STATIC VAR COMPENSATOR TO INCREASE AVAILABILITY OF COLOMBIAN OIL FIELD

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ABSTRACT

This paper describes the application of a Static Var Compensator to improve the electrical system of the Cravo Norte Association (A C N) Oil Field in Colombia.

The Static Var Compensator (SVC) was installed at the receiving end of the 160 km - 230 kV power line that feeds the oil field. The main benefits of the SVC installation are:

- The electrical system is no more affected by the length of the line or the national grid voltage variations. The system voltage has been stabilized at 34.5 kV +/- 2%.
- The power transmitted through the power line has increased by about 30 MW.
- The SVC has added dynamic response to the system to voltage sags, load shedding or generator shutdowns. Variable Speed Drive shutdowns associated with voltage sags have been reduced by about 95%.
- The SVC provides control of voltage unbalance to \( \leq 2\% \) at 34.5 kV.

The paper summarizes this application, including the system aspects that require special control functions in the SVC regulator. Some relevant design features of the SVC are treated, as well.

INTRODUCTION

The large oil field of Cravo Norte Association is located at the far end of the 230 kV network in eastern Colombia. The oil production plant comprises two local power plants and a load that consists mainly of variable speed drives, all supplied from a local 34.5 kV bus connected to the 230 kV power line. The same 34.5 kV transformers also feed the nearby city of Arauca. The indigenous generation is used to increase the power supply and to maintain the voltage at the 34.5 kV bus in case of failures in the 230 kV feeder.

A simplified single-line diagram of the network is shown in Figure 1.

THE CASE

In order to reduce the number of production stops due to voltage drops or power shortages, system studies performed by ISA showed that a Static Var Compensator (SVC) had to be connected to the 34.5 kV bus. The primary task of the SVC is to stabilize the voltage at the 34.5 kV bus and to compensate for the reactive power consumed by the production plant. Furthermore, a fast response of the SVC will improve the bus voltage stability during system faults and reconnections.

Fig. 1: Simplified network diagram.

The total load demand of the Cravo Norte Association production plant, including variable speed pump drives, is approximately 147 MW active power and 77 Mvar reactive power. The drives are voltage sensitive, as well as sensitive to asymmetry between phases.

The installed SVC is capable of generating between 0 and 84 Mvar capacitive reactive power, utilizing a Thyristor Controlled Reactor (TCR) and three harmonic filters. Compensating the reactive power consumption of a large production plant, where the demand for power can change rapidly, requires fast response of the SVC regulator. The SVC control system is designed to continuously compensate for unbalance in the system voltage, by unsymmetrical control of the TCR phases. A weak network makes the voltage very sensitive for changes in reactive power. In case the connection to the 230 kV network is lost and the plant is supplied by the local generators only, the short-circuit power of the system will be considerably lower. A gain optimisation function of the SVC control will continuously measure the short-circuit power in order to adjust the gain of the regulator to maintain a stable regulator function at all times.
SVC Purposes
To summarize the purposes of the installed SVC:
- Increase the power imported from the 230 kV network.
- Dynamic voltage control at 34.5 kV for various load conditions, including system outages and load rejection.\(^1\)
- Dynamic voltage control at 34.5 kV during local generator outages.\(^1\)
- Control of voltage unbalance to \(\leq 2\%\) at 34.5 kV.
- Harmonic filtering of the variable speed drives.
\(^1\) SVC response time < 25 msec.

SYSTEM DESIGN

General Design
The SVC consists of a thyristor controlled reactor (TCR) rated at 84 Mvar and three harmonic filters. The TCR can be controlled continuously between 0 and 84 Mvar inductive reactive power and the filters together supply 84 Mvar capacitive reactive power, which in total gives an operating range between zero and 84 Mvar capacitive. Figure 2 shows a simplified single line diagram:

![Fig. 2: Single line diagram of the Caño Limón SVC.](image)

The filters are tuned close to the 3\(^{rd}\), 5\(^{th}\) and 7\(^{th}\) harmonics, all equipped with damping resistors to provide damping of the filter characteristics. Two external harmonic filters, tuned to the 5\(^{th}\) and 7\(^{th}\) harmonics, and three external capacitor banks were connected to the same 34.5 kV bus prior to the SVC installation. The external filters are automatically switched out when the SVC is energized, since the rating of the filter capacitors in those are insufficient for handling the harmonics generated by the TCR.

A site view of the SVC is shown in Figure 3:

![Fig. 3: Site view of the Caño Limón SVC.](image)

Thyristor Valve
The thyristor valve of the TCR consists of three single-phase units. Each unit is equipped with a vertical stack of BCT (Bi-Directional Control Thyristors). A BCT is two anti-parallel high power thyristors integrated onto one single silicon wafer and assembled into a housing. In parallel with the thyristor, a snubber circuit (series connection of resistors and capacitors) is mounted. The valve assembly is shown in Figure 4:

![Fig. 4: Three-phase thyristor valve.](image)

The thyristors are 4" size, with a blocking voltage of 6.5 kV, and liquid cooled using de-ionized water with low conductivity as coolant. The nickel plated aluminium heat sinks, providing double side thyristor cooling, also serve as electrical connection between the thyristors.

The TCR snubber resistors are liquid cooled, as well.

