CREZ Line Protection Design: Challenges and Solutions

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***Abstract*- CREZ is the name of a large scale transmission program that is progressing in Texas. The network consisting of many 345kV lines and substations is being constructed to support the future development of renewable energy in the area. Because of the projected high penetration of wind power, the requirements to system protection and control are more stringent than ever. In addition, the protection system designs for CREZ lines had to overcome issues brought by interconnection, communication, mutually coupling, series compensation, shunt compensation, etc. This paper describes the challenges that AEP protection engineers encountered in CREZ projects and the solutions they took to design the protection and control systems.**

I. INTRODUCTION

CREZ, the Competitive Renewable Energy Zones, are geographical areas in Texas planned for construction of new power lines that will be able to deliver 18,500 megawatts of wind generation in the future. With over 7 billion dollars investment, the CREZ transmission program includes more than sixty new 345kV double circuit transmission lines with a total length of about 2400 miles. To cope with wind power, the CREZ system also includes many reactive power regulation equipments such as SVC, Series Capacitors, Shunt Reactors, Shunt Capacitors, etc. In order to bring in capital investment and competition, nine Transmission Service Providers (TSP) were selected by Public Utility Commission of Texas to construct the CREZ lines and substations. ETT, the joint venture between AEP and MidAmerican Energy, was assigned to build seven double circuit 345kV lines with total length of about 460 miles, four new switch stations, four series capacitor stations and a number of new terminals in existing substations.

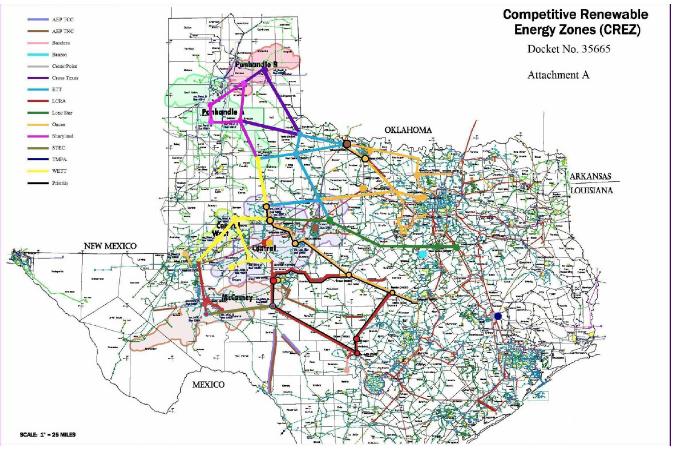

Figure 1. The CREZ Transmission Program, from [1]

II. THE CHALLENGES ON SYSTEM PROTECTION

During the design process for CREZ, the AEP protection and control (P&C) engineers were facing numerous issues brought by renewable generation, interconnection, tele-protection, redundancy requirements, series capacitors, shunt reactors, mutual coupling, and so on. Some challenges were encountered before but some were new as introduced by system configuration or primary equipment. It was a significant task for the P&C engineers to come up with the designs that could address all the issues.

A. *Challenge Brought by Variable Generation*

Since the CREZ lines and substations are built for renewable energy development, they must be able to maintain the system stability when the area has high penetration of wind power. If the protection system falsely operated - either tripping the CB for external faults or making slow clearance for internal faults, the system could be under higher risk to lose stability when it is compared with the system powered by conventional generators.

First of all, wind is a highly variable energy source that is hard to predict. The power flow could swing significantly in a short time frame, which can result in voltage fluctuations. There could also be frequency excursions because the weather plays a role in the balance between the generation and the load. Unlike the system with conventional generators, the stability of such system is indeed a serious issue from the operation standpoint.

When a fault occurs, the minimum system reliability requirement is that majority of the generators should remain online and not trip due to the single contingency such as loss a main transmission line or a main generator unit. For a system that includes many smaller induction generators, the risk of losing generation is higher because the low voltage ride through (LVRT) capability of such generator is far less than that of conventional generator. That is why FERC and NERC had specific concerns to wind generator performance during frequency and voltage excursions. The Figure 2 taken from FERC [8] shows the required LVRT capability of wind generators. Such curve would be easy for traditional generators but is tough to wind generators. In support of renewable energy, the FERC Order 661A [8] also includes some exceptions to waive such stringent requirements. The NERC standards PRC-024-1 [9] is still at drafting stage for the time being. The LVRT curve in PRC-024-1 draft has been

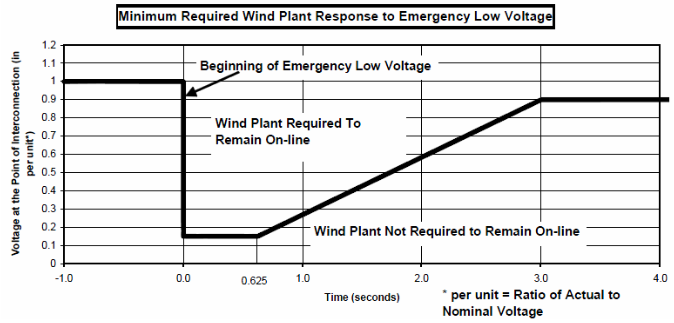

Figure 2. The LVRT requirement, from [8]

modified a few times, showing that it is not easy to achieve balance between the system stability requirements and the renewable energy development.

