

MOV Protection of Series Capacitor Banks



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A series capacitor bank consists of the capacitors and their protective system. MOV's provide overvoltage protection for the capacitors and are a significant member of the protection system. The general purpose of these banks, are to increase the power flow on an existing system by reducing the line impedance.

The application of Series Capacitor Banks dates back to 1928 when GE installed their first bank at the Ballston Spa Substation on the New York Power and Light 33kV grid. The bank was rated at 1.2MVar. Since then series capacitor banks have been installed on systems all over the world.

Series Capacitor Banks Overview

When capacitors are inserted in a transmission line, the series capacitance effectively compensates for the inherent inductance in the line to lower the total impedance. This in effect allows the circuit to transfer more energy with less heating of the lines. The series banks are generally located at either end of the section of the transmission line in one of the existing substations. However, sometimes they are located near the middle of the transmission line section which reduces the worst case potential fault current. With lower potential fault current, the MOV bank can be designed smaller.

In today's world the increasing difficulty in obtaining right-of-way for new power lines coupled with the rising cost of new power lines, are making the use of a series capacitor bank a favorable option for utilities. For long transmission lines where the source and load are separated by hundreds of km, the use of Fixed Series Compensation (FSC's), another common name for this device, is almost a necessity.



Figure 1 New series capacitor bank showing all three phases on 500kV platforms in Brazil



Figure 2: Close up of one Segment of a Series Capacitor Bank Installation. Shown are the MOV units in the front, the triggered gap in the box in the back right, and capacitors to the left of the triggered gap.

As seen in Figure 1, the entire series bank is mounted on a platform and while in service the entire structure above the insulators is energized at the system voltage. The series capacitor platform is connected to the control computer via fiber optic links that effectively isolate the protection controls from the high voltage.

The typical protective bypass system consists of a metal oxide varistor, bypass gap, damping reactor, and bypass circuit breaker. The varistor serves to provide overvoltage protection of the series capacitor during power system faults. The bypass gap is controlled to spark over in the event of excess varistor energy. The bypass breaker closes automatically in the case of prolonged gap conduction or other platform contingencies. The breaker also allows the operator to

insert or bypass the series capacitor. The damping reactor limits the capacitor discharge resulting from gap sparkover or bypass breaker closure. The communication of platform connection to the ground is accomplished using fiber optics.

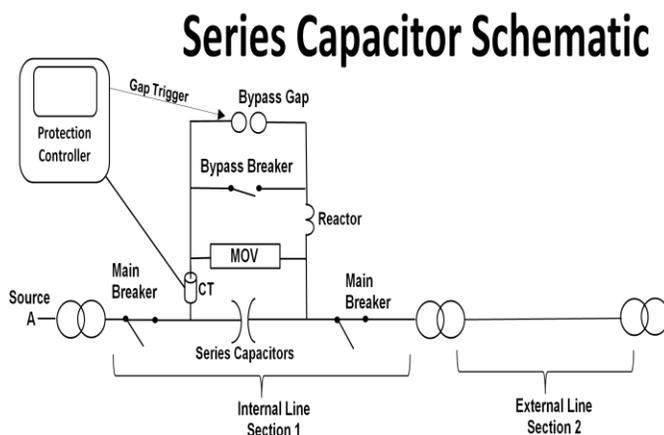


Figure 3 Series Capacitor Bank Schematic

The varistor and the triggered gap operate independently on each phase. The bypass breaker operates on a three-phase basis. The bypass system is capable of operating with single-pole or three-pole tripping and reclosing schemes employed on the transmission lines.

MOVs are connected in parallel with the capacitors at all times, they do not need any special signal to enter the protection scheme. They are ready all the time. If there is a fault on the system the MOV is there to protect immediately.

Role of MOV's in the Protection of the Caps

The varistor role in the protection of capacitors

The very unique part of this MOV application is that the MOV's are protected by electronic controls and the triggered bypass gap.

