

Eagle Pass Back-to-Back Tie: a Dual Purpose Application of Voltage Source Converter technology

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Abstract: IGBT-based Voltage Source Converters (VSC) connected Back-To-Back (BTB) is a new technology that can provide reliable interconnection of power systems. At American Electric Power – Central Power and Light’s (AEP-CPL) Eagle Pass substation, a 36 MVA VSC based BTB tie, interconnecting AEP-CPL’s and Comisión Federal de Electricidad’s (CFE) power systems, provides needed reactive power support for dynamic voltage control at the two ends of the BTB tie. At the same time it maintains a controlled bi-directional power transfer between the two power systems.

The field tests performed during commissioning have demonstrated the capability of the BTB tie to provide independent control of the voltage at both ends and the real power transfer between AEP-CPL’s and CFE’s power systems. Stability of the BTB tie control system is also demonstrated in normal operation as well as during “Black Start” of the BTB tie.

Keywords: BTB, SVC, Light, voltage control, IGBT, VSC, Voltage Source Converter, Black Start, Islanded Network

I. INTRODUCTION

The installation of the Voltage Source Converter-based (VSC) Asynchronous Back-To-Back (BTB) tie in Eagle Pass, Texas, USA, has been successfully completed. The BTB takes advantage of a state-of-the-art power semiconductor platform, using high frequency Pulse Width Modulated (PWM) control of Insulated Gate Bipolar Transistors (IGBTs) in the converter bridges. The project, being the first straightforward commercial application of its kind, was executed as a collaborative effort between American Electric Power (AEP) and Electric Power Research Institute (EPRI), with ABB Power Systems supplying the equipment on a turnkey basis. The equipment is based on ABB’s HVDC Light and SVC Light technologies, which have been combined to form a dual-purpose Back-to-Back VSC. In addition to the challenges related to the application of new technology, the project partners also worked against a very short delivery schedule. The full lead-time of the installation was only 15 months.

The Eagle Pass Back-to-Back VSC asynchronous tie fulfils a twofold mission. Firstly, the tie has the capability of providing fast and dynamic reactive power support to either side of the tie, up to ± 36 Mvar depending on the magnitude of the real power transferred. Secondly it provides the possibility to exchange electric power across the border

(between asynchronous grids), with a bi-directional exchange up to 36 MW, the value being a function of the reactive power support required at either end of the tie.

The capability to control dynamically and simultaneously, both active and reactive power, is an unprecedented feature for VSC-based BTB interconnections. This feature is an inherent characteristic of the VSC. The operation of a VSC does not rely upon the connected AC system as its commutations are driven by the internal circuits. Full control flexibility is further achieved by the implementation of the PWM technique for the control of the IGBT-based bridges. Furthermore, the PWM technique provides an unrestricted control of both positive and negative sequence voltages. This enables a reliable operation of the BTB tie under unbalanced conditions of the connected AC systems. Furthermore, the tie can energize, supply and support an isolated load. In the Eagle Pass case this will allow uninterrupted power supply to the local loads, when connections to one of the surrounding networks would be tripped. Both network sides of the tie can also be energized from “across the border”, without any “block-over” switching arrangements.

The following sections of the paper highlight the innovative technology applied in this interconnection, and the commissioning test results. Extensive simulations and design studies were performed, along with field verification testing at the Eagle Pass site. The paper presents and discusses some of the tests, illustrating the dynamic and steady state performance capability of the BTB tie.

II. EAGLE PASS LOAD AREA

The Eagle Pass substation is located in a remote part of the AEP-CPL, power system, see Figure 1. There are approximately 42 MW of load in the area, which is connected to the rest of the Electric Reliability Council Of Texas (ERCOT) transmission system through two existing 138 kV transmission lines. The nearest significant generation (150 MW) located 145 km away. That generation provides very little voltage support to the Eagle Pass area.

Eagle Pass also has a 138 kV transmission line that ties into CFE’s, Piedras Negras substation, which normally has been operated open. It was mainly used in emergency conditions to transfer load from one power system to the



Figure 1. Eagle Pass location.

other network. However, load being transferred needed to be interrupted since it was not possible to interconnect the asynchronous CFE and AEP-CPL systems together although both are 60 Hz. At this location the CFE system is stronger and has over 2000 MW of generation within approximately 80 km of Piedras Negras, which is just across the border from Eagle Pass.

