APPLICATION OF THE GRID POWER FLOW CONTROLLER (GPFC) IN A BACK TO BACK PROJECT

E. Poggi, D. Nix          D. Woodford              K. Sadek, N. Hilfert, M Rashwan*
Xcel Energy              Consultant               Siemens
USA                      Canada                  Germany, Canada

Summary

The advantages of using HVDC in power transmission over a long distance or in connecting systems have been well known for several decades. Economics always dictates the choice between HVDC and other solutions. This has been the motivating force to seek ways of reducing the cost of HVDC, while maintaining its full functionality. The Grid Power Flow Controller (GPFC) is a product of these efforts that is considerably less expensive than a comparable conventional HVDC system.

The key factor in reducing the GPFC cost is the use of standard ac transformers, instead of the converter transformers. In most applications the power rating of the GPFC transformers is lower by about 15%.

Keywords: HVDC, Back to Back, Grid Power Flow Controller (GPFC)

1. Introduction

Xcel Energy is comprised of the operating companies of Public Service Company of Colorado (PSCo), South-western Public Service (SPS) and Northern States Power (NSP). PSCo is located in an electrical region that is adjacent to SPS but is not electrically connected through AC synchronous ties. Xcel Energy is required, to construct a DC Tie to allow energy to be transferred between PSCo’s and SPS’s service territories. The Eastern half and the Western half of the United States is not electrically synchronized. The dividing line is roughly down the eastern borders of Montana, Wyoming, Colorado and New Mexico. There are six existing DC Back-to-Back converter stations connecting these areas of the United States. The Lamar project will be the seventh tie.

The location of this DC Converter is in a remote area of South-eastern Colorado Northeast of the City of Lamar, CO as shown in Figure 1. In phase 1 of the project, 220 miles of 345 kV transmission line was constructed between Potter County Substation, in Amarillo, TX, and a new 345 kV Finney substation located in Western Kansas. This connection was placed in service in September 2001.

* 200-137 Innovation drive, Winnipeg, Canada, R3T-6B6, mrashwan@brc.mb.ca
The location of this DC Converter is in a remote area of South-eastern Colorado Northeast of the City of Lamar, CO as shown in Figure 1. In phase 1 of the project, 220 miles of 345 kV transmission line was constructed between Potter County Substation, in Amarillo, TX, and a new 345 kV Finney substation located in Western Kansas. This connection was placed in service in September 2001.

The location of this DC Converter is in a remote area of South-eastern Colorado Northeast of the City of Lamar, CO as shown in Figure 1. In phase 1 of the project, 220 miles of 345 kV transmission line was constructed between Potter County Substation, in Amarillo, TX, and a new 345 kV Finney substation located in Western Kansas. This connection was placed in service in September.

In Phase 2 of the project, a new PSCo Lamar 230 kV substation was constructed adjacent to an existing Lamar 230 kV substation (Old Lamar) and placed in service in September 2003. This station will be the western side of the DC Converter station and ties into an existing 230 kV system via a 98 mile, 230 kV line to Boone (the nearest substation to the west). It ties to the eastern system through the DC Tie and a 105 mile long 345 kV line to Finney substation. Both the 230 and 345 kV lines are radial.

A 162 MW wind farm is installed on a radial 230 kV Line approximately 40 miles south of Lamar.

It is noted that there is an underlying 115 kV system at Old Lamar, but its source is also the Boone Substation. During 230 kV line contingency conditions the DC Converter power is minimized to a low value condition.

Construction of the DC Converter began in October 2003. Its scheduled date for commercial operation is January 1, 2005.

2. System Requirements

The GPFC interfaces to an effective short circuit ratio (ESCR) of 2.5 (normal) on the west, 230 kV side. With the loss of the 230 kV line to Boone, the resulting very low short circuit capacity (SCR less than 0.5) necessitates GPFC power be lowered to a few 10’s of MW, but remain operating so that the west side ac voltage remains controlled by the converter. On the east, 345 kV side the normal ESCR is 5.3 but can be as low as 1.7 under contingency operation. Ac voltage control on the east side is achieved by switching reactors and capacitors in 40 MVAR steps.
For operational flexibility, the GPFC power can flow from 210 MW from east to west, to 210 MW west to east. The power flow is continuous over this range, even below 10% rating to 0 MW. This is because steady state operation at 90 degrees firing/extinction angle is possible.