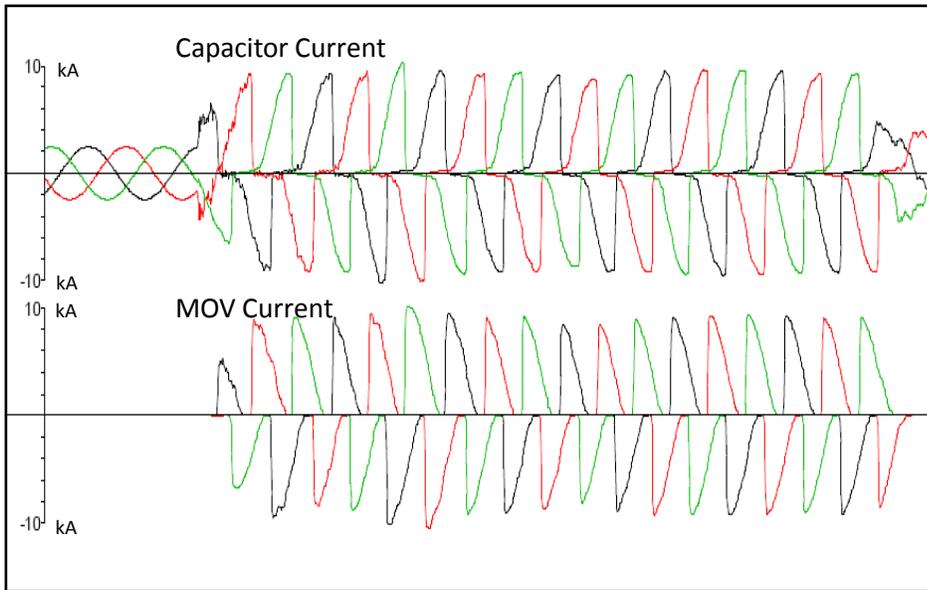


Figure 4: 3 Phases of MOV and Capacitor Current during a fault

The protection controller monitors the current through the MOVs at all times. If at any point the recently accumulated energy exceeds the rating of the MOV bank, then the bypass gap is triggered. The gap is capable of operating and redirecting the fault current away from the MOVs within 1-2 ms.

In Figure 4 a three phase fault is modeled

and shows the current through the MOV and capacitors during the event. Note that the capacitor bank conducts the current for the first half cycle, and the MOV conducts the current for the second half. This is due to the nonlinearity of the MOV.

in series capacitor applications is very simple and at the same time very unique. Simple, because the arresters are installed for one purpose only and that is to limit the voltage across the capacitors during a fault on the system. Unique, because while limiting the voltage during a fault, they also conduct a large portion of the fault current. There are very few other applications of arresters where conduction of power frequency fault current is the responsibility of the arrester.

During a fault event, the MOV conduction results in adsorption of energy as shown in Figure 5. This energy absorption is constantly

Conducting fault current for 50-100 ms is very different from normal switching and lightning overvoltage events that are over and done in a few microseconds to a millisecond. Since the

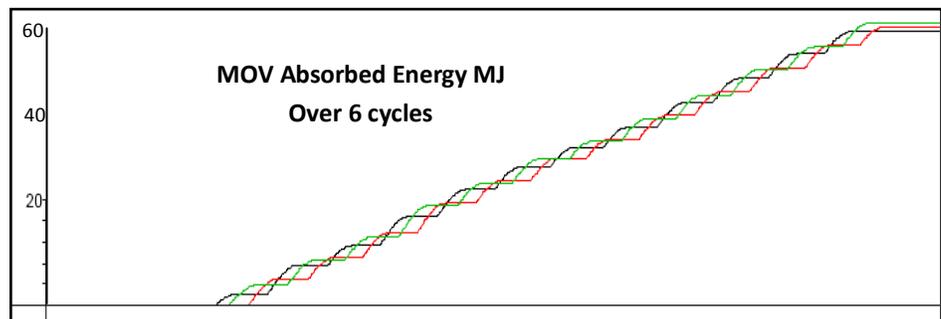


Figure 5: MOV Energy Absorption during a 3 phase fault

monitored and is used as the basis of triggering the bypass gap.

There are basically two types of faults of concern for series capacitor installations. If the fault occurs within the section of transmission line where the series cap bank is located, it is referred to as an internal fault (see Figure 3). If the fault occurs on another section of the transmission line, it is considered an external fault. The difference between the two is only

significant accumulation of energy takes place. When an external fault occurs, the protection controls are all the MOVs have between operation and overload. If the control system fails, it is likely that the MOVs would too.

To achieve high energy absorption capability, MOV columns are mounted in parallel. Figure 6 shows a sizable bank of arresters used to protect a series capacitor installation.



