The Next Fifty Years of Series Capacitors – And the Last Eighty-six

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1. Abstract

Series capacitors are and will continue to be an important element in power transmission systems around the world. Series capacitors in a transmission line allow higher levels of current to flow and therefore more power than could otherwise be delivered through a given transmission line. This paper examines the eighty-six year history of one manufacturer's experience with series capacitors, especially with regard to protection, and also looks ahead at possible developments the field may see in the next fifty years. The next fifty years will likely see widespread application of more series compensated transmission lines as resistance to building new lines combined with remote, renewable generation become the norm, requiring the maximum throughput from the existing transmission infrastructure.

Index Terms: Power Capacitors, Transmission Lines, Varistors.

2. Introduction

Series capacitors directly reduce system impedance and are an effective way of enhancing power transfer on transmission systems. Primary benefits include:

- Improved load division on parallel circuits
- Improved system transient stability
- Improved system steady state stability
- Reduced voltage drops during system swings
- Increased power transfer capability

Since the transmission line current flows through the capacitors they are exposed to system fault currents. Sophisticated protection systems are needed to protect the capacitors during system faults. As such, a considerable portion of this paper focuses on protection in particular. Careful consideration is required for fault duty, overload currents and other transients. In some applications potential sub synchronous resonance must also be addressed. [1]-[3]

The first application of a transmission series capacitor was rated 1.2 MVAr and was applied for load division on a 33kV line in 1928 on the New York Power & Light system in Ballston Spa, New York. [4] Series capacitor units are essentially the same as shunt power capacitors but with customized ratings and often more conservative design stresses. A modern series capacitor installation is pictured in Figure 1.

Figure 1.
Photo of a series capacitor installation.

3. Power Capacitors

Power capacitors were introduced in the early 1900s using linen paper and wax impregnation. These evolved to Kraft paper, then to a combination of paper and polypropylene film in the 1960s, then to all polypropylene film solid dielectrics in the 1970s. The impregnating fluids evolved from wax to mineral oil to Askarel to today's non-PCB liquids. The first power capacitors were limited to about a 5 kVAr rating. Today individual units rated 500 kVAr or more are common, limited to a practical size for handling.

The first EHV series application in the U.S. was on the 500kV Pacific Intertie in 1969, interconnecting relatively large systems. These were also the first major devices to use film/paper dielectric capacitor units.

In order to fully understand how to protect a capacitor bank, it is helpful to understand the internal construction of a power capacitor unit. Power capacitor units are constructed from basic capacitor elements known as rolls. Each roll is a sandwich of electrode and dielectric sheets, wound into a roll. The length and width of the sheets are used to control the capacitance of the capacitor unit. Depending on capacitor unit ratings, these rolls are connected in series and parallel combinations to achieve the current, voltage, and capacitance rating of the capacitor unit. Each power capacitor unit will have a discharge resistor connected in parallel with all the capacitor rolls to assure the capacitor discharges to a safe level over a period of time when removed from service.

Dielectric failures in modern power capacitor units, although rare, are the most common failure mode. When a capacitor dielectric fails, the electrodes puncture the dielectric reducing the capacitor roll with the failure to a short circuit. Because the rolls are connected in series and parallel combinations within the capacitor unit, a single roll failure will result in increased stress on other series rolls in the capacitor unit, but, if properly designed, will not force a cascading failure. The result will be a change in capacitance of that capacitor unit, but not the complete failure of that unit. It is possible to continue to operate that capacitor unit with a failed roll, however it will have higher losses and a different rating.

A. Externally Fused Capacitors

Protection in series capacitor banks were originally externally fused, meaning each capacitor was protected by a single fuse. Fuse sizes would be chosen to remove a capacitor from service when current through that unit significantly exceeded the capacitor rating. All capacitors at the same voltage level were connected together so a blown fuse would have a minimal effect on the overall bank rating. An external current measuring scheme would be used to determine if the bank imbalance current indicated an excessive number of blown fuses and would remove the entire bank from service. Fuse failures are easy to detect from the ground as most are designed with a physical disconnection of the capacitor unit from the bus feeding the capacitors.

