Simplified Designs for Switching Reactive Power Improve Power System Reliability

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***Abstract*— this paper is a general discussion of the methods of switching employed for reactive power compensation, the problems encountered with conventional devices, and the improvements made by the latest advancements in technology. Switching reactive power produces voltage transients, chops currents, and stresses equipment. The switching can be harmful to the reactor, the capacitor, the switching device, and/or the adjacent system components. Successful interruption is a complex interaction between the switching device and the circuit. The industry has developed an assortment of switching devices and countermeasures to address the problem. Methodologies suggested by accepted philosophies might not offer the best alternatives now available with the technology improvements.**

***Index Terms* — reignitions, synchronous openings, restrike point, recovery voltage, current chopping, inrush current**

I. Introduction

Normal operation of transmission and distribution systems require voltages be maintained within a relatively small range. This is typically between 0.95 to 1.05 pu of rated value. Application of shunt reactors and capacitors has proven to be a cost effective method to compensate for excessive reactive power (inductive) during heavily loaded conditions and (capacitive) lightly loaded conditions. Shunt reactors are used to reduce overvoltages found in lightly loaded transmission lines. This rise in voltage is caused by the flow of leading current drawn by the inductance of the system and is called the Ferranti effect. Shunt reactor configurations can be dry type air-core or oil-immersed devices. Shunt capacitors are used to boost voltages when transmission and distribution lines are heavily loaded.

An often overlooked component of the system, when adding a reactor or capacitor, is the switching device. If misapplied, it can lead to equipment damage or unwanted system disturbances. There are several interrupting technologies currently in use for the switching of shunt capacitors and reactors. They are:

Oil devices
Vacuum devices
Air blast devices
SF_6 (sulfur hexafluoride) devices

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II. Basic Switching Theory

Utilities normally switch resistive, capacitive, and inductive loads in the course of daily activities. Of course, most switching loads are a combination of a resistive component and some inductive or capacitive component. As the inductive or capacitive components increase, the switching becomes progressively more difficult. In highly inductive or capacitive loads the voltage and current are not in phase, which results in one leading or lagging the other.

The majority of utility applications require switching of a resistive load, with minor inductive and capacitive components. This is precisely what the majority of the switching devices are designed to handle. Shunt inductors and capacitors, however, present a very specialized set of switching parameters.

When selecting a device for switching highly inductive or capacitive loads, the engineer should pay close attention to the capability of the device chosen. A switching device designed for general purpose switching (e.g., designed primarily for switching resistive loads) may perform the function, albeit not as well as a device that is designed specifically for the task of switching reactors or capacitors. In addition the engineer has to be cognizant of the cost effectiveness of the selection. Many of the general purpose devices are based on expensive and sophisticated technologies better suited to protection schemes.

A. *Resistive Loads*

Resistive loads have their voltage and current in phase. When a resistive load is de-energized, the contacts of the switching device begin to part, the gap is small, and the dielectric strength is low. It is not physically possible to separate fully the contacts instantaneously due to the inertia of those contacts, so the contacts must be accelerated.

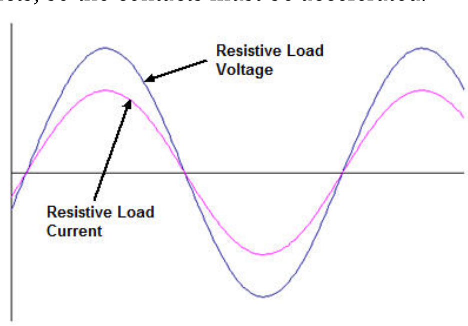

Fig. 1. Resistive load voltage and current waveforms

As the gap widens, the distance increases, which increases the dielectric strength of the gap. Once the voltage waveform crosses zero, the voltage begins to increase in magnitude. The voltage across the opening contacts is referred to as *recovery voltage*. If it increases faster than the gap's dielectric strength, the current will be reestablished through an arc across the contacts. The contacts continue to separate and the gap's dielectric strength increases to the point, the arc is extinguished when the current waveform reaches the next zero crossing. Switching devices are designed to dissipate the energy of this arc and the small associated transient voltage disturbance.

B. Capacitive and Inductive Loads

When the load is capacitive or inductive, the situation is quite different. Basic electricity theory emphasizes that neither the current across an inductor nor the voltage across a capacitor can change instantaneously.