There are two types of wind generators, the constant speed units and the variable speed units. A constant speed unit is based on the regular induction machine that absorbs reactive power from the grid for excitation. Lacking the capability to control the reactive power, this type of generators may contribute to the system voltage fluctuation following the variable wind power. Moreover, such generators could experience instability following a large disturbance. When generator terminal voltage is low, the rotor will accelerate and the torque will increase per speed-torque curve of induction machine. If the pull-out torque is surpassed, the generator will lose its stability. To protect the equipment when terminal voltage is low, the unit over-speed protection would trip it off the grid.

In comparison, the variable speed wind generators such as the popular Doubly-Fed Induction Generators (DFIG) could regulate reactive power and have better LVRT capability. However, such capability is limited. The Figure 3 illustrates the structure of a typical DFIG generator that has back-to-back voltage source converters to connect the stator and the rotor. A linking capacitor in the middle of the two converters is used to maintain DC supply from the stator side converter to the rotor side converter.

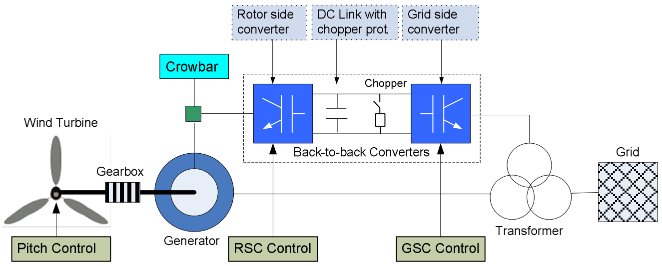

Figure 3. The structure of a DFIG generator

When disturbance occurs, the stator's flux linkage could include large DC component and also negative sequence component in case of asymmetrical faults. Per flux conservation law, the high speed rotating of rotor that is relative to these DC and negative sequence components can induce high EMF and large rotor current. Consequently, the rotor side converter and the linking capacitor could be damaged. To protect the converters and the capacitor, the unit may be tripped off by the overcurrent or overvoltage protections embedded in DFIG controller, even though there is crowbar circuit or special control scheme to bypass or limit the rotor current. The LVRT capability of DFIG generator will depend on the fault type, fault location, fault duration, network topology, control mode and the control parameters.

Another concern with high penetration of wind power is the sensitivity of system protection, especially for transmission line protection. The traditional synchronous machines are able to produce short circuit current that is five to ten times the nominal load current, which may be a challenge to primary equipment, but helps the protective relays to see the fault and isolate the fault instantaneously. In contrast, the short circuit currents produced by wind generators are fairly low. The low wind speed is the obvious problem. In addition to that, the fault current contribution from the wind farms is limited even when there is strong wind, due to the nature of induction generators [15]. Using DFIG as example, the control scheme and protection circuit of the DFIG will modify or isolate the machine excitation current when terminal voltage drops, causing low AC current output that may not differ much from load current. Because of this, a wind farm should be treated as weak source, no matter how large the generation capacity it has. Weak sources will create challenge to protection. Some traditional line protection schemes may not be able to detect the fault. The consequent slow operation of relays will aggravate the wind generators conditions and eventually cause them to trip.

Assuming there was N-1 situation due to loss of important transmission line or large generator, the system may be craving for both reactive and active power to maintain the stability. If large amount of wind generators are trying to absorb reactive power or just trip off-line, the situation would be escalated to cascading trip of more generators until blackout occurs. To prevent such event, both the Wind Farm Owners and the Transmission Service Providers must provide solutions. The transmission system must have very robust protection to minimize the possibility of false operation. The internal fault shall be isolated instantaneously and the relays shall not trip for external faults. Especially for CREZ, there are still many unknowns about future development of renewable energy, it is expected that the most reliable system protection should be applied to ensure the security, sensitivity, selectivity and high speed on fault clearance.

B. *Challenge from Interconnection*

There are altogether nine Transmission Service Providers in CREZ program, creating many interconnections in the transmission network. For example, ETT needs to interface with six other Utilities to build the lines or substation terminals. It is common in CREZ program that one TSP owns the T-line and another TSP owns the T-line terminal. One of the lines even has three ownerships involved. On one hand, this brought the investment and competition into CREZ program. On the other hand, it has created much difficulty to P&C design and maintenance.

Since each TSP has its own standards and protection philosophies that may be rooted from long term operation experience, and any change to standards means effort and cost, it was not easy to achieve agreement on P&C schemes for the interconnection. The most challenging part was the communication-aided pilot scheme. At the very beginning, the power line carrier (PLC) based schemes such as Directional Comparison Block (DCB) scheme or Permissive Overreach Transfer Trip (POTT) scheme were preferred by most TSPs. Because such carrier schemes have long service records in most Utilities. An alternative is the current differential (87L) scheme, which is superior in principle but has high requirement on the communication channels. Even after the consensus on 87L was made among TSPs for CREZ projects, there was still disagreement on how to set up the communication network and what type of relays should be used. These are just some examples of interconnection negotiations. There would be no issue if the line is fully owned by one TSP. But it did become great challenge to coordinate with all the TSPs in CREZ program that is characterized by many interconnections.