3. Features of the GPFC Lamar

The GPFC Lamar is basically a Back-to-Back (B2B) HVDC transmission system as shown in Figure 2. It consists of two thyristor converters that are connected to each other via a smoothing reactor. In comparison to a conventional B2B, the dc bus bars of the GPFC are isolated from ground to avoid the use of converter transformers and also to prevent the zero-sequence harmonics from flowing in the system.

The voltage between the converter dc terminals is a 6-pulse voltage containing dc component and harmonics of 6n order (n=1,2,…). However, the voltage of each of the dc buses to ground is a 3-pulse voltage containing all harmonics of order 3n. Analysis shows that the 3rd, 9th, 15th etc harmonic voltages on the two dc buses are in phase and therefore do not show up in the bus-to-bus dc voltage. Since they are in phase on the two dc buses, these harmonic voltages can cause common mode harmonic currents to flow in the dc buses. Common mode harmonics on the dc buses will appear as zero sequence harmonic currents at the ac side of each converter and therefore their magnitudes depend on the zero sequence impedance of the ac circuit on the two sides of the GPFC.

Figure 3 shows the zero-sequence harmonic currents of the GPFC without any blocking. Figure 4 shows the effect of blocking of these zero-sequence harmonics through the standard ac step-down transformer. Although the GPFC Lamar is a 6 pulse-converter, it is possible to build it as 12 pulse-converter using standard ac transformer with star/delta windings.

The key factor in reducing the GPFC-cost is the use of standard ac transformers instead of the converter transformers. In most applications the power ratings of the GPFC transformer are also lower by approximately 15% than the equivalent converter transformers.

The main advantages are:
- local manufacturing is possible
- shorter delivery
- load tap-changer is not required (less outages and maintenance)

The second main feature of the GPFC Lamar is the permanent and continuous ac voltage control on the weak ac system (west side).

The third main feature is the common ac filter bus (53 kV), where all filter and reactive power sub-banks are connected.

The fourth main feature is the capability of the dc converter to operate continuously at 90 deg. The big advantage of such a system is the possibility to continue operation also if one of the two ac systems is out of operation. In this case the converter valves of the affected side will operate in bypass mode, while the other converter valves will be in 90 deg mode controlling the voltage of the healthy side.

---

**Figure 3:** Zero Sequence Harmonic Path

---

**Figure 4:** Blocking Zero Sequence Harmonics
4. Design aspects of the Lamar GPFC

4.1 System configuration

The Lamar project is characterized by having a very stringent dc power, reactive power, and ac voltage control requirements, as well as the ability to operate continuously with zero dc power. Although these requirements can be met by several technical solutions, it was decided to use the concept of the Grid Power Flow Controller (GPFC) for the project.

The GPFC for the Lamar project is a 210 MW back-to-back HVDC system as shown in Figure 5. It consists of two six pulse thyristor converters connected to each other in a back to back arrangement via two smoothing reactors of 10 mH each and a sixth harmonic blocking filter. The converters are connected to the two ac systems via a 3.9 mH commutating reactors and the step down transformers. The dc bus bars are isolated from ground to avoid any zero sequence current flow into the system. The ac filters, shunt capacitors, and shunt reactors are connected on the 53 KV ac bus.

The GPFC is designed for operation in both power directions at different ac voltages. The dc power range is zero to 210 MW in either direction. Figure 6 depicts the station Layout at Lamar. The system is designed for a continuous overload of 1.05 p.u. up to an ambient temperature of 45°C as well as 1.2 p.u. for ambient temperatures below 0°C. It has a short time overload capability of 1.4 p.u. for 5 seconds.

![Figure 5: GPFC Lamar-(USA) Single Line Diagram](image-url)
4.2 Equipment Ratings:

Thyristor valves:

The thyristor valves as shown below use light triggered thyristors (LTT). This design of valves has been proven and used in several HVDC systems up to 500 KV and 3000 MW bipolar rating.

This removes the need for any auxiliary supply or logic circuits at the high voltage level and hence significantly reduces the number of components in the converter valves as well as the risk of fire.

Station transformers:

Two sets of power transformers each rated 225 MVA are used to connect the converters to the ac system. The line side of the transformers are connected to the 230 KV and 345 KV bus bars. The line side is connected Wye. The valve side is connected Delta on both transformer banks and is rated for 53 KV. The valve side is connected to the series commutating reactors. The transformers are supplied as single phase units with a spare unit provided for each side.