The Eagle Pass area has a load growth of 3% per year. The peak load conditions in 2001 are projected to be high enough to cause a possible voltage collapse after a loss of either existing ERCOT 138 kV transmission line to Eagle Pass. Load flow studies have demonstrated that the installation of a 36 Mvar Voltage Source Converter (VSC) directly at Eagle Pass substation would provide years of relief from this single contingency situation. A VSC would provide needed reactive support instantaneously and could maintain full reactive output at even lower voltage levels that could result from the single contingency outage. Installation of a VSC would be ideal for weak systems whereas the reactive support provided by shunt capacitors is not very effective as it decreases as voltage is reduced.

Two VSCs connected Back-To-Back (BTB) would not only supply the necessary reactive power but also allow active power transfer between the two power systems. A BTB scheme would allow for the Eagle Pass to Piedras Negras 138 kV line to be energized all the time and the instantaneous transfers of active power from either system. This would provide a needed third energy source feeding into the Eagle Pass substation that improves the support to the Eagle Pass area.

With the BTB tie in service and no contingencies, the 138 kV AEP-CPL transmission system would be capable of supporting up to 80 MW of load at the Eagle Pass substation. Currently, the load in the Eagle Pass area is 42 MW. Therefore, there is an ability to accommodate 35 MW transfer to CFE through the BTB tie.

The Eagle Pass substation and the 138 kV AEP-CPL transmission system would support a 36 MW import of power from the CFE system using the BTB. The injection of active

power directly to the Eagle Pass load unloads the 138 kV transmission lines.

The BTB could further be by-passed and used as two SVC Light devices that can provide up to 72 Mvar of reactive support while the active load transfer is by-passed.

Finally, also a black start and supply of an islanded network could be arranged if that should be needed. This would be beneficial during restructuring after a blackout.

III. BACK TO BACK INSTALLATION

A simplified one-line diagram of the BTB tie in Eagle Pass is shown in Figure 2.

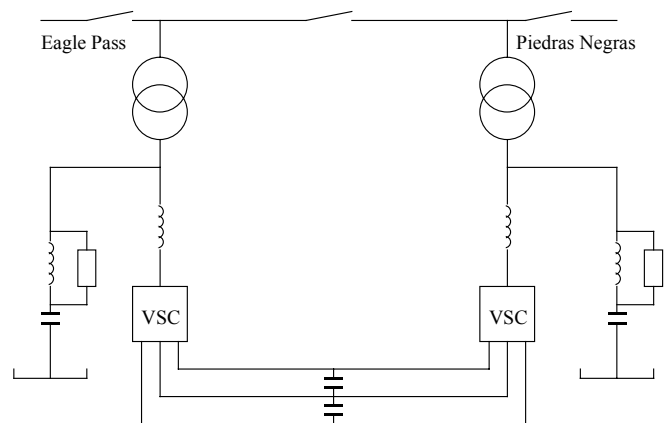


Figure 2. BTB simplified single line diagram.

The BTB scheme consists of two 36 MVA Voltage Source Converters (VSCs) coupled to a common DC capacitor bus. The VSCs are of the NPC, Neutral Point Clamped, type, also called three-level converter, see Figure 3. The VSCs are equipped with IGBTs, Insulated Gate Bipolar Transistors, operated with PWM, Pulse Width Modulation.

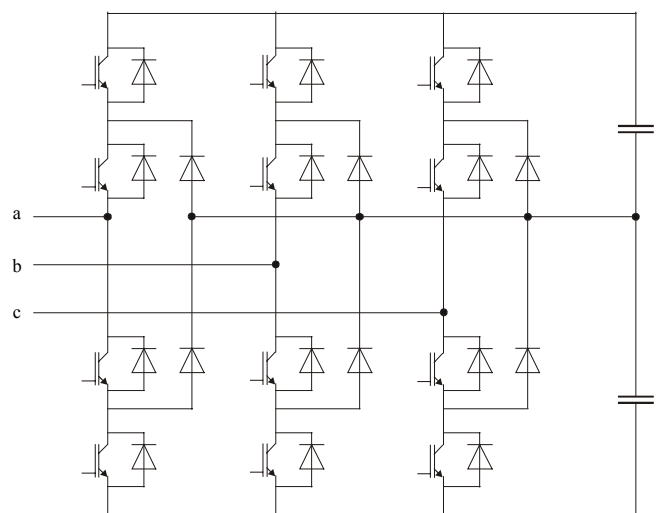


Figure 3. IGBT-based three-level converter.