C. *The Redundancy Requirement*

The redundancy would not become a problem if fund was not an issue. However, money is always an issue. The engineers have to justify the cost with benefits. Since the CREZ 345kV lines will become part of the bulk transmission system in Texas, it was reasonable to elevate the reliability of P&C system to a high level. Per NERC [7], the protection systems should provide redundancy such that no single component failure would prevent the interconnected transmission systems from meeting the system performance requirements. Explicitly, the redundancy should cover the following items:

- AC current source
- AC voltage source
- Protective relay
- Communication channel
- DC circuitry
- Auxiliary trip relay
- Circuit Breaker (CB) trip coil
- Station DC Source

Among these, the redundancy on communication channel for line protection is the most challenging part since there can be different solutions resulting in cost difference. The redundancy on DC source and the separation of DC circuitry also created some challenges in P&C design.

D. *Mutual Coupling of Parallel Long Lines*

Majority of CREZ lines are built as double circuits on the same tower structures. The line length is ranged from 30 miles to 110 miles. It is well known that mutual coupling between the parallel lines can have significant impact to protection schemes. Because of mutual coupling, the ground distance protection or ground overcurrent protection will be affected by the induced zero sequence current and voltage, resulting in underreaching, overreaching or false direction under different conditions. The carrier schemes such as DCB or POTT are based on distance and directional elements, therefore are prone to mis-operation caused by mutual coupling. The consecutive tripping of CBs at the two terminals of a faulty line may also cause coordination problem for the carrier scheme of the unfaulted line, because the current direction may suddenly change to confuse the directional relays and the scheme.

In CREZ projects, there are also lines that share the same right-of-way with the existing 345kV or 138kV lines. Since the ground source of these lines are not tightly coupled, when ground fault occurs on one of the lines, the relays for the unfaulted line are more likely to trip falsely due to the induced zero sequence voltage.

E. *Challenges Brought by Series Capacitors*

In order to increase the power transfer capability and to improve the system stability, a number of series capacitor banks are planned in CREZ system. With all the benefits to the system, the series capacitors (SC) also bring challenges to protection engineers. The conventional protection schemes may mis-operate because the insertion of SC and its auxiliary equipment changes the inductive network that most relays are designed to deal with. From the standpoint of signal processing, the normal phase relationship between current and voltage signals during the fault may be altered by the SC, which may lead to wrong assertion on fault location or fault direction. Some of the known issues are:

- Non-linear apparent impedance from SC and MOV

To prevent damage from over-voltage, the SC is usually protected by Spark Gap and Metal Oxide Varistor (MOV). If the fault current is not high enough, the MOV may not fully conduct and its non-linearity could cause problem to distance relays and directional relays.

- Voltage inversion and current inversion

Most relays utilize the phase relationship between local voltage and current signal, or between local and remote currents, to determine fault direction or fault location. With the addition of SC, the natural relationship especially the phase angles of voltage and current signals could be changed, which is manifested as voltage inversion or current inversion to relays [11], such that protection scheme may trip for external fault or fail to trip for internal faults.

- Sub-synchronous resonance

When there is power generation in the vicinity of a series-compensated line, sub-synchronous resonance could happen either because of the interaction between turbine-generators and SC, or due to the self-excitation of the induction generators under certain network configuration. The corresponding low frequency signals can hardly be filtered out by relays such that the estimated fundamental frequency phasors could have error in both magnitude and phase. Since the phasor estimation is essential to a digital relay, the protection functions could be affected.

- Distance relay settings

The distance protection for series compensated line may be difficult to coordinate. Because of compensation, the zone 1 reach has to be reduced to a small fraction of the line, or even disabled. The zone 2 needs to reach far enough to cover the line with margins when SC is bypassed. But this could cause overreaching when the SC is not bypassed. For ground distance relays, the zero-sequence compensation factors are generally fixed settings. But for a series-compensated line, they can be drastically affected by the fault position and fault current level, resulting in significant error with ground distance loop measurement.

- Reclosing coordination

The SC banks are usually installed on insulated platforms. If the platform flashover occurs, the auto-reclosing is not desirable and the line may be out of service until the platform is isolated and bypassed. In order to restore the line quickly, special schemes need to be designed to distinguish SC zone fault and line faults, in order to coordinate the auto-reclosing of the line CBs.

The system study also revealed that line terminal breakers for the series compensated line could experience very high transient recovery voltage (TRV) when they are tripped. The worst TRV would happen if the CB is tripped after reclosing onto fault. The protection scheme may not resolve the TRV issue for the first instance, but can help to make sure that series capacitor is bypassed before the reclosing.

- The others

There are still some unknowns that are up to specific system configurations and system components. The fault transients caused by interactions among generators, transformers, power electronics, reactors, motors, CVTs and series capacitors are difficult to determine without extensive simulation studies. The performance of protective system may only be evaluated by a close-loop type real time digital simulation system such as RTDS.

F. Challenge Brought by Shunt Reactors

Since the wind is highly variable energy source that could cause power flow swing and voltage fluctuation, many reactive power control equipment such as Static VAR compensator (SVC), shunt reactors, shunt capacitors etc. are deployed in CREZ system. For long transmission lines, it is beneficial to attach the shunt reactors to the lines such that they can be put in service to prevent line overvoltage at no load or light load, and taken out under heavy load or when system needs voltage support. However, the system study has revealed that shunt reactor attached to the double circuit transmission lines could also pose significant challenges to primary equipment. The protection engineers are called for to provide solutions.

First, the energization or reclosing of a shunt compensated line may result in high DC offset, as illustrated by Figure 4. The tripping of the line CBs immediately after closing or reclosing of these CBs could result in sustained arcing between CB contacts. As we know, the AC breaker needs zero crossings of current to stop the current flow. Due to the very high X/R ratio brought by shunt reactor, the DC offset of the current could shift the AC components above the zero line and let the arcing last for a long time. Eventually the CB could fail.