B. Internally Fused Capacitors

In order to reduce connection points, and reduce costs, many manufactures evolved from externally fused to internally fused capacitor banks. With the removal of the fuse assemblies, and integrating the fuse element into the capacitor unit, manufacturers could reduce costs without changing the bank topology or protection methods. Since the fuse elements are integrated into the capacitor unit, the fuse connections can be made to each roll within the capacitor unit. This has the effect of only removing some of the functionality of the capacitor unit instead of the entire capacitor unit when a failure occurs, reducing the impact to the entire bank.

C. Fuseless Capacitors

By the mid 1990's this evolution continued with the fuseless protection systems. To further reduce the effect of a dielectric failure on the capacitor bank, the fuseless protection method only removes the single capacitor section with the dielectric failure. The failure site in the roll results in a low impedance connection. Series/parallel connections are configured in the capacitor bank so that current is segmented into limited strings such that the failure site cannot attract enough current to cause a cascading failure. This is accomplished by not connecting capacitors at the same voltage level together. Overall bank protection is very similar to the proceeding methods by comparing imbalance currents within the bank between near identical sections. This method has been used successfully in series capacitor protection for over twenty years without a cascading failure. Fuseless capacitor protection is considered the preferred method by some utilities. [5]

4. Series Capacitor Bank Protection

Because series capacitors are in series with a transmission line, protection of a series capacitor is accomplished by shorting out the series capacitor bank, not by opening it. Series capacitors present capacitive impedance to current in a transmission or distribution line. When a fault in that line occurs, fault current flows through the capacitive impedance creating a large voltage across the capacitor. Since dielectric breakdown is a function of voltage, the series capacitors are protected by having devices which limit the voltage across the capacitor bank terminals. Modern series capacitor banks use Metal Oxide Varistors (MOV's) to instantaneously clamp voltages across the capacitor.

A. Metal Oxide Varistor

In the 1970s Zinc Oxide replaced Silicon Carbide as the technology used in lightning arresters. The non-linear V-I characteristic of ZnO was a significant improvement over SiC, and eliminated the need for internal shunt and series gaps in HV arrester units. It was recognized that this technology could be used to clamp series capacitor over-voltages.

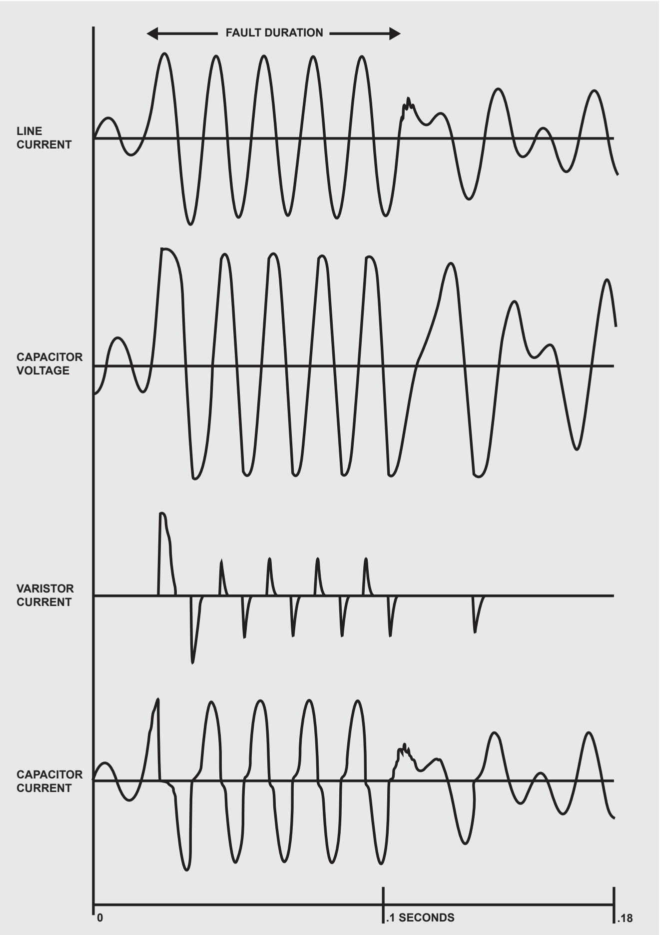

Figure 2.
External line fault oscillogram.