Each VSC is then connected to a three-phase set of phase reactors, which each in turn is connected to a conventional step-up transformer on its respective side of the BTB.

The whole BTB installation is located on the US side at the

Eagle Pass substation. The layout of the BTB installation is shown in Figure 4.

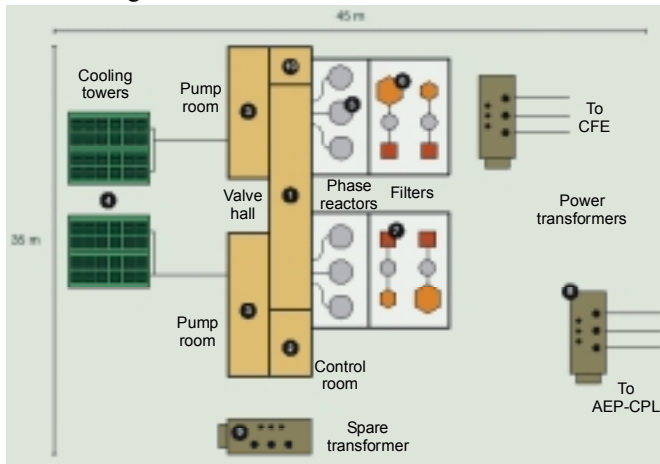


Figure 4. Eagle Pass BTB layout.

IV. BTB OPERATION MODES

The BTB is designed to operate in two control modes. The primary mode is reactive power support for voltage control of the Eagle Pass bus and the secondary mode is active power flow between CFE and AEP-CPL. In voltage control mode, the BTB operates with a control slope to supply reactive power for voltage support. To transfer power in either direction the BTB operates in power control mode, it will continue to transfer power if the voltage at Eagle Pass is within a dead-band. For conditions outside the dead-band the BTB operates in Voltage control mode. The dead-band is designed so that local capacitor switching or changes in remote generation which cause slight voltage swings do not cause the BTB to switch to voltage control mode.

The BTB can perform many functions dictated by the operating configurations of the two VSCs. The following are the major operating configurations for the BTB.

1. Voltage Control Mode

In this mode, the BTB can provide independent voltage control to both the AEP-CPL and CFE systems. This is referred to as the voltage control mode. The BTB provides the required reactive power support on both sides to maintain a pre-set voltage. Active power can be transferred from either side while maintaining a constant voltage on the two systems. Any active power transfers that are scheduled are automatically and instantaneously lowered if needed by the control system to supply the needed reactive power support to maintain a constant voltage.

2. Active Power Control Mode

In active power mode, the BTB provides active power transfer between the AEP-CPL and CFE systems. It then allows power transfer when the voltage is within a dead-band. If the voltage goes beyond this dead-band the BTB automatically goes into voltage control mode. The active power flow is then automatically and instantaneously lowered by the BTB as needed to provide the required reactive power support.

3. Independent Operation Mode of the two VSCs

Should maintenance be required on one side of the BTB, the other side can still provide voltage control to either side of the BTB. This is done by opening the DC bus to split it into two halves. As the DC link is open, no active power can be transferred between the two sides of the BTB for this configuration. Each VSC will then be capable of providing up to ± 36 Mvar of reactive support to either side.

Furthermore, the BTB can provide voltage control to the load if it is transferred to the other power system. The BTB would in this configuration be capable of supplying ± 72 Mvar of reactive support to the system supplying the power. As the by-pass breaker has to be closed in this configuration, no active power can be transferred via the BTB.