Second, when one of the parallel lines is open with shunt reactor attached and the other line is still energized, very high voltage can be induced to the open line. Per Figure 5, the induced voltage to the open conductor can be calculated by Equation (1).

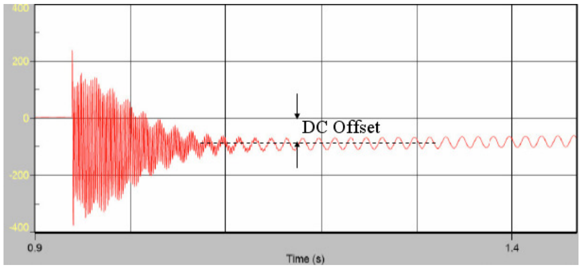

Figure 4. The large DC current offset due to shunt reactor

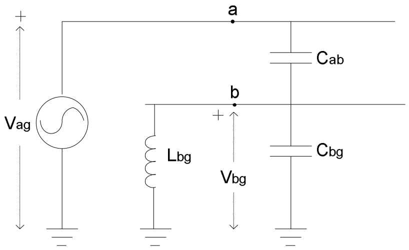

Figure 5. Capacitive coupled circuit representation

$$V_{bg} = V_{ag} \cdot C_{ab} \div \left[C_{ab} + C_{bg} - \frac{1}{\omega^2 \cdot \ell \cdot L_{bg}} \right] \qquad (1)$$

From the equation, the induced voltage V_{bg} could be even higher than the source voltage V_{ag} if the denominator becomes smaller than the numerator, depending on the coupling capacitance (C_{ab}, C_{bg}) and the inductance (L_{bg}) of the shunt reactor. The induced voltage not only causes problem to the insulators, but is also dangerous to maintenance workers.

Third, since the shunt reactors are mainly used to regulate the reactive power in CREZ system, they could be switched in and out frequently during a day. The general CB is not appropriate for frequent switching of shunt reactor because the opening operation of general CB on small inductive current may produce high energy re-ignition that is stressful to the shunt reactor and the CB itself, as shown in Figure 6.

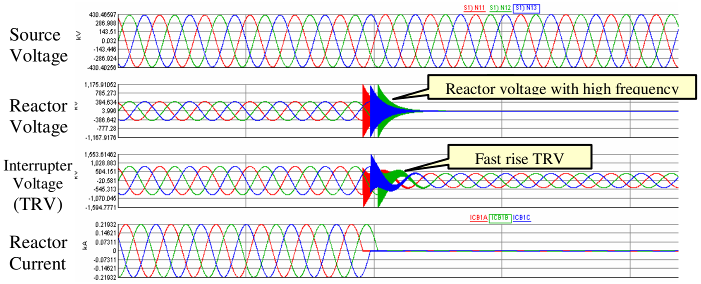

Figure 6. The high TRV to open shunt reactor by general CB

To address this problem, the AEP Station Engineers selected a specially designed Circuit Switcher (CS) for shunt reactor switching operations [10]. However, such CS does not have the capability to interrupt high fault current if the fault is within the shunt reactor zone. The protection scheme has to be designed to handle this issue.

G. Communication Channel Issue

After many discussions among CREZ TSPs, it was determined that the multiplexer based Synchronous Optical Network (SONET) are to be set up to provide the communication channels for line protection. However, there were arguments on how to set up the SONET for interconnection. Technically, two SONET rings would be sufficient to provide redundant communication channels for all the lines that make up the loop. The self-healing feature of the SONET ring actually provides one more layer of redundancy. However, due to legal and security concerns, the sharing of SONET equipment among TSPs became a formidable task. For example, there is security concern when the staff of one TSP requires access to another TSP's substation for SONET trouble shooting. Since the multiplexer has service board that can access the other nodes on the SONET ring, the security of the digital network was also concerned. Even though the SONET network does not fall into the category of NERC CIP standards for the time being, there were concerns that in the future the NERC CIP standards may be extended onto telecommunication network. Another concern is the future maintenance. For example, if the multiplexers for the SONET need to be upgraded with new firmware, all the TSPs involved need to coordinate with the effort.

H. Other Issues

During the CREZ project execution, there were also other issues revealed by ongoing system study. For example, the motor operated ground switches were added to each line terminal to ensure the worker safety due to the induced voltage and current from the parallel circuit. The switching studies indicated that very high TRV could happen to CBs for series compensated lines. In order to deal with the variable wind power in the future, it is also necessary to prepare for wide area reactive control schemes. All these issues are more or less related to the protection and control and they require the protection engineers to come up with good solutions.

III. THE SOLUTIONS

Like many other Utilities, AEP P&C engineers would like to apply standard designs as much as possible to all the transmission projects. But with afore-mentioned challenges of CREZ system design, the engineers have to be adaptive. After all, the ultimate goal is to design a very robust P&C system that will contribute to the overall system reliability. Based on the existing standards and the state-of-art relays, the AEP engineers created a set of CREZ P&C standards for AEP/ETT system, which not only address the CREZ challenges but also provide enhancement to the AEP Standards Library.