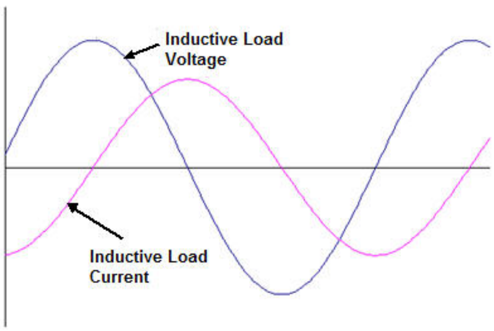

Fig. 2. Inductive load voltage and current waveforms

In the case of an inductive load, the voltage leads the current by 90° (Fig. 2). With a capacitive load, the current leads the voltage by 90° (Fig. 3).

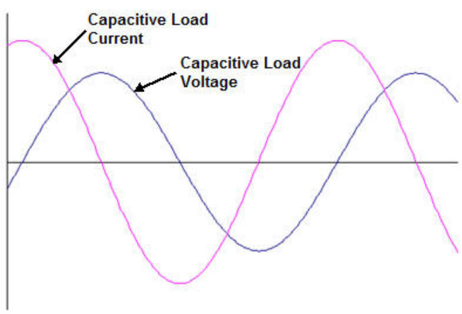

Fig. 3. Capacitive load voltage and current waveforms

Switching capacitive and inductive loads into the circuit results in an *inrush current*, as the voltage adjusts to the system voltage. The inrush current magnitude is directly related to the inductance of the source supply circuit when switching in a capacitive load. As the current decreases, the voltage increases. The voltage and current waveforms oscillate at a frequency higher than the power system's frequency.

Switching a reactor into the circuit gives rise to inrush current, which is a transient phenomenon related to saturation in the shunt reactor's magnetic circuit. In principle, it is the same as the inrush current of a transformer, but there are two differences. An air-core reactor keeps no remanence, because there is no iron core. However, the damping of the asymmetric condition – "the dc component" – is slow, due to the inherent low losses in a shunt reactor. Experience has shown that most modern switching devices perform this function adequately with little if any consequence.

When the switch closes on the capacitor, the voltage crosses zero, and the current is at its maximum value. As the current decreases, the voltage increases. The voltage and current waveforms oscillate at a frequency higher than the power system's frequency.

Switching capacitive and inductive loads out of the circuit is a challenge for the switching device since the current leads or lags the voltage by 90^{o}. The current is interrupted close to its zero crossing when the voltage is at its maximum value. As the interrupter contacts part, the capacitance is trapped on the load side of the interrupter. The dielectric strength, of the gap, increases as the gap gets larger, but the voltage difference across the contacts increases more rapidly. If the voltage across the gap exceeds the gap's dielectric strength, a *restrike* occurs. This restrike causes an arc that reestablishes current flow. At the next current zero, the switching device will attempt to interrupt the current again. If it is not successful, the device will experience a second restrike and successful interruption will have to wait until the third current zero. Figure 4 shows the worse case that may occur. It most likely occurs when using fault clearing vacuum interrupters on capacitor banks, which are more likely to interrupt the high frequency current zeros.