Figure 6: MOV Columns Protecting a Series Capacitor Bank

the magnitude of the fault. A nearby internal fault will result in significant fault current and significant duty on the varistors. A distant fault on an external section can result in a few percent higher than the normal maximum rated current of the cap bank. These two faults are handled differently by the control system and the MOVs. If the control system senses a high current internal fault it sends a signal to the triggered gap to bypass immediately. This pulls the MOVs out of the circuit before any

Specifying MOV Banks for Series Compensation Systems

The suppliers of Series Capacitor Banks are generally the specifiers of all components in an installation. The characteristics of the MOV columns are arrived at using an iterative process during a comprehensive system study developed specifically for series capacitor applications. The system study is unique for each installation and is based on the system fault current and operating schemes as

specified by the end user utility. Since the size of the MOV bank is a function of many variables, sophisticated models have been developed to speed up and improve the quality of the specification. Once the Series Capacitor Bank Supplier has ran numerous models and found the optimum size of the varistor bank, they look to the MOV suppliers for final design and configuration specifications.

Dimensioning MOV Banks

The banks of MOV columns have several critical criteria that need to be met for them to operate properly over the life of the series bank. These characteristics are Maximum Energy Absorption Capability, Maximum Peak Current Capability, Maximum Clamping Voltage at the highest fault current, Minimum Re-insertion Time, Matched Aging Characteristics, and Matched Voltage/Current (VI) Characteristics.

The Required Maximum Energy Absorption

capability and the desired clamping voltage are

often the two factors that determine the number of columns used in an MOV bank. Based on testing and historical performance the MOV supplier knows the maximum energy absorption capability of each disk and column used in this type of application. The energy requirement in this case is very different from standard lighting and

switching energy

capabilities. Besides

absorbing energy over relatively long periods of time (100ms vs. 2 ms), the columns are in parallel and share the current per their design.

The maximum energy of the group of parallel columns is a simple sum of the energy

absorption of each disk times the energy de-rating factor used in the design.

Matched VI Characteristics or Maximum Current Sharing Deviation

is a characteristic guaranteed by the MOV suppliers. It is verified in the routine tests performed on all banks of MOVs. It is also the most onerous task in manufacturing this type of MOV product. It requires pains-taking data collection, and time consuming tests to verify and adjust to match.

First the VI characteristic of each disk is measured at several points on its VI curve. A typical VI Characteristic of an MOV column is shown in Figure 7. It shows the range where it is important to match the VI characteristic. Above that range matching is not useful since it is likely not a current level the column will ever experience. The area above the critical matching range is in the lightning protection range. The area below the matching range is also not of real importance, since the current

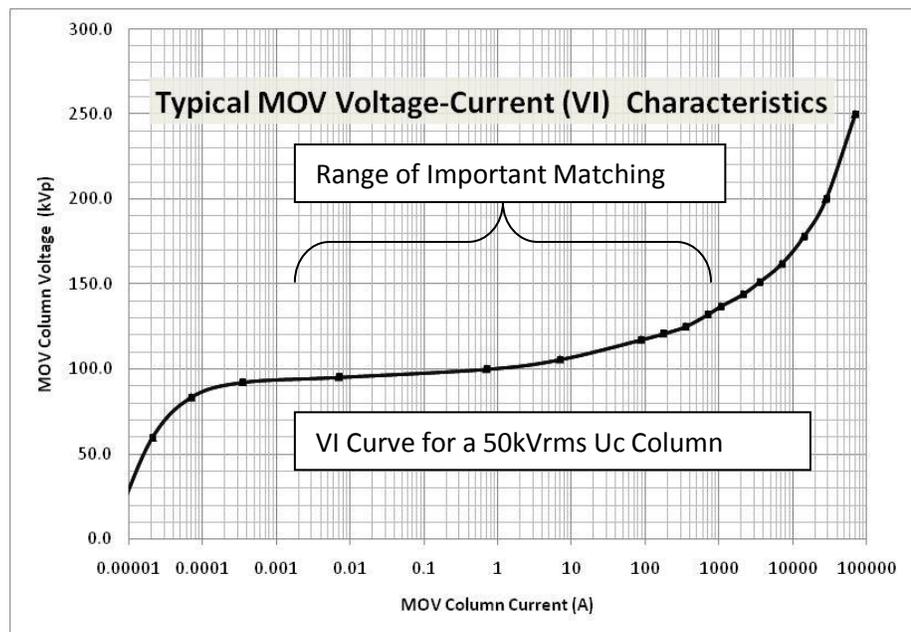


Figure 7 Typical VI Curve of a MOV Column

and losses in that region are insignificant and could not lead to heating imbalance in the bank. If three points on the VI curve can be matched when assembling a MOV column for this application, the bank will be perfectly matched. If three points between two columns are