4. The BTB during contingencies

If a contingency occurs, that is, the loss of one of the 138 kV lines into Eagle Pass substation, the remaining 138 kV line can only support 50 MW of load at Eagle Pass substation. When this occurs, the voltage falls below 0.98 p.u. and the BTB switches to voltage control mode. Active power is reduced automatically and instantaneously to make sure the 50 MW load level at the Eagle Pass substation (AEP-CPL load plus the export to CFE) is not violated. The BTB supplies the required reactive support to maintain a 1 p.u. voltage. Load flow studies have shown that the transmission line contingency on the AEP-CPL side will have little impact on the power transfers from CFE to AEP-CPL.

V. COMMISSIONING TEST RESULTS

During the BTB tie commissioning, measurements were made for different phases of BTB operation using a Transient Fault Recorder (TFR). The TFR data files were then analyzed to verify the performance of the BTB. Among the TFR files, the following are the results of the main operation cases, namely

1. BTB energization.
2. Steady state operation.
3. Capacitor bank switching.
4. Black start capability.
5. Remote line faults on the network.

In the plots below, unity voltage corresponds to 138 kV on the line side of the BTB transformers. On the low voltage side, unity voltage is 17.9 kV. Nominal BTB current is the base for current.

1. BTB energization

First, the CFE side of the BTB was deblocked in SVC Light mode. This corresponds to a time of approximately 0.52 s in Figure 5. The AEP-CPL side of the BTB was then off-line, i.e. disconnected from its line. After deblocking, the DC voltage control smoothly regulated the DC voltage to its reference level, see subplot 6 of Figure 5. Note that both DC

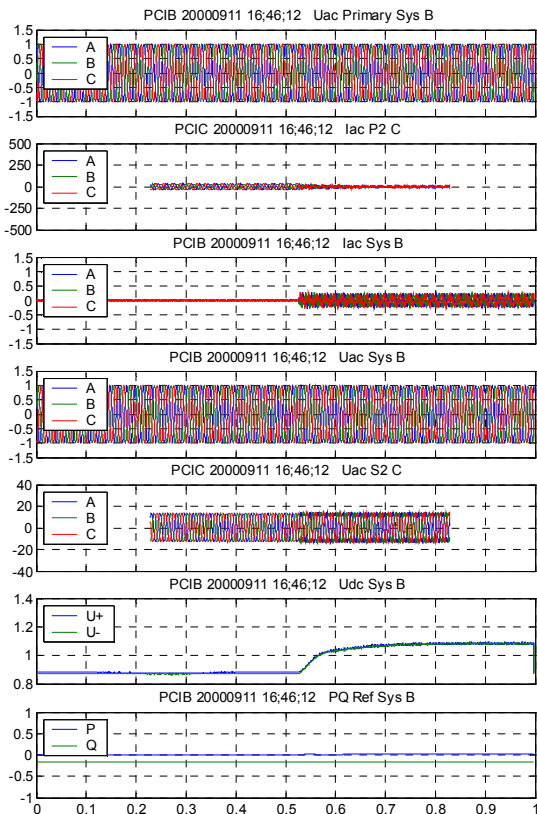


Figure 5. BTB energization.

Subplot 1. CFE 138 kV voltages.

Subplot 2. CFE step-down transformer secondary currents in Amps.

Subplot 3. CFE Phase reactor currents.

Subplot 4. CFE 17.9 kV voltages.

Subplot 5. CFE 17.9 kV phase-to-ground Voltages.

Subplot 6. DC voltages.

Subplot 7. CFE converter Active (top curve) and Reactive (bottom curve) Power Reference.

voltages are shown. Thanks to the “built-in” diode bridge inside the converters (see Figure 3) there was already a DC voltage present prior to deblocking.

The current through the CFE step-down transformer, subplot 2 of Figure 5, before deblocking is equal to the filter current. At valve deblock, the VSC compensates the filter current and thus the transformer current is reduced to zero. The measuring ranges for subplots 2 and 5 are shorter than for the other subplots due to TFR properties.

The other side of the BTB, the AEP-CPL side, was then deblocked with the CFE side still energized. On the CFE side, no transients were recorded during the start of the AEP-CPL side.

2. Steady state operation

The next step was to order a 36 MW power exchange, nominal power of the BTB, to be exported from AEP-CPL to CFE. Figure 6 shows voltage and current quantities recorded on the AEP-CPL side after ramping up the power. Curves on the CFE side are similar.