A. Using 87L for Line Protection

Facing the stringent requirements of renewable energy and many variables of the CREZ system, there is no doubt that the most reliable protection schemes should be applied. At the early stage of CREZ projects, there were keen discussions among TSPs about the pilot schemes for interconnection. The carrier-based schemes such as DCB or POTT were attractive at the beginning because the cost is low and every TSP had much experience with it. The alternative is to use line current differential (87L) scheme, which is reliable but has high requirements on communication channels. The P&C engineers had to make a balance between technical merits and the cost, same as many other projects.

Technically, the 87L scheme is superior to carrier schemes such as DCB or POTT. The DCB or POTT are relying on the single-ended protection elements such as distance elements (21P/21G) and directional overcurrent element (67G), which are in turn based on the voltage-current relationship in magnitude and phase, in sequence components and phase quantities. In comparison, the 87L scheme utilizes local and remote signals. It can discriminate fault and fault location simply by looking at the current flow in and out the line terminals. Since 87L scheme is basically independent of voltage signals, it is not only simpler in principle but also more reliable in practice. By using 87L and high speed digital communication channels, some of the challenges that CREZ system was facing can be naturally resolved. First, 87L is immune to the mutual coupling effect, which is a serious consideration to almost every CREZ line. Second, 87L is reliable for series compensated line and its adjacent lines, because issues like nonlinear component, sub-synchronous resonance, voltage inversion, etc. would have little effect to 87L. Third, 87L is immune to power swings, which rarely happen but can be detrimental to the system when serious event occurs like that in 2003 North America Blackout. In that event, the system condition was exacerbated after relays being tripped by power swings. Fourth, the 87L settings are easy for coordination. The engineers usually do not need extensive studies for 87L settings. As a matter of fact, even the default 87L settings could be used for most lines, which is unthinkable for other types of protection. In addition to all these merits, the 87L also have superior performance for high impedance faults, evolving faults, cross-country faults, weak-feed applications, etc., which are all challenges to protection engineers when they are dealing with carrier schemes.

Because of its simplicity and reliability, the current differential principle is actually widely applied in power system for transformer protection, bus protection, generator protection, etc. The reason that line differential scheme has not acquired its popularity is because of the cost associated with the communication channels. In order to compare the terminal currents in real-time, the high speed digital channel is needed. The optical fibers would be ideal for 87L. But it can be costly to install fiber cables in long distance. The Optical Composite Ground Wire (OPGW) cable is typically used by Utilities to take the advantage of the transmission line construction. Because of the savings on labor, the cost of OPGW is relatively low for new construction projects.

After extensive discussions among TSPs, mainly to address the need of system protection, the PUCT and ERCOT committees finally decided that each CREZ double circuit line should have at least one OPGW installed. The fibers in OPGW can also be used for SCADA, synchrophasor, video surveillance, wide area control etc. It was a wise decision to get much benefit with moderate investment. More importantly, this decision sets up a good foundation to utilize the most robust protection schemes for CREZ lines, which will contribute to the overall system reliability in the future.

Since 87L has much advantage and the good digital channels are available. The AEP/ETT design for all the internal lines will use the state-of-art 87L relays for redundant protection. The dual 87L schemes are also applied to most interconnection. For a few interconnections, the DCB scheme is still used as backup scheme, which was a compromise other TSPs.

B. SONET Ring Setup for 87L

In CREZ projects, majority of lines are planned to have only one OPGW installed on top of the tower, together with a regular ground wire. After all, the OPGW costs more even with savings on labor. This brought the channel redundancy issue. The full redundancy for bulk transmission system requires that line protection should maintain its integrity even if one OPGW cable is cut off. In order to achieve channel redundancy, the protection and telecommunication engineers came up with the design of using the self-healing SONET rings. The Figure 7 shows an example of 4-node SONET ring for T-lines that connect four substations.

The SONET ring is based on a number of multiplexers connected by single mode optical fibers embedded in the OPGW. Each multiplexer is a ‘node’ on the SONET ring. The relays are connected to the multiplexer using multimode fiber and IEEE C37.94 interface. During normal operation, the relays for the line will communicate with each other through the shortest path, i.e., between the two adjacent nodes for the line. If one OPGW is cut-off, all the multiplexers on the ring will automatically re-route the data packets through the alternate long path immediately, such that the communication between the two relays is maintained by seamless channel switching. The redundancy therefore is achieved by utilizing the OPGW of other lines, which is more economical than putting two OPGW’s on the same towers.

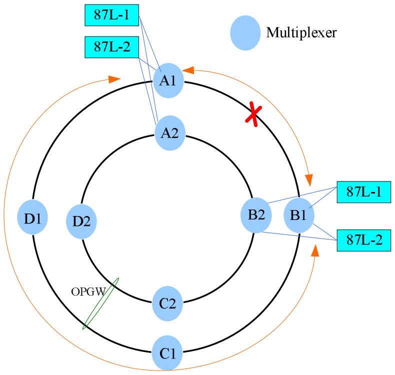

Figure 7. The SONET ring and relaying

Since the multiplexers are part of the critical protection scheme, they must be as reliable as the relays. The data packets must be delivered and received with fidelity and with very low latency under all kinds of conditions. The multiplexers should be able to re-route the transmitting and receiving of data packets at the same time to avoid asymmetrical communication for 87L. They should also be hardened IEDs to withstand harsh environment in a substation.

