

IEEE Guide for Protective Relay Application to Transmission- Line Series Capacitor Banks

IEEE Power and Energy Society

Sponsored by the
Power Systems Relaying Committee



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IEEE Guide for Protective Relay Application to Transmission- Line Series Capacitor Banks

Sponsor

Power Systems Relaying Committee
of the
IEEE Power and Energy Society

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Abstract: The application of protective relays on transmission-line series capacitor banks is covered. Ample discussion of the protection and control issues related to series capacitor bank installations is provided to the reader. Specific examples related to protective functions and testing procedures are provided.

Keywords: bypass gap, bypass switch, externally fused capacitor, fuseless capacitor, harmonic protection, IEEE C37.116™, internally fused capacitor, metal oxide varistor, MOV, series capacitor, unbalance protection

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Introduction

This introduction is not part of IEEE Std C37.116™-2018, IEEE Guide for Protective Relay Application to Transmission-Line Series Capacitor Banks.

This guide provides additional descriptions and application examples to the IEEE Special Publication on “Series Capacitor Bank Protection.” The guide’s purpose is to provide the reader with ample discussion of the protection issues related to series capacitor bank design. In addition, automatic control functions and general testing procedures are covered. This is an application guide and does not attempt to address all of the protective requirements of all series capacitor banks in every situation. Additional reading material is suggested so the reader can develop a better understanding for a specific protection application.

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IEEE Guide for Protective Relay Application to Transmission-Line Series Capacitor Banks

1. Overview

1.1 Background

Series compensation provides an economical means of maximizing power transfer and improving transmission efficiency over long distances by reducing the series impedance of the transmission line. This guide describes the protection and modern control philosophies of series capacitor banks. The application of this protection requires a thorough understanding of the interrelationship of the power system requirements, the bank's major equipment, and the installation of the equipment.

Background information describing the major equipment and system considerations is presented first. Next, protection issues related to the capacitor units, metal oxide varistor (MOV), bypass system, and capacitor bank platform are discussed. Platform power, automatic control functions, and monitoring systems are discussed. Lastly, functional and performance testing of series capacitor protection and control systems is included with detailed considerations on staged fault testing. ~~Examples showing the calculations for unbalanced voltages and currents in internally fused, externally fused, and fuseless capacitor banks are provided in the Annex E, Annex F, and Annex G.~~ Graphs and recordings of system and protection performance from staged tests of series capacitors are offered in Annex ~~F~~ E.

1.2 Scope

This guide describes the application of ~~protective relays~~ protection systems on transmission-line fixed series capacitors and provides alternative approaches to the design, testing, and maintenance of protective ~~relays~~ systems based on the latest knowledge and the application experience of the industry. This guide ~~will also cover~~ covers issues related to the reliability of the protection system.

The protection and control of distribution system series capacitors and application of variable series capacitors, ~~such as or~~ thyristor-~~controlled~~ protected series capacitors, are not covered in this guide.

1.3 Purpose

The purpose of this guide is to provide the reader with ample discussion of the protection issues related to series capacitor bank design. Applications of series capacitors are sufficiently diverse that protective relay engineers need some guidance on the reasons and considerations for different protection and control schemes. This guide is intended for engineers involved in the areas of protection specifications, evaluation, and operation of series capacitor banks.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Special Publication TP-126-0, Series Capacitor Bank Protection.^{~~1,2~~}

IEEE Std 824TM-2004TM, IEEE Standard for Series Capacitor Banks in Power Systems.^{1,2}

IEEE Std 1726TM-2013, IEEE Guide for the Functional Specification of Fixed-Series Capacitor Banks for Transmission System Applications.

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.³

bypass gap: A system of specially designed electrodes arranged with a defined spacing between them, in which an arc is initiated to form a low-impedance path around one segment or a subsegment of the series capacitor bank. The conduction of the bypass gap is typically initiated to limit the voltage across the series capacitors and/or limit the duty to the varistor connected in parallel with the capacitors. The bypass gap includes the electrodes that conduct the bypass current, the triggering circuit (if any), and an enclosure.

bypass switch: A device such as a switch or circuit breaker used in parallel with a series capacitor and its protective device to ~~shunt line current~~ bypass or insert the series capacitor bank for some specified time or continuously. This device ~~may~~ should also have the capability of ~~inserting and~~ bypassing the capacitor ~~into a circuit carrying a~~ during specified ~~level~~ power system fault conditions. The operation of ~~current. This~~ the device ~~has also been known as the bypass circuit breaker~~ is initiated by the capacitor control, remote control, or an operator. The device may be mounted on the platform or on the ground near the platform.

capacitor element: The basic component of a capacitor unit consisting of two electrodes separated by a dielectric.

capacitor unit: An assembly of dielectric and electrodes in a container (case), with terminals brought out, that is intended to introduce capacitance into an electric power circuit.

discharge current limiting reactor: A reactor to limit the current magnitude and provide damping of the oscillatory discharge of the capacitors during a closing operation of the bypass switch or the start of conduction of the bypass gap.