When an MOV conducts, it absorbs energy. The amount of energy an MOV can absorb is a function of the physical characteristics of that MOV. Some of these characteristics include: volume, heat dissipation, and the formula of the metal oxide (different metal oxides have different energy capabilities). In order to protect the MOV, a switch is inserted in parallel with the MOV. The rate at which energy is absorbed dictates the speed required of the bypass switch. There is a reactor in the capacitor discharge path to limit the discharge current to a safe value for the capacitors, air gap, and bypass switch.

Figure 2 shows various voltages and currents during an external line fault and clearing. Note that the MOV clips the capacitor voltage peak on each half cycle, and that fault current alternates between the capacitor and the MOV. When the fault is cleared the capacitor is instantaneously in service, maximizing system stability.

If the internal line fault current is relatively low, the MOV can be sized to allow for the closing time of the bypass switch, eliminating the need for a spark gap or air gap. The simplicity of MOV protected series capacitors has led to highly reliable equipment performance. [1]-[2]

In 1979 a prototype series capacitor bank with MOV as the primary protection was successfully subjected to a staged fault field test on the 345kV Bonneville Power Administration system at the North John Day substation. The varistor had 72 parallel columns of 14 series connected ZnO disks. Careful matching of parallel columns is required to achieve current sharing on these highly non-linear devices. [1]-[2] Since 1985, all of GE's series capacitor installations have included the use of Zinc Oxide MOV.

B. Air Gap

Early series banks used simple air gap protection systems with parallel switches to extinguish the arc created in the gap once it fired, to protect the capacitors. To allow for gap deionization there was a long delay until the capacitors could be restored to service following a line fault. In the late 1960's, a key specification requirement for the Pacific Intertie banks was "high speed" (3-5 cycle) reinsertion following fault clearing to improve power transfer capability. Figure 3 illustrates the effect of reinsertion time. There were two different technologies applied in these devices. One system used a high pressure air gap/switch to rapidly extinguish the arc and restore gap dielectric strength. The other system used a voltage sensing Triggered Vacuum Gap with a fast vacuum switch that could reinsert the bank in 3 cycles after fault clearing. Typical gap spark-over settings for both technologies were 3 p.u. of rated capacitor voltage. This was necessary to withstand reinsertion transient voltages.

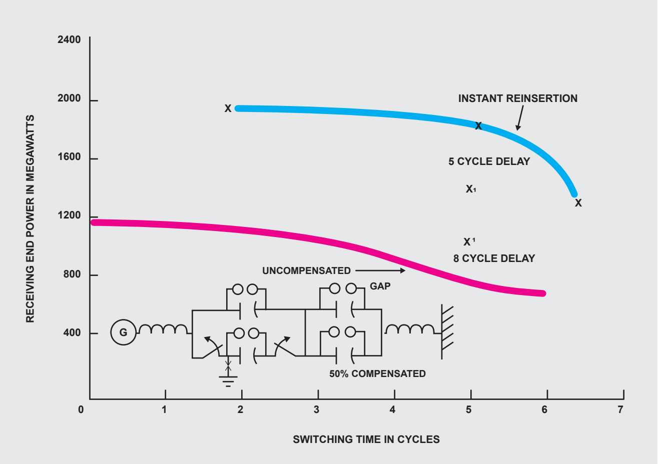

Figure 3.
Effect of reinsertion delay on power transfer.

In modern series capacitor protection systems with very high fault currents there are basically two bypass switches, a Triggered Air Gap (TAG) and bypass breaker. A TAG is a very fast bypass switch that can operate in the hundreds of microseconds range. The best TAGs are self-contained and integrate energy absorbed by the MOV without relying on communications with a ground based control system.

GE's present TAG design uses plasma injection to initiate the arc across the gap and was first installed at Hydro Québec's Chibougamau substation in 1994. The next generation TAG currently under development uses "Modular Arc" technology and will be smaller and lighter.

C. Bypass Switch

Once a gap is conducting, the only way to reset it is to remove voltage across it and current through it. The bypass switch closes automatically on all TAG conductions. The bypass switch can also be triggered by external signals such as failure of the line breakers. It also allows manual or remote bank insertion and bypass.