From Figure 1, the CREZ lines are crossed over like jigsaw puzzles, so it was not a problem to set up a number of SONET rings per transmission network layout. However, the SONET ring setup for interconnection was challenged by legal and security concerns that are explained previously. After many discussions among the TSPs, it was finally determined that fibers will be shared, but multiplexers will not be shared to construct the rings, meaning that multiple SONET rings may be set up for a physical loop that involves interconnection. The Figure 8 gives an example.

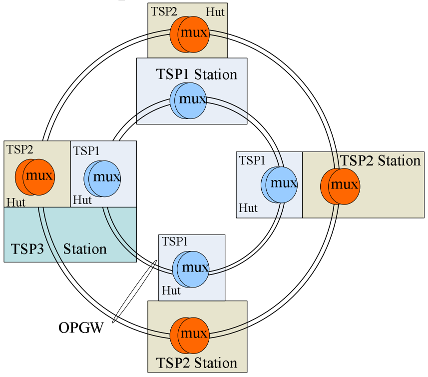

Figure 8. The multiple SONET ring for interconnection

In this example, the four substations are owned by three TSPs respectively, as illustrated. Some lines are owned by TSP1 and some are owned by TSP2. The TSP1 and TSP2 will have to set up their own SONET rings separately with the shared OPGW. To deploy the SONET nodes (multiplexers) in other TSP’s territory, the TSP1 will have to install a telecomm hut outside the substation fence that is owned by TSP2 or TSP3. Same for TSP2, they have to install telecomm hut outside the fence of Stations owned by TSP1 and TSP3.

This arrangement looks cumbersome because four or more SONET rings may be setup for a physical loop, while two SONET rings would be sufficient for all the protection. It also costs more to install telecommunication hut outside other TSP's substation fence. However, this arrangement can resolve the concerns on maintenance and security since each TSP will have sole ownership of the complete SONET ring. It may be cost effective to share the nodes among TSPs, but the ambiguity on the ownership might cause more trouble in the future. More importantly, it was the only solution that all the TSPs could agree upon in CREZ projects.

The standard IEEE C37.94 interface is used to connect the relays to the multiplexers. Since most 87L relays can have redundant C37.94 ports, each relay can be cross-connected to the dual SONET rings such that full redundancy can be achieved, as illustrated in Figure 7. In addition to the 87L function, the Direct Transfer Trip (DTT) signals and some asynchronous RS232 signals are also transported over the SONET. Some TSPs would use the DTT cards or asynchronous cards provided by multiplexer vendor. The AEP approach is to standardize on C37.94 interface for all relaying if possible. The DTT signals are transferred via the 87L relays when dual 87L relays are used. If not, the off-the-shelf I/O units supporting C37.94 or converters are used to simplify the multiplexer configuration and leave only optical fibers between the protection panels and multiplexer panels.

C. *Auto-reclosing*

The AEP general practice for 345kV line auto-reclosing (AR) is to have one shot of high speed three-pole AR, initiated by the trip signal from pilot protection only. If the line is connected with a generating plant, AR is either disabled, or slow AR with synchronism check is used. For CREZ, a different AR strategy is taken due to the specialty of the system.

Since the future CREZ system will have a lot of wind generations tied to it and most of the wind farms will be tied to the weaker portion of the overall system. There is a stability concern with permanent faults and unsuccessful reclosing. Using the general AR practice, one permanent fault could let the system experience up to three shocks: the initial fault, the fault after auto-reclosing, and fault after manual closing by dispatcher. If three attempts are made to bring the 345kV transmission line back to service, more wind farms generators could trip due to extended voltage sag or power angle instability. Consequently the overall system could be at risk. To address this concern, AEP proposed to have one shot of high speed AR for single phase ground (L-G) faults only. Because L-G faults are the most frequent type of faults and have the less impact to the system if the fault is permanent. Actually, most L-G faults are temporary such that the probability of successful reclosing is high. In comparison, the 3-phase faults or phase-to-phase faults would occur less and have more possibility to be permanent faults.

Since the 345kV breakers have separate three poles, the possibility of single-pole AR was considered at the early stage of CREZ project. Compared with three-pole AR, the single-pole AR is advantageous in maintaining system stability. However, single-pole AR also brings much complexity to protection and control schemes. Considering that CREZ projects have many interconnections and that 3-pole AR is the common practice of most TSPs, it was finally decided to use three-pole AR.

In order to have three-pole reclosing for L-G fault only, the phase selector of the modern line relay is utilized. The 87L relay manifests its advantage again because the phase selector from current differential scheme is superior to any other types of phase selectors, which are generally relying on the local current and/or voltage signals.

To reduce the impact of reclosing-onto-fault, the AR scheme is designed with a leader/follower sequence. One CB designated as leader will reclose first to test the line, if the reclosing is successful, the other CBs will reclose under synchronism condition. The typical AR interval is about 30 cycles. For series compensated line, the AR interval can be longer to allow enough time for the Spark Gap to deionize. When defining the leader or follower CB, the AEP approach is to assign leader CB at the stronger end of the line because a strong terminal also means the system behind the relay has more stability margins.

D. *Redundancy Design*

Since the CREZ lines are critical to system reliability, the AEP engineers had the redundancy in mind throughout the design process. Every EHV component such as bus, line, shunt reactor, shunt capacitor, transformer etc. is covered by redundant protection using state-of-art relays. In addition, there are dual battery systems and dual chargers to ensure the continuous DC supply. This however increases the complexity of the protection and control circuitry. Ideally, the two DC systems should be completely separated such that one failure point in DC system would not affect the other. However, the complete separation was not as easy as it sounds.