³*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

external line fault: A fault that occurs on adjacent lines or equipment other than on the transmission line that includes the series capacitor installation.

fuseless capacitor bank: A capacitor bank without any fuses, internal or external, that is constructed of (parallel) strings of capacitor units. Each string consists of capacitor units connected in series.

insertion: The opening of the capacitor bypass switch to insert the series capacitor bank in series with the line.

internal line fault: A fault that occurs on the transmission line section that includes the series capacitor installation.

protective device: A bypass gap, varistor, or other device that limits the voltage on the capacitor segment or subsegment to a predetermined level when overcurrent flows through the series capacitor.

protective level: The magnitude of the maximum peak of the power-frequency voltage allowed by the protective device during a power system fault. The protective level may be expressed in terms of the actual peak voltage across a segment or subsegment or in terms of the per unit of the peak of the rated voltage across the segment or subsegment.

reinsertion: The restoration of load current to the series capacitor from the bypass path.

series capacitor bank: A three-phase assembly of capacitor units with the associated protective devices, discharge current limiting reactors, protection and control system, bypass switch, and insulated support structure that has the primary purpose of introducing capacitive reactance in series with an electric circuit.

~~metal-oxide-varistor (MOV)~~: An assembly of ~~protective~~ varistor units that limit overvoltages to a given value. In the context of series capacitor banks, the ~~MOV~~ varistor is typically defined by its ability to divert fault current around the series capacitor units, limiting the voltage to a specified protective level while absorbing energy. The ~~MOV~~ varistor is designed to withstand the temporary overvoltages and continuous operating voltage across the series capacitor units.

3.2 Acronyms and abbreviations

<u>BIL</u>	<u>basic insulation level</u>
<u>CCVT</u>	<u>coupling capacitor voltage transformer</u>
<u>CT</u>	<u>current transformer</u>
<u>CVT</u>	<u>capacitor voltage transformer</u>
<u>DFR</u>	<u>digital fault recorder</u>
<u>EHV</u>	<u>extra high voltage</u>
<u>EMI</u>	<u>electromagnetic interference</u>
<u>EMTP</u>	<u>electromagnetic transients program</u>
<u>HMI</u>	<u>human machine interface</u>
<u>ISO</u>	<u>independent system operator</u>
<u>LC</u>	<u>inductor/capacitor</u>
<u>MOV</u>	<u>metal oxide varistor</u>
<u>RAS</u>	<u>remedial action scheme</u>
<u>SCPU</u>	<u>series capacitor protection unit</u>
<u>SER</u>	<u>sequence of events recorder</u>
<u>SSCI</u>	<u>subsynchronous control interaction</u>
<u>SSFC</u>	<u>subsynchronous frequency component</u>
<u>SSR</u>	<u>subsynchronous resonance</u>

TAG	triggered air gap
TPSC	thyristor-protected series capacitor
TRV	transient recovery voltage
VT	voltage transformer

4. Preliminary considerations

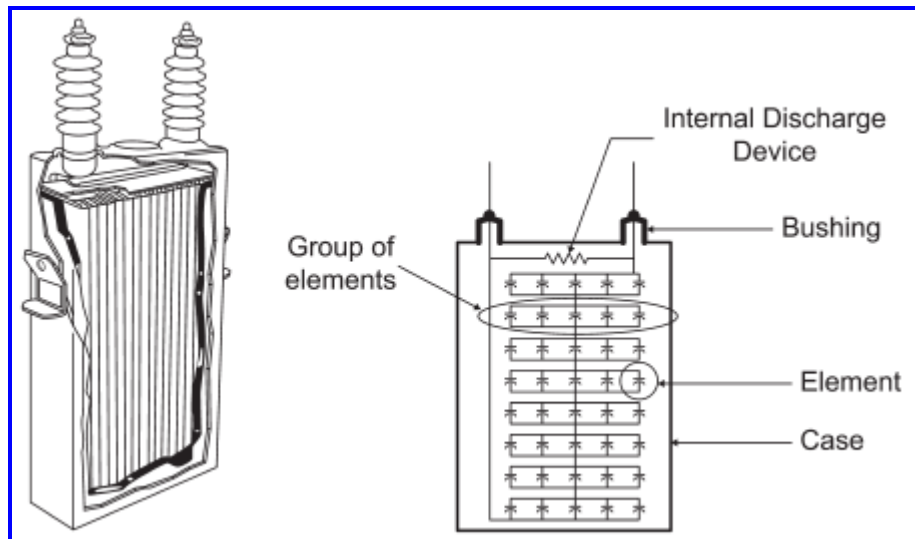
4.1 Major equipment considerations

The capacitor bank is made of numerous individual capacitor units connected in series and parallel to form a series capacitor bank with the required reactance and current-carrying capability. Because it is not feasible to build a series capacitor bank that will carry the maximum expected fault current for a prolonged period, series capacitor banks are designed with a protective feature that allows the bank to protect itself. This is accomplished through bypassing the capacitor bank current around the capacitor units under extreme conditions using bypass gaps or MOV [arresters](#).

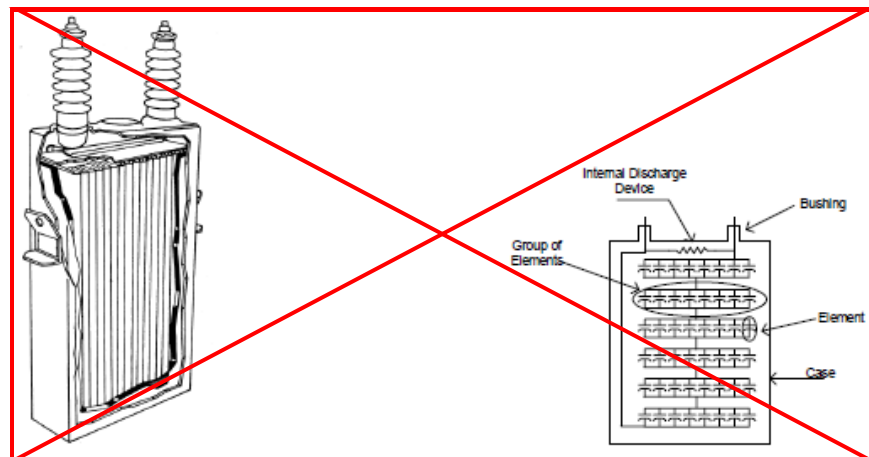
Other major equipment found in a series capacitor bank includes a bypass switch and a current-limiting reactor.