The rated maximum continuous current of the TCR valve is \(997\ A_{\text{rms}}\). To prevent overloading the TCR valve, a current limiting function is employed for voltages lower than 1.1
p.u., which limits the current to 997 A rms. The valve is designed to withstand overload conditions as follows:

- Short-time operation at 1.5 p.u. voltage for 50 ms
- Operation at 1.3 p.u. during 1 second
- Continuous operation at 1.1 p.u. voltage.

A photograph of the three-phase thyristor valve is shown in Figure 5:

Fig. 5: Three-phase, 34.5 kV TCR valve.

**SVC Control**

The Caño Limón SVC regulates the voltage on the LV side of the transformers, the 34.5 kV bus. The closed loop voltage control is based on the signal from the voltage transformer on the 34.5 kV bus (Figure 6).

The closed loop control and the protective control functions are realised with a MACH 2 control system. MACH 2 is a very advanced microprocessor based control system used for SVC, series compensation and HVDC systems in a vast number of installations throughout the world.

The system conditions at Caño Limón require special control functions to be implemented, for regulation of system unbalance and to adapt the regulator parameters to the system characteristics.

**Negative Phase Sequence Control**

The loads at the 34.5 kV bus are mostly variable speed drives and other industrial loads, as well as the feeder to the nearby city of Arauca. Single-phase transient faults on the 34.5 kV lines connected to the 34.5 kV bus of Caño Limón can cause imbalances not tolerated by the AC drives, which to a considerable extent can be regulated by the negative sequence control function in the SVC.

The negative sequence control function measures each phase voltage to determine the system unbalance. The regulator will act outside a dead-band of 2%, equal to the maximum acceptable system unbalance level at steady-state conditions. The negative sequence susceptance of the SVC is calculated and the value is split between the three phases, including the negative sequence voltage vector angle. Each TCR valve is therefore controlled independently to counteract the system unbalance.

Figure 7 shows the response of the negative phase sequence controller when the negative sequence level of the system is changed from zero to 5%.

Fig. 7: Negative Phase Sequence Controller response.

The top graph of Figure 7 shows the difference in phase voltages with 5% negative sequence. The middle graph shows the negative sequence susceptance references for each phase, which will be added to the positive sequence susceptance reference. As shown in the bottom graph, the negative sequence level is regulated from 5% to 2%, which is the size of the regulator dead-band. The step in negative sequence is performed at $t = 1$ s.

**Gain Optimizer**

With a low fault level, changes of the reactive power generation can cause oscillations in the system voltage. The MACH 2 control system detects oscillations in the
susceptance reference value, and reduces the regulator gain until a stable behaviour is maintained.

To further enhance this function, the control system has a Gain Optimizer function that will bring the gain back to the original value when the system conditions are restored.

Small steps, small enough not to disturb the system, are added to the voltage reference, and the over- or undershoots of the response are measured. Based on the size of the over- or undershoots, the gain will be changed.

An example where the gain is reduced and the Gain Optimizer is activated is shown in Figure 8.

![Fig. 8: Gain Optimizer function.](image)

Small steps of approximately 1% in the bus voltage are used to determine the strength of the network. As shown above, the gain is increased from 89% to 100% during two pulses.

**RTDS TESTING**

The MACH 2 control system was tested using a Real-Time Digital Simulator, RTDS, which has several advantages compared to a TNA (Transient Network Analyser). A correct representation of the transmission lines, loads and the SVC is easily implemented in the RTDS [1]. Several different models can be used to represent different network conditions, without long setup time in the simulator.

The 230 kV transmission lines feeding the Caño Limón substation were included in the RTDS model, as well as the three 230/34.5 kV transformers supplying the Cravo Norte Association 34.5 kV bus and the nearby city of Arauca. Besides the SVC, three external capacitor banks, the two external harmonic filters, dynamic load representing Arauca and the production plant, and two local generators were included on the 34.5 kV side of the transformers.

The redundant MACH 2 control system was connected to the RTDS using analogue and digital inputs and outputs. The analogue output signals from the RTDS were connected via amplifiers to the analogue input boards in the control system, to simulate the current transformer signals. The external filters, controlled by the SVC control system, were connected to the digital input boards of the RTDS, to make it possible to switch the filters modelled in the RTDS from the control system.

The main purpose of the RTDS testing was to verify the SVC control system functionality. The voltage controller of the SVC is one of the key functions for fast and stable reactive power compensation, which therefore were carefully tested.

The step response of the SVC, among several other control functions, cannot be completely verified during field tests due to limitations in the system, while the RTDS can be used to simulate various system conditions. Especially fault cases are of great interest, due to their impossibility of realization in the field.

**FIELD EXPERIENCES AND CONCLUSIONS**

As a result of the installation of the SVC in January 2008 the following improvements and/or benefits have been obtained:

- The power import from the 230 kV network in normal conditions was increased by 30 MW.
- A maximum power import of 120 MW has been achieved during abnormal critical conditions.
- The statistics of loss of oil field due to trips of AC drives and/or pumps caused by voltage dips has been reduced by more than 95%.
- The voltage profile of the 34.5 kV busbar at Caño Limón has been maintained within a margin of ±2% with the SVC in operation.

The SVC has also yielded excellent control of negative phase sequence voltages generated due to transient faults on the lines connected to the 34.5 kV busbar of Caño Limón and some abnormal imbalances in the load. It has been the task of the SVC to mitigate this imbalance between phases, to reduce negative phase sequence voltage at the 34.5 kV bus from 5% down to 2%.

**REFERENCES**