matched, then it is guaranteed that the routine matching test will show success. If two points are matched, then it is possible to succeed in the verification test, but not a guarantee. If only one point is matched, then success in the matching verification test is not likely.

These points are accurately matched using sorting schemes unique to each manufacturer. Once the matched columns are partially assembled, each column is impulsed at a current in the range it will operate and compared to all other columns to which it will be mounted in parallel with. If the segment or phase calls for 300 matched columns, then the comparative test is performed on 300 columns. This routine test is required by IEC and IEEE standards and the results are used to guarantee the specified matching characteristics. Because MOV disks and columns are very nonlinear, measuring the residual voltage during a comparative test does not result in accurate enough current sharing data, only the current through the column can be used for the comparison. Also since it is unrealistic to test 300 columns in parallel and measure the current through each one at the same time, usually 10-20 columns are tested at a time and the groups are compared to reference samples. This test technique is common to all manufacturers and result in very accurate matching.

Maximum Peak Current Capability characteristic is also very well known by the MOV suppliers based on historical applications and tests. This characteristic becomes important if the MJ rating of the bank is low, but the fault current requirement is high. Once the bank of MOVs is designed, the maximum column current is simply the total maximum fault current divided by the number of columns. If the maximum capability of the MOV column is exceeded, the number of parallel columns is increased.

Maximum Clamping Voltage also known as the protective voltage at maximum fault current is used to determine the maximum protective level of the bank. This value is very important because this is the fundamental purpose of the MOV bank. The maximum clamping voltage at

maximum fault current must be below the withstand level of the capacitor. The capacitor withstand levels are a function of the insulation and configuration of the capacitor bank. If the capacitor bank is to survive the expected life of the installation, then this value needs to be well known and absolutely guaranteed. The maximum protective level of a series capacitor bank is the ratio between the peak voltage across the MOVs during a maximum fault event divided by the peak value of the voltage across the capacitors at rated continuous current. Typical protective levels are 2.0-2.5.

Minimum Re-insertion Time is an increasingly important characteristic of this application. It is so important that some utilities have chosen to install redundant series banks specifically to never be caught without serried compensation on the system. Besides running the transmission line at a lower maximum power flow, the utility is losing revenue if a bank is out of service and sometimes losing system stability.

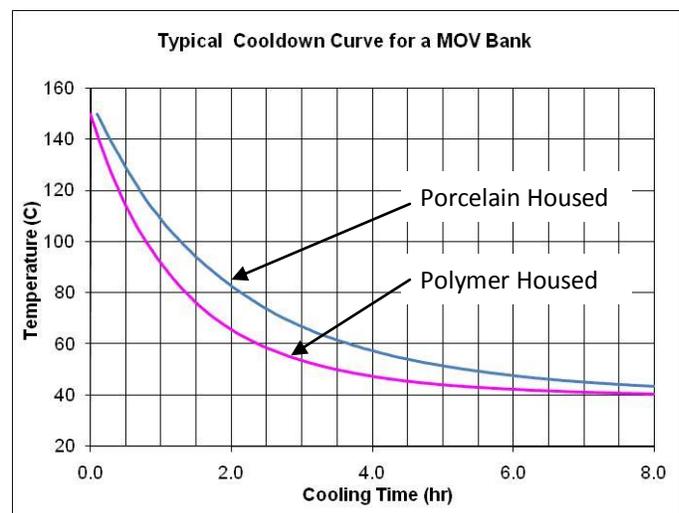


Figure 8: Typical Cool down Curve for a MOV Bank

The re-insertion time is a function of the thermal cool down speed of polymer housed MOV column. In Figure 8 it can be seen that with a starting temperature of 160C in an ambient of 40C, a polymer housed MOV column can cool down to within 20C of ambient in about 4 hours. Since most porcelain house MOV columns have four columns of disks inside one porcelain housing, they generally have a

slower cooldown time than polymer housed designs.