4.1.1 Capacitor unit

The capacitor unit (see Figure 1) is the building block of a series capacitor bank. The capacitor unit is made up of individual capacitor elements, arranged in parallel-connected or series-connected groups, within a [stainless](#) steel enclosure. The internal discharge device is a resistor that reduces the unit residual voltage to 50 V or less in 5 min. Capacitor units are available in a variety of voltage ratings (240 V to 24 940 V) and sizes (2.5 kvar to about 1000 kvar).



(New)



(Deleted)

Figure 1—The capacitor unit

The capacitors are designed to withstand higher currents such as those experienced during emergency loadings (typically the 30 min rating), system swings, and during faults as specified by the purchaser. [The capacitor bank rating should be designed to operate continuously according to IEEE Std 1726™-2013.](#)⁴

⁴ For information on references, see [can be found in](#) Clause 2.

The capacitor units are designed to withstand the specified continuous rated current, emergency loading, swing current, and power system faults, within the maximum allowable capacitor unbalance condition as determined by the control and protection system.

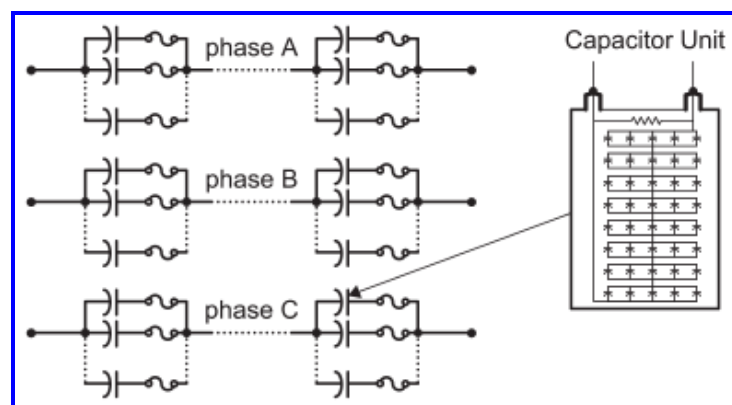
The capacitor fuses, either internal or external, should be designed to operate correctly according to IEEE Std 824TM-2004.³

4.1.2 Capacitor fusing and unit arrangement

The capacitance of the bank is accomplished by connecting capacitor units in series and parallel to provide the required capacitive reactance with the continuous current rating. Three different types of fusing arrangements are being applied on series capacitor banks. These types and the associated arrangement of the capacitor units are outlined in 34.1.2.1, 34.1.2.2, and 34.1.2.3.

4.1.2.1 Externally fused capacitor bank

The typical arrangement used with externally fused capacitors involves the connection of groups of fused capacitors in parallel, as necessary to meet the current rating of the bank. These groups are connected in series to realize the voltage and impedance ratings of the bank (see Figure 2).



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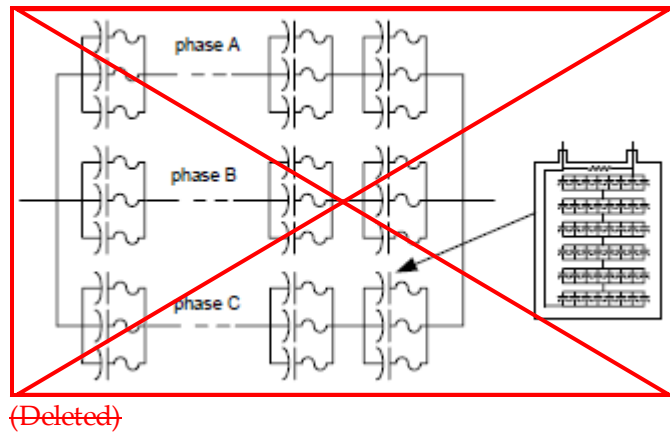


Figure 2 – Externally fused capacitor bank

Dual-element fuses consisting of two fuses in series are typically applied to each capacitor unit. One of these fuses is a current-limiting type that is used because of the high stored energy in the parallel capacitors [group](#). The second fuse is an expulsion type that will operate for lower current conditions and provides a visible break.

A failure of a capacitor element welds the foils together and short-circuits the other capacitor elements connected in parallel in the same group. The remaining capacitor elements in the unit remain in service with a higher voltage across them than before the failure and an increase in capacitor unit current. If a second element fails, the process repeats itself resulting in an even higher voltage for the remaining elements.