3. Capacitor bank switching

One possibility to check the transient response of the BTB was to switch on one of the capacitor banks at the AEP-CPL

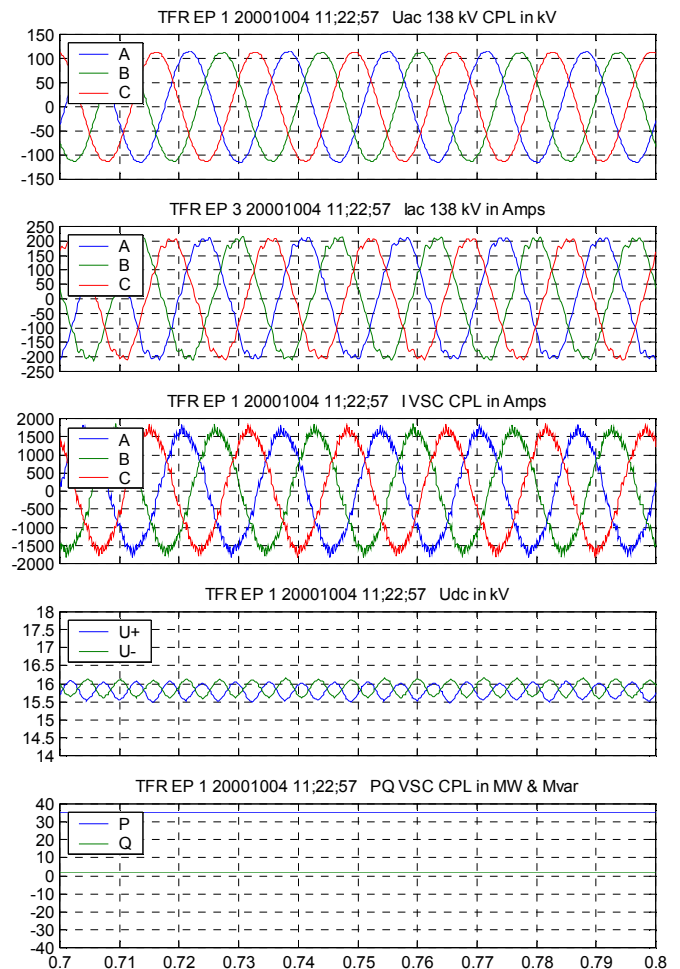


Figure 6. 36 MW power transfer from AEP-CPL to CFE.

Subplot 1. AEP-CPL 138 kV voltages.

Subplot 2. AEP-CPL step-down transformer primary currents in Amps.

Subplot 3. AEP-CPL Phase reactor currents in Amps.

Subplot 4. DC voltages in kV.

Subplot 5. AEP-CPL converter Active (top curve) and Reactive Power (bottom curve) Reference in MW and Mvar respectively.

Eagle Pass substation. In the actual case, the reactive power from the BTB was before the switching equal to 18 Mvar before capacitor switching. As the capacitor bank was switched on, the BTB had to reduce its output with 15 Mvar, the capacitor bank rating, down to 3 Mvar. The system responded fast as shown in subplots 2, 3 and 7 of Figure 7. The active power reference, subplot 7 in the same figure, was transiently modified to stabilize the DC voltage.

4. Black start

Next, to test the Black Start function, the CFE side of the BTB tie was first energized as during normal energization. On the AEP-CPL side the line breaker, connecting the BTB tie to the AEP-CPL network, was open but was in the control system simulated as if it had been closed. In this way, a small islanded “network” consisting mainly of the AEP-CPL transformer was created. Any larger islanded network was not possible to create, as this would have forced a power outage in parts of the city of Eagle Pass. Black Start was then initiated.