Matched Aging Characteristic is another very important MOV bank characteristic. All MOV material has characteristics that change over time when energized. The changes are in the low voltage region of the VI curve and do not affect the clamping voltage of the column, but can affect the losses or matching characteristics at lower voltages. If one column ages differently than another, it is feasible that the current matching and energy sharing can become out of balance. This imbalance could lead to premature failure of the bank due to overload of one column during a fault. The even aging characteristic is achieved by the manufacturer by using disks with the same impulse history and same processing history in the entire segment or parallel group.

Special Testing of MOV for Series Compensation Systems

IEC standard 60143.2-1994 and IEEE 824-1994 are the two mature and comprehensive standards that cover the protective equipment of series capacitor banks. These two standards are not unified, but they are very similar. They both call out type or design tests as well as acceptance and routine tests. For design tests all fundamental bank characteristics are covered. The type tests are carried out on single columns that have been prorated from a voltage and current perspective. The required tests consist of Residual Voltage Verification Test (Clamping Voltage Characteristic), Accelerated Aging Test, Current Sharing Test, Energy Absorption Test, and pressure relief test if requested by the customer. It is important that the energy absorption test be demonstrated for both short time fault events (subcycle) and for long term fault events (5-10 cycles). The longer term fault events put a stress on MOV material differently than any other stress is seen in other applications. The long term stress can lead to failures at inherent defects in the MOV material that short term stresses do not.

Routine Tests

Routine tests are not specifically called out in standards and are left up to the discretion of the manufacturers. They need to be robust enough to cull out all defects that could otherwise cause a failure in this unique application. For arrester used for lightning and switching surges, multiple square wave surges within a short period of time of sufficient energy level are generally used to verify arrester quality. For MOV disks used in series capacitor applications, the routine tests need to demonstrate both single pulse 8ms surges and multi cycle 8ms pulses since both will be required to protect under these conditions. These extra energy tests are in addition to the normal residual and Vref tests that need to be carried out.

Installation Considerations

The installation configurations are a function of the platform dimensions, MOV dimensions and clearances, and metering requirements. It is desirable to use the minimum possible space for the MOV columns which allows for the reduction in the size of the platform. Since the MOV columns are always at the same potential as the columns around them clearances can be much smaller than in standard arrester applications.

Another consideration in installation is that the unit needs to appear as one single MOV which means the connecting bus work needs to be of minimum inductance and minimum resistance. In Figure 6 note the robust bus work on the top and bottom of the arresters.

Another important consideration in mounting MOV columns is the metering of leakage current. By metering the leakage current of the MOV, the MOV's state of health can be monitored. Of course monitoring each column on large banks is not economic so groups of columns are mounted on separate bases. On separate bases, the leakage current of one group can be compared to the leakage current on an equal group. If the values are different, then an inspection is recommended.

Failure Modes and Failure Considerations

How to deal with the failure of a single MOV column has long been a concern for users of MOV in series capacitor protection. The main issue is that once the bank is energized it begins its aging process. The effect of this aging is only an issue if there is a partial failure of the segment. Since the segment is matched from the start and all columns within the MOV bank have aged at the same rate, it is nearly impossible to substitute in a single column into a group of columns and do it in such a way that current would continue to be shared.