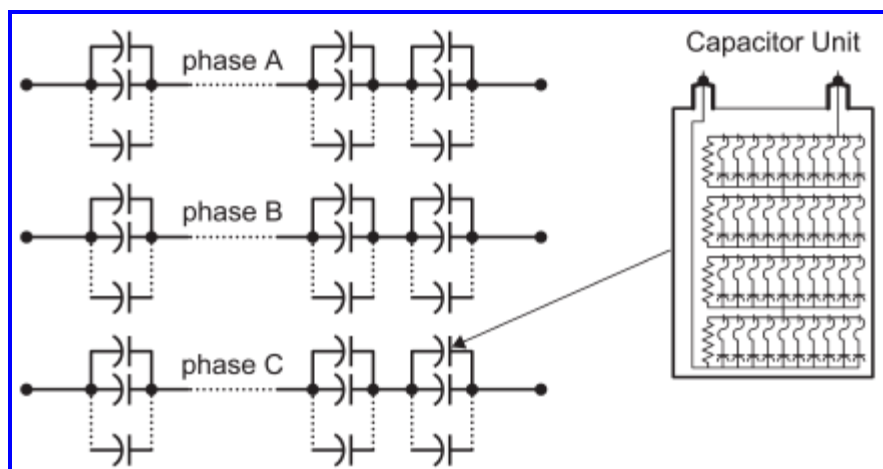
Successive failures within the same unit will cause the fuse to operate, disconnecting the capacitor unit and indicating which one failed. This results in increased voltage on the parallel units. The magnitude of this voltage increase is dependent on the number of units in parallel in the manufacturer's design.

The available unbalance signal level decreases as the number of series groups of capacitors is increased or as the number of capacitor units in parallel per series group is increased.

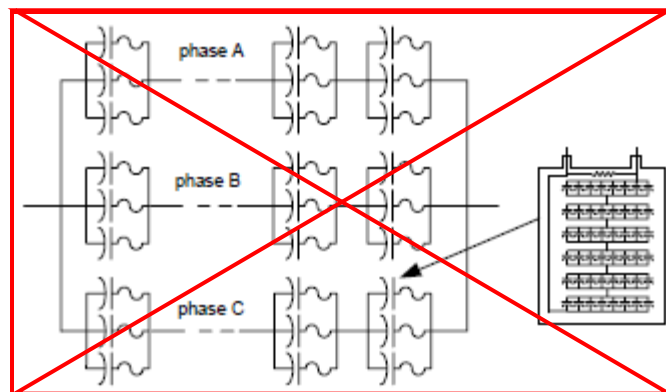
The capacitor units can have only one insulated terminal with uninsulated terminal connected to the rack or two insulated terminals (~~bushing~~ bushings).

4.1.2.2 Internally fused capacitor bank

The typical arrangement for the bank when using internally fused capacitor units also involves groups of fused elements connected in parallel. These groups are then connected in series to realize the rating for the unit. The units are connected in series and parallel as necessary to meet the overall ratings of the bank (see Figure 3).



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Figure 3—Internally fused capacitor bank

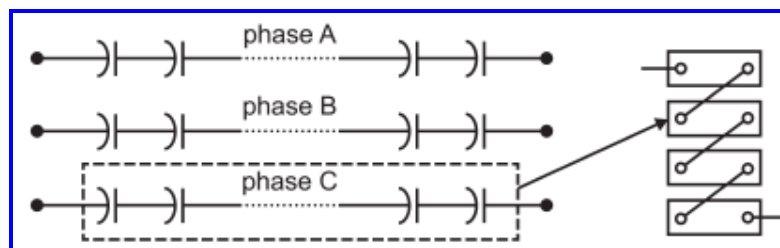
The failure of a capacitor element results in a discharge current from the parallel elements through the associated internal fuse, which blows the fuse. This results in increased voltage on the parallel elements within the unit and a much smaller increase in the voltage across the associated unit. The magnitudes of these voltage increases are highly dependent on the number of elements in parallel in the manufacturer's design.

The capacitor units may have one or two insulated bushings.

4.1.2.3 Fuseless capacitor bank

The capacitor units for fuseless capacitor banks are identical to those for externally fused, as described in [34.1.2.1](#), [or elements inside the unit may also be series elements in a string that are in parallel](#). A bank is made of strings of series-connected capacitor units between phase and neutral, [as shown in Figure 4](#). These strings of capacitors are connected in parallel as necessary to attain the current and impedance ratings of the bank. The number of units connected in series is as required to achieve the necessary voltage capability.

[For capacitor units designed similar to externally fused banks](#) the failure of a capacitor element results in a short circuit of the associated group of elements within the capacitor unit. This results in an increase in current through, and increased voltage on, the remaining elements within that capacitor unit and the other capacitor units in the associated string. The degree of this increase is dependent on the total number of elements in series in the string. The capacitor unit with the shorted element remains in continuous operation. [Modern](#) capacitor units used in fuseless applications have an all-film dielectric system.



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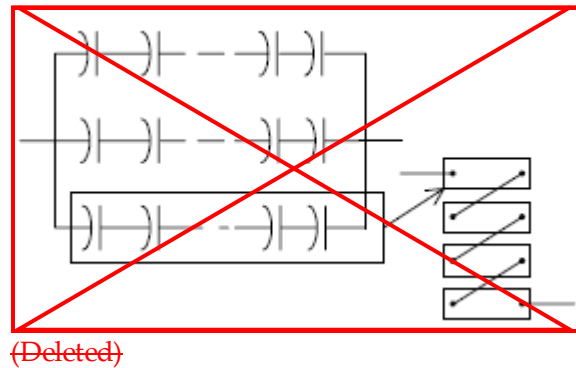