Like many other Utilities, the AEP standard CB control scheme utilizes only one IED relay to provide control, monitoring, alarm, CB failure protection and reclosing for each CB. It would be complicated and unnecessary to deploy two control relays for each CB. But it becomes inevitable to have both DC systems connected to one single relay and the relay itself will be powered by only one DC system. The design was trying to separate the two DC circuits as much as possible on this single relay according to its I/O layout.

The cross tripping was also considered during the design. Each CB has two trip coils. For A and B line protection relays, it is better not to cross tripping such that they are completely separated on AC and DC circuits. However, since there is only one CB control relay for each CB and this relay has trip signal inputs from both A and B line relays for breaker failure and reclosing, it was determined to let it repeat the trip outputs to both trip coils. This way, either A or B protection will actually actuate two trip coils, one directly and one indirectly. The trip from CB control relay is similar to the re-trip logic of the CB failure scheme, which helps to alleviate the consequence of false breaker failure initiation due to human error.

By using SONET rings, the communication channel redundancy is achieved with reasonable cost, as compared with two OPGW's for each T-line. And by using 87L protection, there is no problem with only one CVT since the voltage signals become less critical for protection. The single CVT will still have separate secondary coils for A and B line protection relays.

E. Shunt Compensated line protection

The P&C schemes are specially designed for shunt compensated lines. To address the issues brought by high DC offset and high induced voltage, the shunt reactor needs to be isolated whenever the line is de-energized, no matter it is due to line faults or from switching operation. The Circuit Switcher (CS) control relay for the shunt reactor has undercurrent function enabled for this. In addition, whenever the line protection relays trip the CBs, they will send signals to trip the CS as well. Since the CS for shunt reactor cannot interrupt the high fault current. Any protection trip signal to CS will be delayed by a typical setting of 13 cycles, which accounts for breaker failure delay.

For a ground fault on the line, the line relays will trip and initiate AR sequence for line CBs and the CS. If the leader CB is reclosed successfully, the CS should be closed next to put in the shunt reactor to avoid the overvoltage on the line, but under the condition that shunt reactor was in service before it is tripped. Based on reclosing time coordination, the follower CBs would reclose after the reclosing of CS.

There is also a motor-operated-switch (MOS) for shunt reactor isolation. If the CS fails to open after the line relays operate for a line fault, the MOS should be opened to isolate the shunt reactor and the CS. When this happened, the line CB reclosing cycle is paused until the MOS is completely open.

The shunt reactor itself is protected by dual current differential (87T) protection and restricted ground fault protection. If a fault occurs within the shunt reactor zone, all the line CBs including remote CBs shall be tripped instantaneously. The MOS and CS shall be tripped too. In AEP design, the line CBs and MOS are tripped by lockout relays that are picked up by 87T relays, while the CS is tripped with delay by 87T relays. The lockout trip to line CBs will be bypassed after the MOS is open, which allows the dispatcher to close the line CBs through supervisory control. There is no AR if the fault is within shunt reactor zone.

From Figure 9, the two breaker CTs are separately connected to each 87L line relay, instead of being summed up externally to the relay. This will enhance the 87L restraint capability for high through fault current [13].

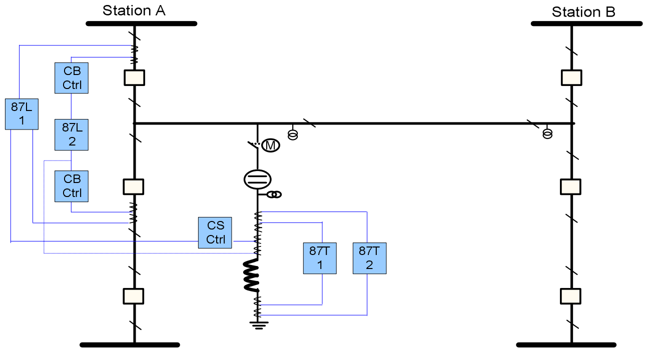

Figure 9. The shunt compensated line protection

One type of 87L relay can support maximum four separate CT inputs, so the shunt reactor CTs are connected directly to the relay. The other type of 87L relay has maximum two separate CT inputs, so the shunt reactor CTs are summed with one of the breaker CTs. Either way the shunt reactor is excluded from the line protection zone. This is beneficial to the 87L protection because the shunt reactor will be switched on/off frequently such that the line charging current may or may not be compensated during normal operation. It is also because the shunt reactor and line capacitance would have different response to transients and they cannot completely cancel each other for through fault current. By excluding the shunt reactor from 87L zone, the voltage based charging current compensation feature of modern 87L relays can be enabled all the time to eliminate the error brought by line capacitance.

F. Series Compensated Line Protection and Control

By using dual 87L for series compensated line protection, the probability of mis-operations will be reduced mainly because the voltage signals and its associated problems are excluded in the 87L function. The current inversion may be the only concern for 87L scheme. But since most series capacitors in CREZ system are installed in the middle of the line to provide 50% compensation, the current inversion is unlikely to happen because it happens only when the Thevenin equivalence from the fault point is capacitive [11]. In addition, since the MOV will conduct for high fault current, which effectively bypass the SC for internal faults, the current inversion can hardly happen.

The protection for SC bank and its auxiliary equipment is implemented by dedicated controllers, which are provided and configured by the SC vendors. The Figure 10 illustrates the typical SC protection functions, of which the pick-ups will close the bypass CB for equipment protection. If the platform flashover or the live tank bypass CB flashover happens, the line protection will see the fault and trip, but it is not typical to have a special reclosing scheme for such faults.