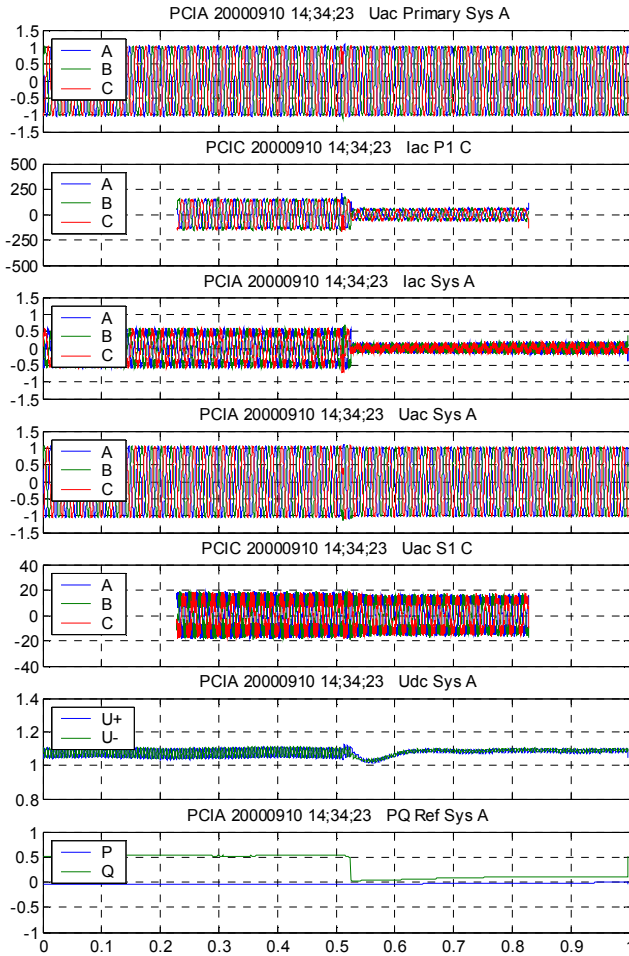


Figure 7. Capacitor bank switched on
 Subplot 1. AEP-CPL 138 kV voltages.
 Subplot 2. AEP-CPL step-down transformer secondary currents.
 Subplot 3. AEP-CPL Phase reactor currents.
 Subplot 4. AEP-CPL 17.9 kV voltages.
 Subplot 5. AEP-CPL 17.9 kV phase-to-ground Voltages in kV.
 Subplot 6. DC voltages.
 Subplot 7. AEP-CPL converter Active (bottom curve) and Reactive Power (top curve) Reference.

As shown in Figure 8, The AEP-CPL 138 kV voltage was ramped from 0 kV. The ramp ended at 138 kV although the plot, due to TFR limitations, does not show more than the part up to about 60 kV. On the CFE side, the voltages and currents remained undisturbed during the ramping phase. During operation of the islanded “network”, see Figure 9, the AEP-CPL 138 kV bus was supplied by the BTB at almost no load condition. The only load on the AEP-CPL side consisted of the harmonic filters rated totally 6 Mvar. The system was anyhow observed to perform well. The modulation on the DC voltage in Subplot 5 is due to the frequency difference between AEP-CPL side, having constant frequency, and the CFE side. On the CFE side, the system operated as normal.

5. Remote faults on the network

Finally, during a remote fault, the BTB was in operation at zero power. Lightning conditions in a remote area caused a voltage dip in the AEP-CPL network. Figure 10 shows the BTB response during stabilization of the voltage in Eagle