Figure 4—Fuseless capacitor bank

4.1.3 Overvoltage protective devices

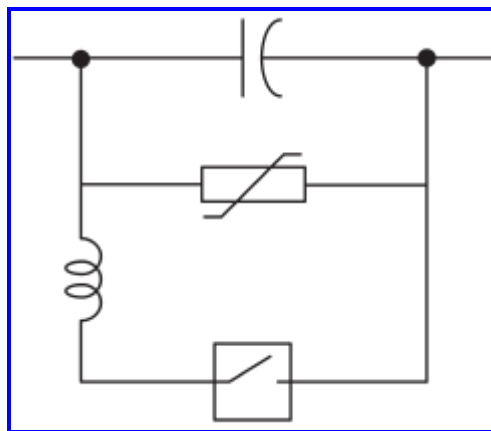
The practical application of series capacitor banks on transmission systems almost always requires that the bank ~~include~~ includes a protective device to limit the capacitor bank overvoltages, exceeding the protective level of the capacitor bank segment, that occur during power system faults. A description of each type is given in 4.1.3.1.2.1, 4.1.3.1.2.2, and 34.1.23.3.

4.1.3.1 MOV gapless system

MOVs are one type of overvoltage protective device. A simplified one-line diagram is shown in Figure 5. The MOV is usually connected in parallel with the capacitors. The bypass switch is also connected in parallel via a current-limiting reactor. The MOV is constructed of a series and parallel array of metal oxide nonlinear resistor elements. These elements are placed into enclosures for protection against the environment.

The MOV limits temporary overvoltages across the capacitors by conducting the excess transmission line current, usually due to faults, that would otherwise cause excessive capacitor voltage. This conduction occurs on each half-cycle of the power frequency current of the overcurrent condition, or until the parallel bypass switch closes or the fault is cleared by the line circuit breakers. The maximum voltage that results across the series capacitor depends upon the nonlinear voltage-current characteristics of the MOV and the magnitude of the overcurrent. Because the MOV voltage increases with current, the protective level is usually defined as a coordinating current representing the expected MOV current during a power system fault. Energy is absorbed by the MOV during conduction. The selection of the MOV energy capability and protection of the MOV against overstress are important aspects of the series capacitor protection system.

The MOV is designed with current and energy absorption capabilities that are consistent with anticipated power system fault conditions. In addition to the protective level, critical factors that determine MOV requirements are the equivalent impedance of the power system, the duration of the fault, and transmission-line circuit breaker reclosure sequence. With this information, the MOV current and energy absorption can be determined.



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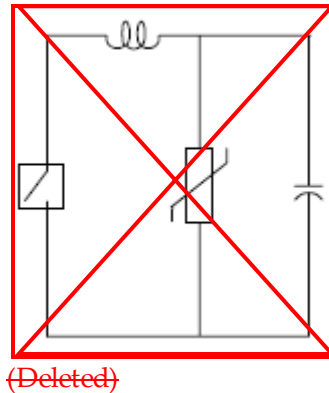
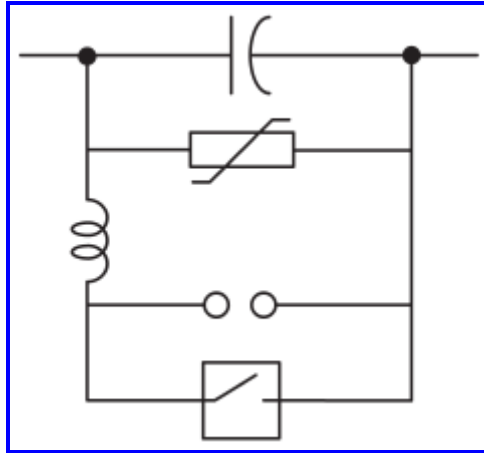


Figure 5—Capacitor bank with MOV

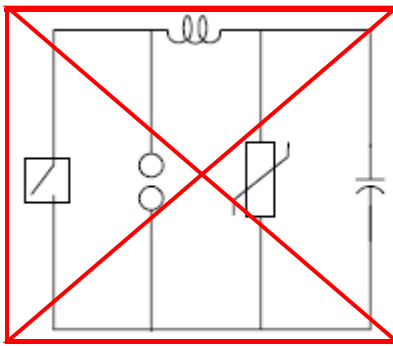
Typically, for the protective device consisting of an MOV with no forced bypass gap, the MOV will be designed to withstand the current and energy associated with the specified internal line faults. Internal line faults near the series capacitor bank can cause much higher MOV current and energy. This is especially true if the installation is located at the end of the line near a substation with a high short-circuit current. However, it is also important to establish the MOV duty during external line faults. For the latter condition, the series capacitor in the unfaulted line should remain in service during the fault and the critical post-fault period to enhance power system stability [if required](#).

4.1.3.2 MOV with forced triggered bypass gap

In many applications, the protective device also includes a forced triggered bypass gap. This gap is fired for power system fault conditions that result in higher duty to the MOV. The gap does not normally spark over due to the voltage that appears across series capacitors, ~~since~~ [because](#) that voltage is limited by the MOV. Rather, the sparkover of the bypass gap is triggered based on the duty to the MOV. A one-line diagram of this protective device is shown in Figure 6. Note that the bypass gap is connected in parallel with the bypass switch. The electrodes of the gap are [typically](#) contained in an enclosure that limits the ingress of precipitation.



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Figure 6—Capacitor bank with MOV and bypass gap

Even though this system includes a forced bypass gap, the MOV performs the primary overvoltage limitation in a manner identical to the limitation for the MOV-only system described in 34.1.3.1. In this case, the MOV is normally designed to withstand the duty associated with specified external line faults. However, the gap is triggered during more severe faults to limit MOV duty, especially during internal line faults.