D. MOV and TAG Protection

While there have been significant design improvements in the components and the protection controls, the same basic system as introduced at North John Day in 1979 is still in use today. Figure 4 shows a one-line diagram of the circuit. The MOV limits the voltage across the capacitor under all conditions, with a typical protective level of about 2.0 p.u.

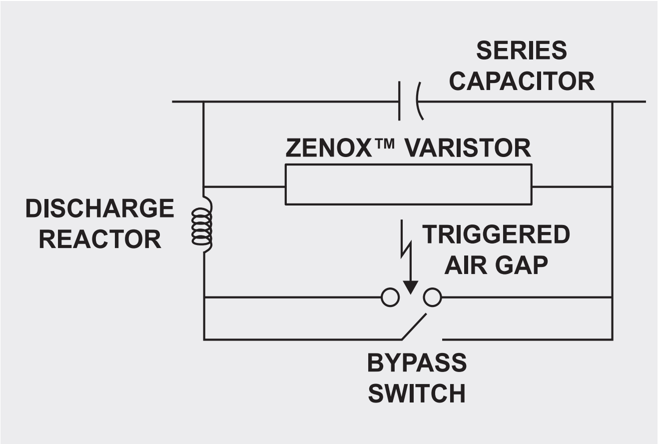

Figure 4.
One-Line diagram of an MOV protected series capacitor.

5. Thyristor Controlled Series Capacitors

A Thyristor Controlled Series Capacitor (TCSC) is a series capacitor bank designed to adjust the amount of VAR's in series with a transmission line dynamically. TCSC systems have many uses including instantaneous adjustment of compensation during a fault sequence to re-establish system stability, controlling power between parallel circuits, and adjustments to the VAR rating of a series capacitor bank dependent on current in the compensated line. Due to their complexity and expense, Thyristor Controlled Series Capacitor banks are relatively rare, but there are systems that have been in operation since the mid 1990's.

6. The Next Fifty Years

Electric power systems were originally built around the arrangement of central power generation stations serving local customers. The transmission system is now expected to carry bulk power in ways it was never designed for. The expectation is that this transmission requirement will only increase. As power generation sources continue to evolve, lately towards renewables, the transmission grid is asked to transmit more and more power over longer distances. [6]

Series capacitors will continue to be an effective tool for system planners as they can facilitate more power to flow through the same transmission network. As technology improves and the need for transmission continues, one should expect a trend towards more lines with higher levels of series compensation. At the time of writing, the authors' company has supplied one hundred ninety-six series capacitor banks over the last eighty-six years including three TCSCs. A further eleven series banks are presently under construction. Based on this extensive experience and the trends seen in the industry of late, some observations are made below on the possible future of series capacitor bank offerings.

A. Sub-Synchronous Interactions

One of the challenges that can come with application of series capacitors are sub-synchronous interactions (SSI) with other elements of the power system. [7] It should be noted that the vast majority of series capacitor installations have been applied without any issues associated with sub-synchronous interactions and require no mitigation. [8]

However, as wind generation is often remote to the load centers and can be connected with long radial lines, series compensation on these lines can produce a concern of sub-synchronous resonance (SSR) and/or sub-synchronous interactions. [9] It has been demonstrated that changes in the controls of type 3 wind turbine generators can mitigate the problems with sub synchronous control interactions between wind turbines and series capacitors. [10], [11] It has been the experience of the authors' company that mitigation of some of these concerns may also be possible using passive filtering built into the series bank itself. [12] Future series capacitor installations may more commonly include mitigation of sub-synchronous interactions which may be either active such as TCSC or passive filtering. These new mitigation techniques may allow placement of series capacitors in locations that were once not feasible.

B. Polymer

A materials change that may have an effect on the future of series capacitors is the advancement of polymer. Traditionally the MOV has been housed in a porcelain housing. A change to a polymer MOV housing material has two significant and desirable benefits. One is the weight savings on the series platform. Depending on the short circuit strength of the system where the series capacitor is installed, there can be a significant number of MOV on a series capacitor platform. This weight savings is potentially enough to reduce the structural requirements of the platform itself. This is especially true in high-seismic applications. Second, the polymer's physical properties are desirable in the case of mechanical damage or in the event of a catastrophic failure. A disadvantage of polymer is that it is less effective in dissipating heat. This change in material may facilitate a lower structural costs which may help with the economic feasibility of new banks.

