 Ω</td>
<td>30 Ω</td>
</tr>
<tr>
<td>Type of protection</td>
<td>Gapped</td>
<td>Gapped</td>
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<tr>
<td>ZnO rating</td>
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<td>165 MJ</td>
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</tbody>
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