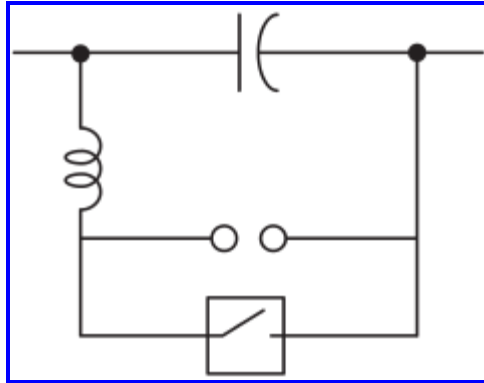
The MOV with [a](#) forced bypass gap is most often applied on banks located at the end of the line, especially if the fault current is greater than 10 kA to 20 kA rms. For a close-in fault on the line side of the series capacitor bank, the potential duty to an MOV can be quite high. In this ~~case~~ [example](#), the gap is triggered based on the high duty to the MOV at the start of the fault. Firing control thresholds are selected to [help](#) avoid firing the gap during a normal external line fault. In most designs, the gap will typically conduct within 0.5 ms after the thresholds are exceeded. The logic for the triggering and the equipment to achieve it are different among ~~the~~ various suppliers. However, the conduction is not instantaneous, so the MOV is exposed to high current for a finite time. Therefore, the MOV is designed to withstand the high fault current until bypass occurs.

Once the bypass gap conducts, most designs used with ~~MOV~~ [MOVs](#) do not have much ability to interrupt the current. In general, this is not an important factor ~~since~~ [because](#) the gaps are normally triggered only when the MOV duty exceeds the thresholds associated with an internal line fault. For an internal line fault, the line, along with the series capacitor bank, is temporarily removed from service. This eliminates the gap current, and the gap deionizes and regains its voltage withstand capability prior to normal line reclosure.

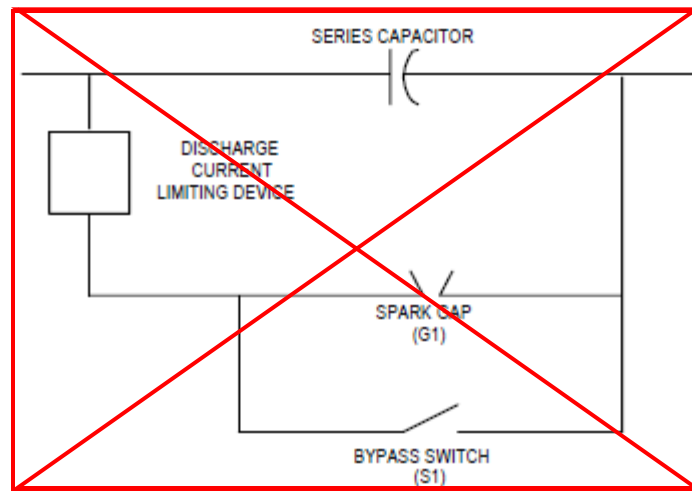
4.1.3.3 Spark gap scheme

Most new series capacitor schemes are as described in [34.1.3.1](#) and [34.1.3.2](#). However, [many existing series capacitors still in service use only a spark gap](#) for ~~completeness,~~ [bypass of the series capacitor bank](#). A brief description of the spark gap scheme is provided in the following paragraphs.

Figure 7 shows a simplified schematic diagram of a capacitor bank protected with a single gap. The main element of this protection is a spark gap ~~(G1)~~, which is self-triggered. A bypass switch ~~(S1)~~ is connected across the gap to bypass the bank. A discharge current-limiting device is connected in series with the gap and the bypass switch. The discharge current-limiting device consists of a low reactance current-limiting reactor, which may be paralleled with a resistance (see [34.1.4](#) on discharge current-limiting devices).



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Figure 7—Capacitor bank protection with a single gap

The gap setting is coordinated to naturally spark over and, effectively, bypass the capacitor bank for transient overvoltages above the short-time rating of the bank. The discharge current-limiting device limits the capacitor discharge current when the gap sparks over. The spark gap arc is extinguished by either opening the line circuit breaker or closing the bypass switch. After the fault clears, and if the bypass switch is closed, the protection and control scheme reinserts the capacitor into the line by opening the bypass switch. However, the inherent tendency for the spark gap current to extinguish near a line current zero-crossing leads to transient overvoltages across the capacitor during the reinsertion. If reinsertion is attempted too soon, it is likely to cause reignition of the ionized gap, especially when the line current is high. A deionization time (typically 400 ms to 1000 ms) is generally necessary, and depends on the fault type. When reliable high-speed reinsertion is required for system stability, the gap setting must be high enough to withstand reinsertion transients. In some applications, this may require a bank rating much higher than would be necessary for overload current considerations.

[For modern gap devices](#) the triggering level is often set by a separate trigger circuit. Operation of the triggering circuit causes the power gap to operate. This achieves the desired accuracy, and allows the trigger level to be changed in small increments. ~~However,~~ It is important that the gap is triggered at the correct level, but is not spuriously triggered. [Alternative series capacitor designs may be considered if high-speed reclosing is desired.](#)

4.1.4 Discharge current-limiting reactor

Typically, the discharge current-limiting reactor is connected as shown in Figure 5 and, hence, does not carry current when the bank is inserted.