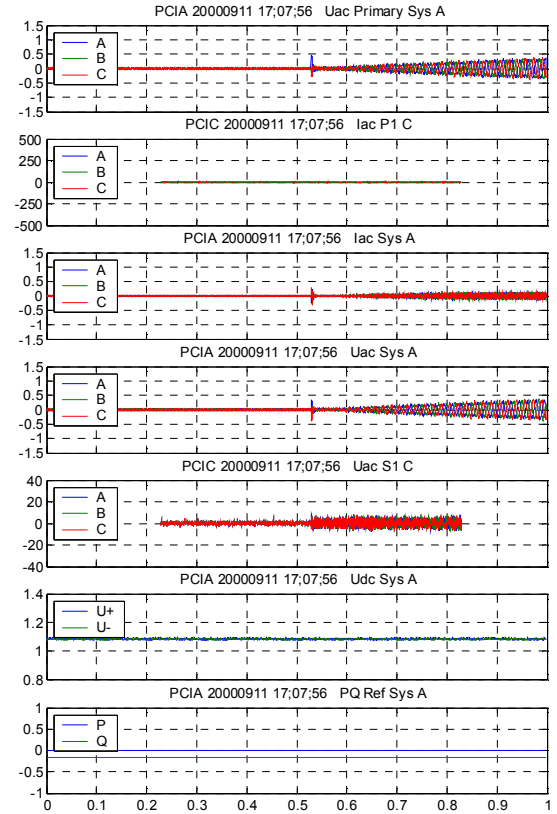


Figure 8. Black start.
 Subplot 1. AEP-CPL 138 kV voltages.
 Subplot 2. AEP-CPL step-down transformer secondary currents
 Subplot 3. AEP-CPL Phase reactor currents.
 Subplot 4. AEP-CPL 17.9 kV voltages
 Subplot 5. AEP-CPL 17.9 kV phase-to-ground Voltages
 Subplot 6. DC voltages.
 Subplot 7. AEP-CPL converter Active (top curve) and Reactive Power (bottom curve) Reference.

Pass. The BTB current (capacitive) during the fault condition was increased to almost 1 p.u. to support the bus voltage at Eagle Pass.

VI. CONCLUSIONS

The Eagle Pass BTB tie has successfully demonstrated an unprecedented capability of providing reliable asynchronous interconnection between the ERCOT system and the Mexican interconnected network, this is relevant considering the difference of short-circuit power at the interconnection points. Furthermore, the use of VSCs with PWM technique has enabled the flexibility in providing independent voltage control, at the two ends of the BTB, and a bi-directional active power transfer between the interconnected power systems.

VII. REFERENCES

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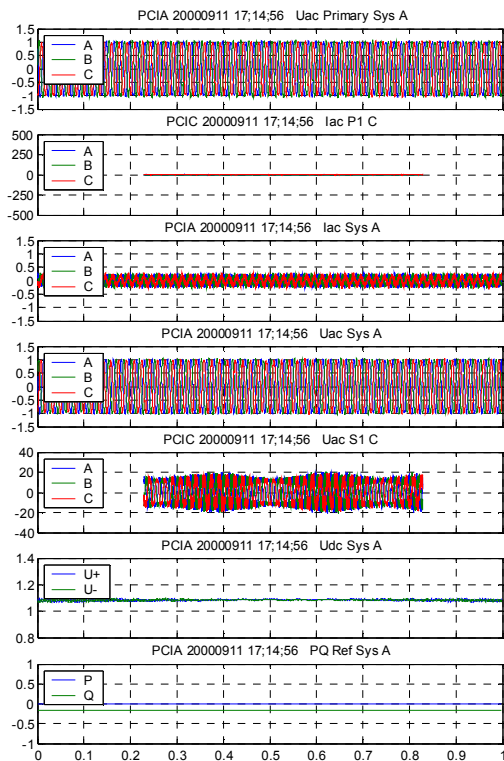


Figure 9. Operation with islanded “network”.

- Subplot 1. AEP-CPL 138 kV voltages.
- Subplot 2. AEP-CPL step-down transformer secondary currents.
- Subplot 3. AEP-CPL Phase reactor currents.
- Subplot 4. AEP-CPL 17.9 kV voltages.
- Subplot 5. AEP-CPL 17.9 kV phase-to-ground Voltages.
- Subplot 6. DC voltages.
- Subplot 7. AEP-CPL converter Active (top curve) and Reactive Power (bottom curve) Reference.

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VIII. BIOGRAPHIES

Tomas Larsson (S 1992, M 1999) was born in Sävsjö, Sweden, on May 9, 1964. He received his M.Sc. and Ph.D. degrees from the Royal Institute of Technology, Stockholm, Sweden, both in Electrical Engineering, in 1991 and 1998 respectively.

Dr Larsson joined ABB Power Systems in 1998 where he presently is involved in projects concerning Voltage Source Converters, reactive power compensation and flicker mitigation.

Åke Petersson was born in Växjö, Sweden on April 15, 1958. He received his M.Sc. degree in Electrical Engineering from Chalmers Institute of Technology, Gothenburg Sweden, in 1982. He then joined ABB (at that time ASEA) and has over the years held various engineering positions related to the application of power electronics in high voltage electrical systems.