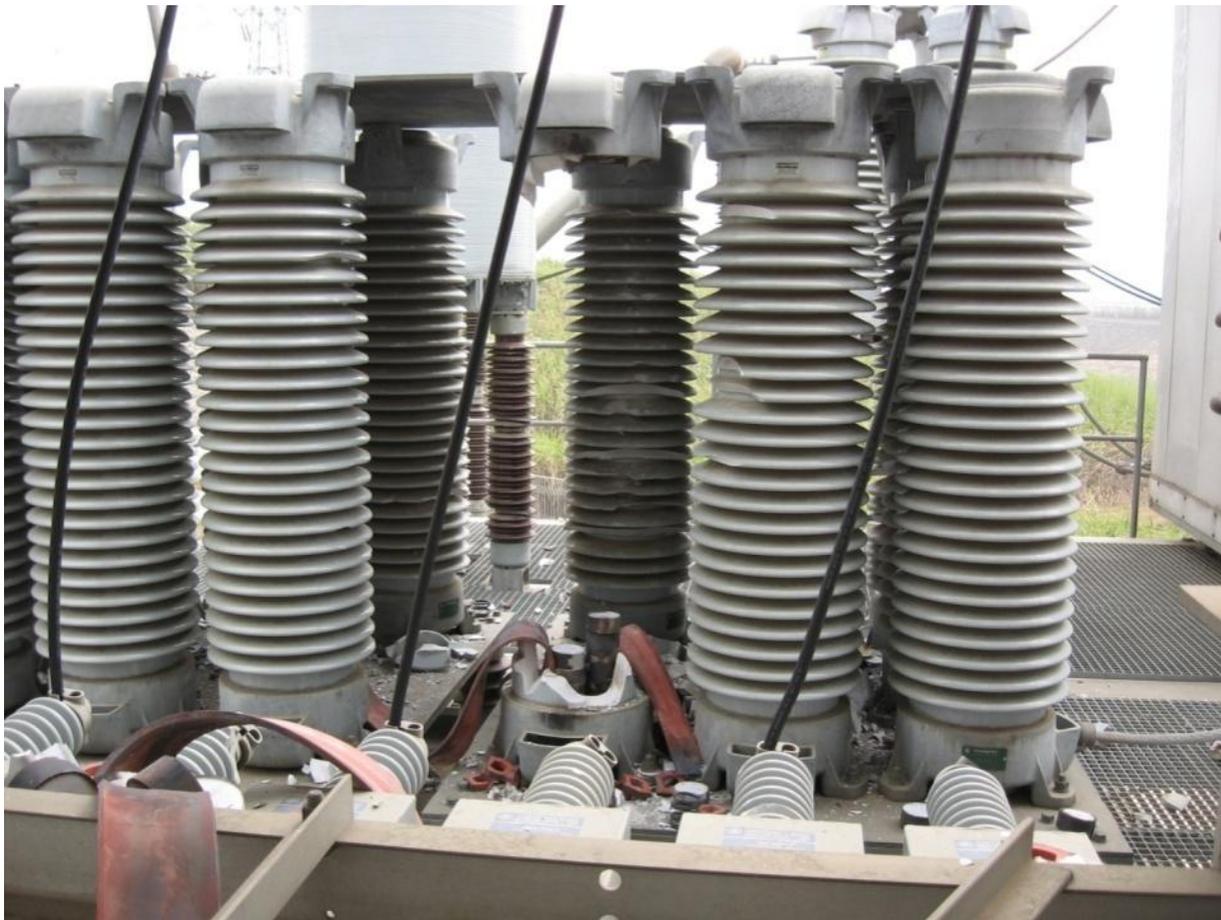
From the early days of MOV protection of series banks, the solution has been to install spares in each bank of columns that are put in service at the same time as the original columns. These “Hot Spares”, as they are sometimes called, see the same fault duty, and the same voltage profile over the life of the bank. If there is a failure in the bank, it is a matter of just extracting the failed columns and re-energizing the bank.

Collateral damage is another concern in the failure mode of large banks of MOV columns (See Figure 9). For single column polymer housed units, the collateral damage is not expected to be as significant, and the risk of exceeding the hot spare quantity is not as high.

Trends in the Market

The trend in the market place at this point in time is for increasingly more series capacitor banks due to the demand for more efficient energy transmission. At the same time it can reduce the cost of energy transmission. This trend is being driven by the more popular trend of Green. This is a perfect example where the product itself may or may not be green, but the Green Affect can be significant. Without the MOV columns, series capacitor installations would be considerably more expensive and perhaps not even feasible.

The only very clear trend in this application is the conversion of housings to polymer in place



(Figure 9: Single column failure and collateral damage on a porcelain house unit

of porcelain which is a trend in the MOV arrester applications also. This trend is being driven by the ease of installation because rigging equipment is not necessary, by the potential for less collateral damage in the event of a failure, and by the improved size reduction of the banks. The porcelain housed MOV protectors for series capacitor banks is near its end of life.

Where ever there is a separation between the point of generation and the user, there will be long transmission lines. These lines are inductive by the fact that they are long conductors. This inductive component will need compensation no matter where the line is. As in Figure 10, you can see that they are used in cold climates as well as warm.



Figure 10: A Series Capacitor Bank with MOV Protection in a cold climate

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