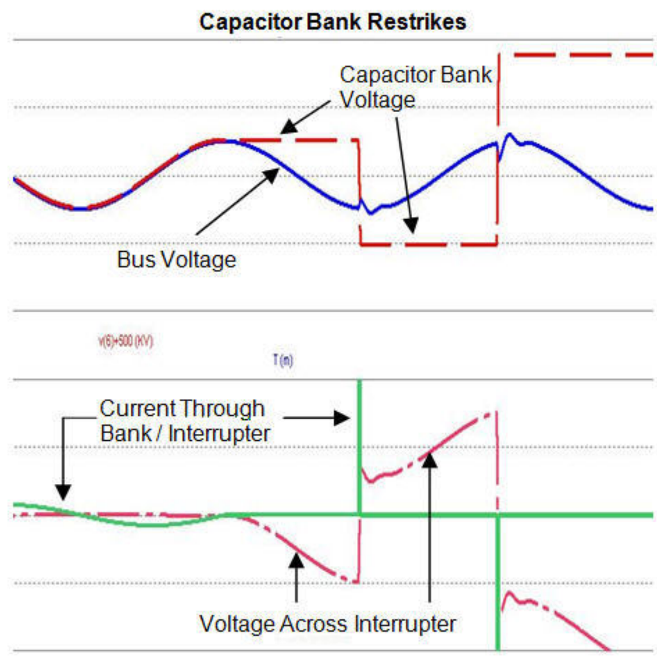

Fig. 4. Effect of multiple restrikes

III. Switching Shunt Reactors

Shunt reactor switching can impose a severe duty on the connected system and the switching device. Interrupting the relatively *small inductive current, generally less than 300 A*, is easy for most switching devices resulting in the interrupting device try to *clear at a forced current zero (current chopping) or at the first current zero due to the low magnitude of the current.* At this point, the device's interrupter contacts are still very close to each other. The gap's dielectric strength is typically not sufficient to prevent a reignition due to the very fast recovery voltage (Fig. 5). Since a shunt reactor is often switched daily, the repeated high magnitude *reignitions* that occur can result in premature interrupter or reactor failure. Devices used for shunt reactor switching need the ability to mitigate reignitions and current chopping.

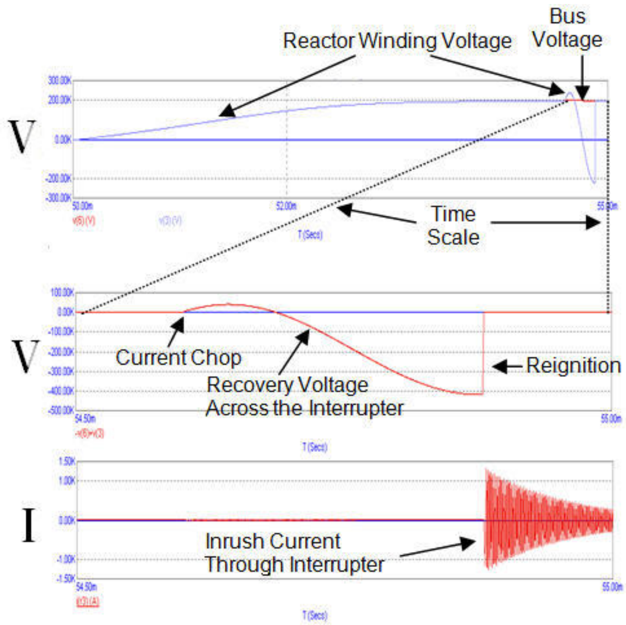

Fig. 5. Shunt reactor reignition

A. *Power Circuit Breaker*

Power circuit breakers are general purpose devices designed for line/bus switching and protection. They have been used for shunt reactor switching for many years. Circuit breakers will almost always interrupt the current at a forced current zero or the first current zero following contact separation. At this point, the contact separation is usually not sufficient to withstand the *recovery voltage* imposed upon it, causing a phenomenon referred to as reignition. Multiple reignitions will eventually result in contact wear and nozzle punctures that can result in breaker failure if corrective maintenance is not performed in time.

To mitigate the problem with contact wear and nozzle punctures, many suppliers have gone to a technology that gives the breaker the ability of synchronously opening relative to the current. This adds complexity, as it requires the use of three mechanisms, a controller, and increased maintenance as a result.

There has also been more awareness recently that interrupter life is affected. Manufacturers and users report problems beginning at about 500 operations. In addition, each reignition (refer to Fig. 5) is similar to a lightning strike on the reactor windings which can result in premature reactor failure

Fig. 6. Shunt reactor switched with a SF_6 breaker

If circuit breakers are used for reactor switching, it is recommended that metal oxide surge arresters be located close to the breaker. This helps mitigate the associated transient voltages across the reactor.

The circuit breaker used as a reactor switching device has the following advantages:

- Full interrupter ratings
- Bushing mounted current transformers
- Local visual gas system indicator
- Remote gas monitoring
- Making and breaking the circuit in SF_6

They also have the following disadvantages:

- Short Interrupter life and high maintenance costs
- High initial cost (e.g., synchronous close designs)
- Synchronous closing is inherently difficult to achieve repeatability over a large number of operations
- Multiple mechanisms (one per phase) to achieve synchronous closing and opening
- Failure of one mechanism to operate can result in single phasing of the reactor

B. *Vacuum Breaker*

Fig. 7. Air-core dry type shunt reactors switched with a vacuum device

Vacuum breakers can be applied to switch medium voltage shunt reactors. It is recommended that metal oxide surge arresters be located close to the vacuum breaker to mitigate the transient voltages across the reactor.