Presently he works for ABB Power Systems in Västerås, Sweden, focusing on the application of FACTS systems in transmission grids.

Abdel-Aty Edris (SM 1988) was born in Cairo, Egypt. He received his BS with honors from Cairo University in 1967, MS from Ain-Shams University, Egypt in 1973, and Ph.D. from Chalmers University of technology, Sweden, in 1979.

Dr. Edris spent 12 years with ABB Company in Sweden and in the USA,

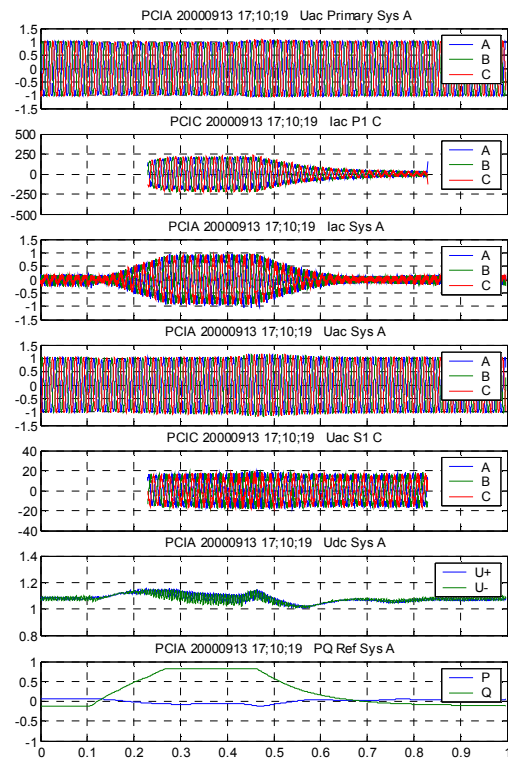


Figure 10. Remote fault case

- Subplot 1. AEP-CPL 138 kV voltages.
- Subplot 2. AEP-CPL step-down transformer secondary currents in Amps.
- Subplot 3. AEP-CPL Phase reactor currents.
- Subplot 4. AEP-CPL 17.9 kV voltages.
- Subplot 5. AEP-CPL 17.9 kV phase-to-ground Voltages in kV.
- Subplot 6. DC voltages.
- Subplot 7. AEP-CPL converter Active (bottom curve) and Reactive Power (top curve) Reference.

in the development and application of reactive power compensators and High Voltage DC Transmission systems. In 1992 Dr. Edris joined EPRI as Manager of Flexible AC Transmission System (FACTS) Technology.

Dr Edris is Target Leader of EPRI’s Substations and Transmissions Asset Utilization. Dr. Edris is a member of several IEEE and CIGRE Working Groups.

David Kidd received his BSEE from New Mexico State University in 1987. He spent 10 years at El Paso Electric Company in system protection. In 1997 he joined AEP in the Texas Transmission Planning group where he has been working with FACTS Technology. He a member of IEEE and works with various groups within the Electric Reliability Council of Texas (ERCOT).

Rich Haley has a BSEE from Oklahoma State University. He has 20 years of experience from project management of e.g. HVDC and series capacitors. He has also experience from areas such as protective relays and high voltage substations, transmissions lines, and microwave systems.

Rich Haley is a Registered Professional Engineer in the State of Oklahoma and Texas and a member of the National Society of Professional Engineers and the Oklahoma Society of Professional Engineers

Florencio Aboytes received his B. Sc. And M.Sc. in Electrical Engineering from Instituto Tecnológico y de Estudios Superiores de Monterrey, Monterrey, México, in 1968 and 1969 respectively, and a Ph.D. in Electrical Engineering from Imperial College of Science and Technology, London England in 1974.

He has been with Comision Federal de Electricidad (CFE) since 1975. Currently he is Head of CFE’s Advanced Engineering Unit. He is also serving as professor and chairman of graduate studies committee, University of Nuevo Leon in Monterrey, Mexico.

Dr Aboytes areas of expertise are modeling, analysis, operation and control of electric power systems. He is a Fellow member of IEEE, member of CIGRE SC 38 and of the Academy of Engineering in Mexico.