C. Protection and Sensing

Protection and sensing systems have progressed since the first series capacitor was installed in 1928. The most significant change obviously being from analog to digital based devices. The desire for noise immunity, decreased temperature sensitivity, and overall robustness of protection and controls is as high as ever. It is expected that over the next fifty years speed and accuracy will continue to increase, while immunity from environmental affects will become more prevalent. Legacy measuring devices using electromagnetically induced currents in an iron core, for example, may one day be replaced with "lighter" devices without an iron core.

Protection devices for series compensation banks have historically used non-standard substation protection devices. As more sophisticated and faster protection devices become available on the market, and support interfaces to a wider variety of sensors, ground based series compensation protection systems may migrate to hardware platforms that have other applications within substations and switchyards. This will simplify training of testing and maintenance personnel while reducing the number of spare parts required in inventory at a substation.

The complexity of the series compensation platform represents a significant design limitation. Because series compensations systems are in series with a transmission line, even the "low voltage" side is still considerably above ground potential. This makes getting signals from the platform to the ground-based control system very challenging. Most systems today use an optical isolation method, but this requires sensitive optics and electronics that need to operate at line potential. Future protection systems will work to minimize or eliminate platform electronics to maximize robustness of the system and simplify maintenance and troubleshooting.

Fast bypass devices may also continue to evolve as technology advances. Modern series capacitor bypass devices use a combination of varistor, triggered air gap, and bypass switch. The faster the gap-switch combination can react, the less zinc is needed in the form of varistors. As the varistors are expensive, this can result in overall cost reduction. If a bypass switch can react quickly enough, the triggered air gap may become unnecessary. Or, conversely, if a gap can be rated for sustained high current, or distributed, the bypass switch could be eliminated. It is possible that the next fifty years will see the removal of one of these devices from typical series capacitor installations.

All of these protection improvements will tend to drive higher reliability and better precision at lower cost. As the cost of series capacitors decreases, adding more series compensation to the transmission system will only become more economically achievable.

D. Return of Distribution Series

Distribution Series capacitors have been around for decades, but they may find a new market in the next fifty years driven by several factors.

As distributed generation becomes more prevalent, voltage regulation will become a growing challenge as it will be very difficult to predict actual distribution flows. This makes protection extremely challenging and requires significant instrumentation, communication, and complex algorithms to calculate capacitance needed to maintain voltage levels. Series compensation is an elegant solution to this problem as it generates VARS proportional to current through it. As load profiles change, the series compensation naturally adjusts to match the need.

Impact from Geomagnetic Disturbance is another issue that can be diminished through the use of distribution series capacitance. It has been observed that transmission lines with series compensation do not have the same issues with Geomagnetic Disturbances as non-compensated lines, as the series capacitor acts as a DC block and does not allow the ground currents to flow through the transmission lines. A similar phenomenon can be expected in smaller distribution lines. A series capacitor may prove to be a simple and helpful solution where a distribution line is determined to be at high risk.

E. Capacitor Ratings

The rating of a capacitor unit has grown over the years and has demonstrated that fewer capacitors of higher rating usually prove more economical. The practical limit is based on the weight of the capacitor and the personnel and equipment handling that weight. Advancements in material could enable an even higher rated capacitor unit than is available today. Some utilities already consider the weight of a capacitor unit beyond the limit of what one person can safely handle. If cranes and other lifting devices are required anyway, the industry could push towards fewer, heavier capacitors with higher ratings, in the name of overall cost savings.

7. Summary

Since their first application eighty-six years ago and through the work of giants such as Charles Concordia [7], the industry has gained much insight. Series capacitors have been applied throughout the world and are now in wide use. As the transmission systems around the world are required to move more power over longer distances, the series capacitor will continue to be an effective tool for transmission planners and system operators. As series capacitor protection systems, materials, and technologies continue to advance, their use in the transmission system will only increase. The series capacitor will continue to be a part of the power and energy world through the next fifty years.

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