In some applications, however, the discharge current-limiting reactor is connected in series with the capacitors. This arrangement is infrequently used to reduce losses where the segment is frequently bypassed, and may be used to eliminate the potential for harmonic current magnification where the reactor is paralleled with the capacitor during bypassed operation. It is also used to reduce the duty on the disconnect switch, typically used in parallel with the bank. If the discharge current-limiting reactor is in series with the capacitors, the reactor is rated to withstand the same current magnitudes and durations as required for the capacitor segment.

4.1.5 Bypass switch and bypass gap

As in the case of the MOV, the interrupter of the bypass switch and the bypass gap are also exposed to voltages resulting from currents through the capacitors. In addition, this equipment is exposed to protective level voltage during power system faults. This equipment is designed to withstand these voltages. [The speed of bypass may have a significant effect on the line breakers. If line transient recovery voltage \(TRV\) is greater than the line breaker rating, high speed bypass of the series capacitor bank will be required or the line breakers will have to be replaced.](#)

4.1.6 Thyristor-protected series capacitors (TPSCs)

An alternate approach to protecting ~~the~~ series capacitors has been developed using power electronic devices. Thyristor valves, providing fast bypass and reinsertion of the series capacitor bank, have been used to replace the MOVs and bypass gaps as overvoltage limiting devices. Thyristor valves have been used for some time in series capacitor banks for the control of the capacitive reactance.

Further details of the TPSC can be found in IEEE Std 824-[2004](#).

4.2 System conditions

The main purpose of the control and protection equipment is to protect the bank and to avoid equipment damage. It is also important that no aspect of the duty cycle under various system conditions be compromised. The protective equipment should not provoke undesired operations under specified normal or contingency duty cycle. System conditions are therefore prerequisite information for the design and validation of protection and control equipment.

The utility is responsible for the development and specification of various ~~type~~ [types](#) of technical data required for the design. Preliminary system studies are conducted to select an appropriate location for the capacitor bank on the line and to issue general characteristics, including MOV energy requirements. The results of these studies will allow the manufacturer to appropriately design the equipment, mainly the capacitor bank and the MOV. The duty cycle that the bank is designed to withstand will depend on local utility practices, the power system configuration, and the nature of the disturbance. The number of event duty cycles that the protective equipment must withstand (for both internal and external line faults) before bypassing the bank for an extended period (hours) are specified by the purchaser and ~~is~~ [are](#) a critical factor in determining series capacitor equipment ratings.

[Refer to IEEE 1726-2013 for guidance on studies and equipment ratings.](#)

4.2.1 System representation

Series capacitor applications require extensive system studies to identify the general parameters for design. The system data and equivalent network should be provided to the series capacitor manufacturer for the specific installation to allow independent confirmation and for determination of capacitor protective levels. As a minimum, the system model should include line characteristics, shunt reactors, equivalent source impedance, and voltage. For studying interactions between a power system and a control system, an approximate model of the distributed parameter line can be obtained by cascading several ~~identical line~~ [PI sections](#) [section equivalent circuits](#). However, accurate results would only be obtained by using a distributed parameters line model with the positive-sequence and zero-sequence networks. ~~The $N \times N$ matrix needs to be specified for systems with asymmetrical lines.~~ The model should also include an accurate MOV model representation. In some cases, system studies are run with different MOV models. The relationship between voltage and current in the model used for the studies could be expressed as a table of V-I points or an exponential formula. There may be differences between the appropriate curve used for system studies and the curve used for the control equipment model. In practice, however, these differences will be small. More significant factors that could cause variations in the energy calculations are the specifics of the duty cycle—in particular, the time duration of each fault event.

After the MOV characteristics have been finalized with the supplier (dimensioning, protective voltage level, coordinating current, V-I characteristic, etc.), the system studies are often rerun, particularly those studies pertaining to MOV energy absorption during the duty cycle and during system swings. For some utilities, an additional purpose for rerunning the studies is to generate accurate electromagnetic transients program (EMTP)-based studies for short-circuit evaluation of the actual control and protection system, particularly the MOV protection. With the computation power available today, transient simulation studies can be performed with the entire system model as opposed to the use of equivalents.

4.2.2 Fault current

Studies are conducted to investigate the system performance for the worst case internal and external line faults. Typically, the external line fault will define the rating of the MOV when a bypass gap is used in parallel. The internal line fault usually defines the rating of the MOV in a gapless scheme. Different contingencies for external line faults with various types of faults and duration are considered in order to evaluate the stress on the MOV. The utility may choose to specify an MOV that has sufficient energy absorption capacity for external line faults, in order to prevent any gap operation under these conditions. The most severe internal line faults normally occur near the capacitor bank itself. The studies must then evaluate the highest MOV current and the maximum short-time energy level. These parameters are essential to evaluate if any additional energy capacity is required by the MOV. This is an important consideration with respect to sizing MOVs, and for bypass gap-only schemes, where capacitor bank reinsertion and gap arc extinction must be considered.

Fault currents should be defined with no ambiguity. It is important to indicate if reference is made to a maximum system fault current or to a fault through the capacitor bank. The fault current must be evaluated with an appropriate program that takes into consideration the nonlinear impedance of the protective device. The current through an inserted capacitor bank will result in high voltages across the capacitors, and the apparent impedance of the bank will change according to the voltage-limiting action of the protective device. Such differences in total fault currents on a compensated line are illustrated in Figure 8.