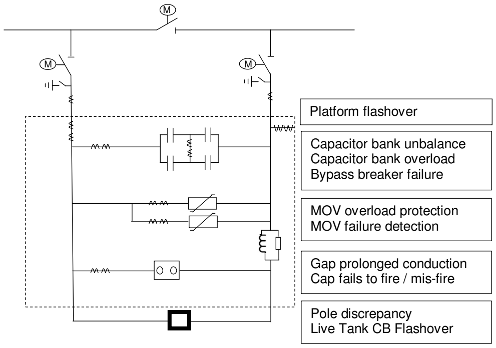

Figure 10: The capacitor bank protection

To reduce the outage time for SC platform flashover or bypass CB flashover, a scheme was designed to automatically isolate and bypass the SC platform using motor-operated-switches (MOS) for faults within the SC zone. First of all, the scheme must be able to distinguish the SC zone faults from the other line faults. The SC platform is supported by insulators and it has only one point connecting the live equipment, so the CT installed at this point and an overcurrent relay is able to detect the platform flashover. Similarly, a donut type CT installed at the bottom of the live tank bypass CB can be used to detect the bypass CB flashover. The scheme to make a differential zone for SC bank was considered but was given up due to the extra cost on the free-standing CTs.

Second, the SC zone fault signal and the MOS (bypass MOS and isolator MOS) status signals need to be sent to the line terminals to pause or resume the AR process. The SONET ring and modern IEDs can facilitate this scheme. The Figure 11 provides an example for a SC station in the middle of a CREZ line. In this example, dedicated I/O device is installed at each terminal to exchange data through multiplexers and C37.94 interfaces. At the line terminal stations, the similar I/O device has hard wire connections with the CB control relay and line relays. At the SC station, the I/O device is connected to the SC bank controller.

If the platform flashover or bypass CB flashover happens, the line relays should see the fault, trip the line CBs and initiate the AR. Meanwhile, the flashover should be detected locally at SC station and the information is passed to line terminals. The AR would be paused until the automatic isolation/bypass operation is finished at SC station.

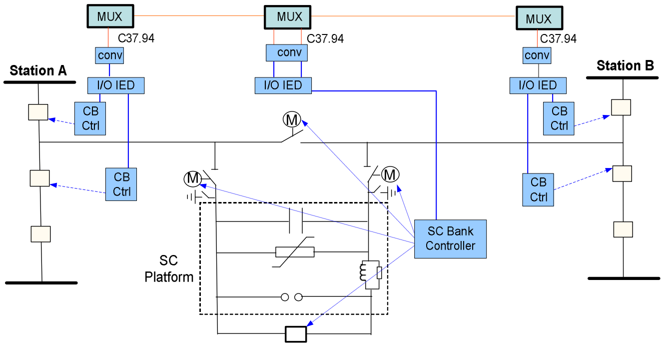

Figure 11: The Auto-Reclosing Scheme for a SC Line

G. *RTDS Simulation Tests*

To ensure the P&C design to meet the system reliability requirement, a series of RTDS tests were performed in AEP P&C Lab to verify the scheme design, the relay templates and the relay settings for CREZ lines.

With dedicated hardware and software to perform parallel computing, RTDS is able to resolve all the power network equations with a typical computing interval of 50μs. Because of such small time step, the signals produced by RTDS and the associated amplifiers would have no difference from the actual power system seen by protective relays, such that the relay response can be examined in a close loop test environment. Many faults under various operational conditions can be simulated to verify the relay settings and schemes. The Figure 12 shows the typical RTDS set up for relay tests.

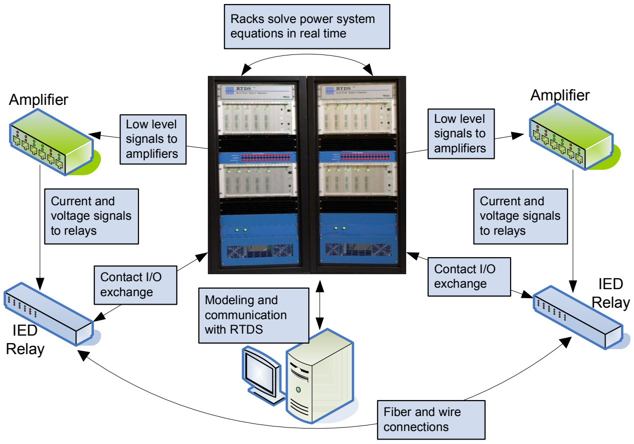

Figure 12. The RTDS Relaying Test System

By using RTDS, a relay can be tested with much more faults in one day than during its life time. A number of issues were actually found during the design and RTDS tests. It is hoped that all the possible mis-operations will occur in the Lab instead of happening to the actual CREZ system in the future.

IV. CONCLUSIONS

The CREZ system is so far the largest transmission program in U.S. for the development of renewable energy. The P&C engineers were facing numerous challenges brought by the system, the primary equipment, the communication and the relaying schemes. By using optical fiber based SONET rings and dual current differential schemes, many issues have become easier to resolve. This paper provides details on the challenges and the solutions taken by AEP engineers. Through the CREZ project execution, the APE Standard Library has been enhanced and good examples have been set up for the similar transmission projects in the future.

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