Commutating reactors:

The commutating reactors are air cored air cooled. These reactors also limit the current stresses on the valves during valve short circuits. The value chosen is 3.9 mH per phase.

AC filters:

The ac filters are connected to the 53 KV bus between the transformer valve winding and the series commutating reactors as shown in Figure 5. The use of up-to-date triple-tuned filters will reduce the amount of switchgear and protection equipment.

4.3 P/Q Controls:

In an HVDC system dc voltage and current can be controlled by adjusting the firing angles of the converters. In a long distance scheme the dc voltage is usually maintained at the maximum specified level to minimize the transmission losses. In a back-to-back system on the other hand, the transmission losses are negligible and therefore the dc voltage can be adjusted to any level within the specified limits. This
extra degree of freedom provides the possibility of controlling the reactive power exchange at the two terminals as well as the active power. The GPFC controller uses this possibility to keep either the reactive power or the ac voltages at the two terminals within the specified limits. The maximum and minimum reactive powers that the converters can absorb are determined by the active power order. Depending on which control mode is selected, either the reactive powers or the ac voltages at the two ends are compared to the desired limits defined by the higher order controls. The error signals are then fed to two PI controllers to find the best reactive power level at both ends. Having the active and reactive power orders, the controller can now calculate the dc current and voltage orders that will be sent to the converter controllers. The operator has the option to disable the P/Q controller and directly input the dc current order. The controller will then use the P order to calculate the dc voltage order.

Figure 6: GPFC Lamar-Station Layout

5. Behaviour of the GPFC in steady state and during faults (Simulation Results)

Extensive simulation studies have been carried out using the PSCAD / EMTDC electromagnetic transient simulation program. Steady state, transients and fault conditions were studied and control parameters were optimized for operation on weak AC systems. Similar to the conventional HVDC systems, the rectifier side is set to operate in the current control mode, while the inverter normally controls the DC voltage. If for some reason the DC current falls below certain margin, inverter will switch to current control mode where it reduces its DC voltage to maintain the DC current. An extinction angle control function is also included in the inverter controls as a back up to ensure safe operation of the inverter and avoid commutation failure. An active/reactive power controller receives the power order from the operator (or
higher level controls) and determines the current and voltage orders such that the reactive power exchange at both ends remains within the specified limits.

Figure 7. shows a number of traces from the steady state simulation of GPFC Lamar. As expected, the sixth harmonic is dominant in the DC current. The average voltage of one DC bus bar is positive with respect to the ground while the other one is negative. The third harmonic is dominant in these bus to ground voltages.

Compared to a 12-pulse HVDC system, the converter AC side currents contain more harmonics due to the 6-pulse operation but currents flowing into the power grid are essentially harmonic free due to the presence of the triple-tuned filters. The secondary side phase-to-ground voltages of the power transformer contain a considerable amount of zero sequence harmonics as shown in the fifth trace here of Figure 7. If the secondary side windings are Wye connected, these zero sequence harmonics can also be seen at the neutral point voltage as shown in the last trace.

Figure 8 shows the simulation results when the power order is ramped from 210MW to 140MW and back to 210MW again. When the power order is reduced, GPFC controller reduces both DC current and DC voltage orders to reduce the active power while keeping the reactive power exchange at the same level. The fourth trace shows the reactive power exchange between the GPFC and the power grid at one side. It is clear from this trace that the controller is able to maintain the reactive power exchange close to zero after a short transient. Firing angles both at the rectifier and inverter move towards 90 degrees as the power order is reduced.

![Figure 7: Simulation results for steady State operation at full load](image1)

![Figure 8: Simulation results when the power is ramped from 210 to 140 MW and back.](image2)
6. Conclusion

GPFC is an innovative solution that will be utilized in the Lamar Project (Denver-USA) as an economic interconnection between two AC systems of Xcel utilities providing both power transmission and AC voltage control capability.

Compared to conventional back-to-back HVDC systems, GPFC utilizes only conventional AC power transformers instead of converter transformers. AC transformers are simple and easily manufactured worldwide, while construction of converter transformers requires special facilities. This makes AC transformers less expensive and faster to deliver. In addition, the power rating of the GPFC transformer is 15% lower than the comparable converter transformers due to the fact that it carries only the active portion of the converter currents. The simplicity of the design and the use of LTT valves make the GPFC a very reliable device with high availability.

7. References