The vacuum breaker is a switching device that has the following advantages:

- Lower initial cost than a circuit breaker with this ability
- Compact design
- No SF_6 gas used - *GREENER*

The disadvantages are:

- Multiple gaps per phase interrupters increase reignitions as one interrupter reignition causes cascading failures for bottles
- Voltage distribution on bottles subject to application restrictions
- Magnetic fields from reactor can trigger difficulties by concentrating the arc in one location causing reignitions and failures
- Limited interrupting capability
- If individual mechanisms are used per phase, then failure of one mechanisms to operate can result in single phasing of the reactor

C. Circuit Switchers

Circuit switchers were originally designed for primary protection of substation transformers. Similar to circuit breakers, they have been used for shunt reactor switching for many years.

Fig. 8. Oil-immersed shunt reactors switched with a circuit switcher (horizontal interrupter)

Circuit switchers have the following advantages:

- Compact design (vertical interrupter design)
- Being able to handle moderate numbers of operations
- Significantly less mass of SF_6 - *GREENER*
- If provided with an integral disconnect, it provides a visual isolation point for the reactor

The circuit switcher has the following disadvantage:

- External arcing in air during closing (i.e., older installations)
- No fault closing rating
- Limited or no fault interrupting capability

D. Special Purpose Reactor Switch

The special purpose reactor switch has a uniquely designed interrupter. The geometry of the arcing contacts and gas nozzle are specifically designed to better control the interaction between the gas, contacts, and nozzle material during switching a purely inductive load out of the circuit.

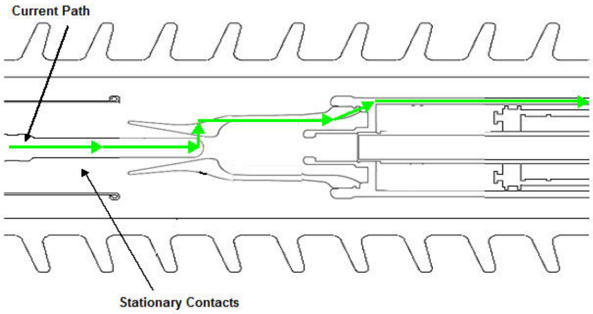

Fig. 9. Special purpose reactor switch interrupter diagram

Through its design improvements, the likelihood of restrikes is significantly reduced. The interrupter extends the minimum arcing time so that when current interruption takes place, the dielectric strength between the contacts will withstand the recovery voltage, thus minimizing the frequency of reignitions.

The design of the interrupter is counter intuitive to breaker designers. Breakers are designed to interrupt at the first possible point in time. Interrupting in the first cycle is very important to a protection scheme, but makes the breaker more likely to experience reignitions. A switch, designed specifically for interrupting inductive loads, on the other hand can take advantage of extending this minimum arcing time. This is achieved by the switch's design rather than relying on the breaker technique of having separate mechanisms on each phase and with a controller to achieve this same functionality.

Special purpose reactor switchers have the following advantages:

- Compact design
- Significantly reduced reignitions
- Interrupter designed to withstand reignition without damage or life reduction
- Eliminates need for synchronous opening controller
- Mitigates turn to turn voltage transients on reactor
- Reduces current chopping
- Significantly less mass of SF_6 - *GREENER*
- Local visual gas system indicator
- Remote gas monitoring

The disadvantages are:

- Switching only, no fault interrupting capability
- Not suitable for general application as a breaker

Fig. 10. Special purpose switch for switching shunt reactors

The chart in Figure 11 shows a comparison between the performance of the special purpose reactor switch and traditional circuit breakers.

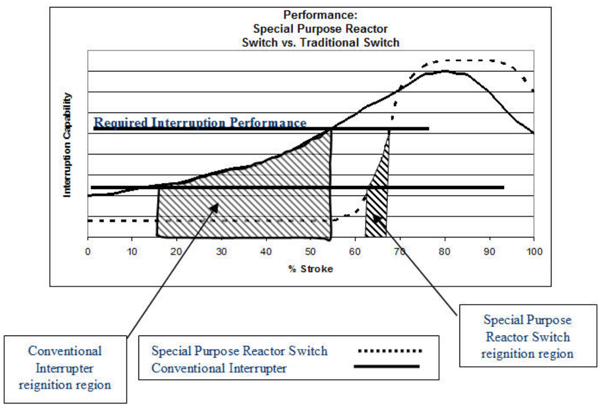

Fig. 11. New technology vs. old technology performance

This delayed arc clearing results in improved switching performance that will extend the life of the switching device as well as reduce the electrical stress on the reactor itself.

IV. SWITCHING SHUNT CAPACITORS

When a switch closes, connecting a capacitor bank to the system, inrush current flows from the power source charging the capacitor. The capacitor bank experiences an immediate drop in system voltage toward zero, followed by a fast voltage recovery (i.e., overshoot). The peak voltage magnitude depends on the system voltage at the moment of energization. This voltage can reach 2.0 times the normal system peak voltage for grounded banks and as high as 4.1 times the normal system voltage for ungrounded banks (Fig. 12). The resulting voltage levels are typically not harmful to utility systems, but because of their relatively low frequency the transients are able to pass through step-down transformers to customer loads. *The resulting secondary overvoltages can cause nuisance tripping of adjustable-speed drives, computer network problems, as well as customer equipment damage or failure.*

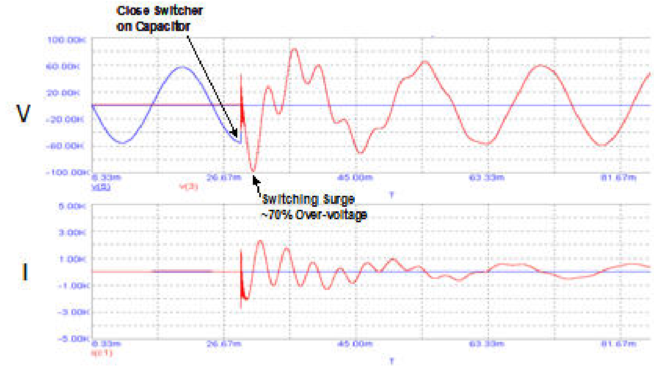

Fig. 12. Switching with no Transient Suppression

When de-energizing a capacitor bank, it is important to minimize or eliminate restrikes as the resulting overvoltages can cause capacitor failure.

Devices used for switching shunt capacitor banks need the ability to mitigate voltage transients and inrush currents.

A. *Vacuum Switches, Circuit Breakers, and Circuit Switchers*

For many years, the oil filled circuit breaker was the only device available to interrupt shunt capacitor banks. They were fitted with pre-insertion resistors, which worked very well, but added to the expense. In addition, circuit breakers were not designed to deal with the extreme number of daily operations or the duty cycles required for switching shunt capacitors.

SF_6 and vacuum circuit breakers and circuit switchers were a step closer to having a device specifically designed for capacitor switching. They could handle the high numbers of daily operations and had improved dielectric strength. To minimize switching transients on closing, they still, however, needed either pre-insertion resistors (voltage and current) or pure inrush reactors (current only). These switching devices still had difficulty preventing restrikes on opening, which often led to damaged capacitor banks or premature failure of interrupter nozzles and contacts.

B. *Circuit Switchers with pre-insertion inductors*

Recognizing the need for transient mitigation, circuit switchers were introduced with pre-insertion inductors, which included some resistance for mitigating voltage and current transients.

Fig. 13 Circuit Switcher with Pre-Insertion Inductor

Insertion is accomplished through a sliding contact between the blade and the inductor, on each pole of the switch.

This operation introduces impedance that limits the initial inrush current and reduces voltage transients. The impedance (inductor) is shorted out (bypassed) a few cycles after the initial insertion transient damps out. *The insertion method utilized limits the ability of this solution to handle closing in on fault. It also can result in increased maintenance to maintain proper alignment.*

C. Synchronous Close Breakers and Vacuum Switches

When synchronous closing technology became available, it was added to power circuit breakers and vacuum switches. It provided a real breakthrough in capacitor switching. It also helped handling transient voltages, but required multiple operating mechanisms (one per phase). Failure of any one mechanism to operate or a delay opening resulted in single phasing of the capacitor bank. This causes the recovery voltage, on ungrounded banks to increase significantly.

The transient recovery voltage (TRV) of the opening phases can increase by 20% above the tested capability, which most likely will cause restrikes on every operation. In addition, keeping three mechanisms operating within specifications added to the utility's maintenance workload and proved to be a challenge.

Some utilities took the approach of adding both synchronous closing and pre-insertion resistors. It was mistakening believed this reduced maintenance and provided a more reliable switching device.

D. Special Purpose Capacitor Switch

A special purpose capacitor switcher was introduced into the market in 2003. The primary objective, of the design, was to achieve a reliable long life solution for mitigating the transients that occur when switching in a capacitor bank. The resulting product, capable of a high number of operations (10,000), utilizes closing resistors to mitigate voltage transients and inrush current.

Fig. 14. Shunt capacitor bank with a special purpose capacitor switch

In this design, the resistor, resistor contact design, and resistor insertion method were the key elements. They achieved a reliable long term solution for mitigating the transients that occur when switching in a capacitor bank. Additionally, the contacts and nozzle were designed to minimize or eliminate the possibility of restrikes during the disconnection of the capacitor bank from the system. Some models include interrupting capability, although this was a lower priority in the initial approach to the design.

These contact and nozzle designs are the solution to insuring that the device could survive high frequency inrush currents. They virtually eliminate restrikes as compared to new technology breaker designs that focus on very high-speed interrupting performance required for protection schemes.

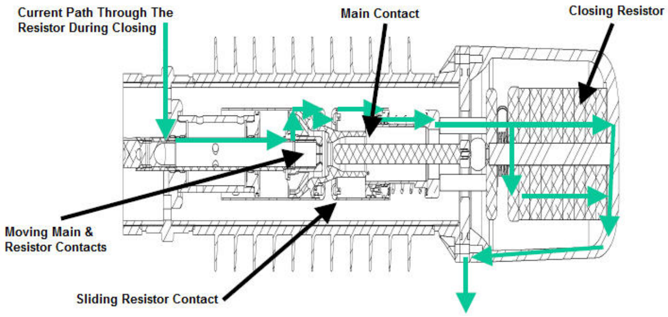

Fig. 15. Special purpose capacitor switch interrupter diagram

Both making and interrupting the circuit occur in the special purpose switch interrupter's SF_6 gas environment. The use of a single gap per phase puffer helps make it restrike free. It is a more cost effective solution than using a complex power circuit breaker for a fundamental task.

V. CONCLUSIONS

Switching pure resistive loads has been handled successfully for many years using power circuit breaker and circuit switcher technology. Switching shunt reactors however, can produce severe dielectric stresses to both the reactors and the switching device. Switching shunt capacitors places stress on the system, the capacitors, and the switching device. Therefore, it is only advisable that reactors and capacitors be switched with devices designed for the task.

From a utility's point of view, it would be desirable that the switching device be reliable, improve availability, and be cost effective. Switching mechanisms need to have components with a long mechanical life. The contacts and nozzle designs have to be of a robust design, which can handle the arc from restrikes and current chopping. Designs based on general purpose circuit breakers with added ratings, may reduce the intrinsic performance in these special applications. Improved interrupter designs that do not depend on precise timing of mechanical systems or need learning algorithms are therefore inherently more reliable.

The application of capacitor and reactor banks is increasing, which has exposed weaknesses in some device designs. It has shown difficulties with switching techniques, which in turn uncover system reliability issues and excessive outages. Significant improvements in product life and system stability can be gained using purpose built devices for switching shunt reactors and shunt capacitors.

VI. References

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VII. Biographies

Joe Rostron, P.E., Member, IEEE, has 39 years of experience with advanced high voltage technology and holds 32 patents. He is currently the Sr. V.P. of Technology Development at Southern States LLC, Hampton, Georgia, U.S.A. & President of SSIPower. Joe was recognized as Outstanding Inventor in 2008 by Southern States. He has previously worked at Westinghouse, ABB, and Siemens in various engineering and development related positions. Joe is a member of ASME and IEEE. Joe is the Past Vice Chairman-Quality and Reliability IEEE Switchgear Subcommittee. He graduated with a BSME from Washington State University and an MBA from the University of Pittsburgh. He is a registered professional engineer in the state of Pennsylvania.

Gene Wolf, P.E., Fellow, IEEE, has been designing and building electrical substations for over 35 years in voltage levels from 46kV to 500kV. He started his utility career with Kansas Gas and Electric, retired as the Principal Engineer of Stations for Public Service Company of New Mexico, and founded Lone Wolf Engineering, LLC an engineering consulting company. Gene is a Fellow of IEEE and a MSEE graduate of New Mexico State University's Electric Utility Management Program. He is the past Chairman of IEEE's Power and Energy Society's (PES) Transmission and Distribution Committee. His other IEEE/PES leadership positions include sponsor of the Renewable Energy and Intelligent Grid Subcommittees and past Chair of the HVDC & FACTS Subcommittee. He is also a registered professional engineer in the states of California and New Mexico.