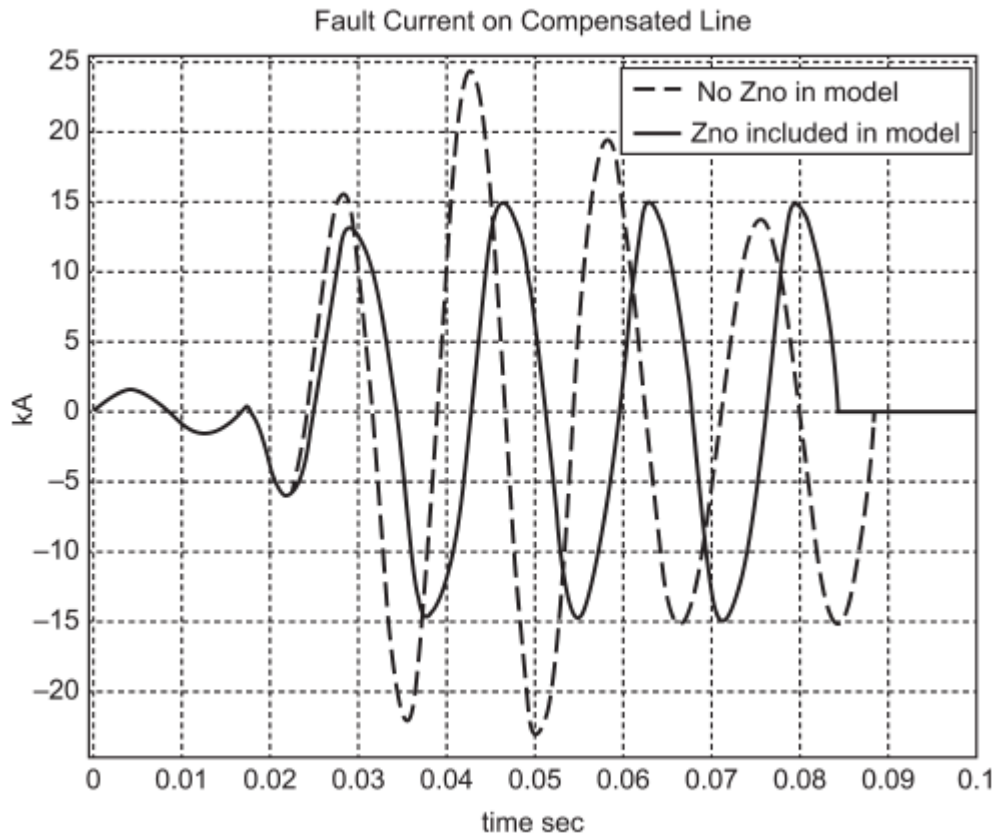


Figure 8—Fault current on compensated line

4.2.3 Line harmonics

Harmonics generated by nearby power electronics equipment need to be considered in the design to [help](#) avoid interaction with the bank in all possible configurations. During a bypass operation, an inductor/capacitor (LC) configuration is formed by the discharge reactor in parallel with the capacitor bank. Current resonance excited by the presence of harmonic current on the line has been observed in some installations. If such conditions are identified at the early design stage, several actions could be taken by the protection and control system to eliminate potential damage to the equipment.

4.2.4 Low-frequency transients

A fault or switching event on a system with series capacitors can create low-frequency current transients on the lines adjacent to the series capacitor. The magnitude and duration of the transients depend on the amount of series capacitance and the series inductance of the system. If the event causes the series capacitor protection to bypass the bank, the transients will begin to damp.

The low-frequency transients in the currents will affect the capacitor's protection and the adjacent transmission lines' protective relays. The capacitor's protection could operate due to the low-frequency transients, even when the steady-state values are below the protective level. The transmission lines' protective relays will see higher than steady-state current values, which could cause overreaching of the relays. More details about low-frequency transients are provided in Annex [B](#) [A](#).

4.2.5 Subharmonic resonance

The low-frequency transients created by faults or switching on a series-compensated system can interact with the power system and cause harmful resonance conditions. Either subharmonic resonance or subsynchronous resonance (SSR) can occur. It is important to evaluate the system to determine whether these conditions could occur.

Subharmonic resonance might occur if an unloaded transformer is energized. The inrush currents have instantaneous values that are much greater than the transformer-rated current. Normally, for an uncompensated system, this high current persists for only a few seconds. For a system with a series capacitor, these abnormally high currents may continue to flow. This condition may result in a harmful resonance condition, which can cause overheating of the transformer and/or overstressing the capacitor cans (even during normal load conditions). In order to eliminate the subharmonic resonance condition, the bank should be bypassed. Subharmonic resonance conditions are very unlikely to occur in [extra high voltage \(EHV\)](#) transmission systems unless the transmission system is energized with the series capacitors in service.

4.2.6 Subsynchronous oscillations (SSR and SSCI)

SSR is a far more significant problem, which might occur when a nearby series capacitor interacts with thermal turbine generator shafts. This condition might cause a harmful resonance condition that could cause damage to the shaft of the turbine generator. If SSR conditions are suspected for a series-compensated system, these should be identified during the initial system studies. SSR is covered in greater depth in the book *Subsynchronous Resonance in Power Systems* ⁴ ([Anderson, Agrawal, and Van Ness \[B3\]](#)) and other publications given in Annex ⁵.

[Another type of oscillations can occur when wind farms are located near series-compensated lines. Wind turbine generators with power electronic converters and controls that operate near series compensated transmission lines are often susceptible to undamped subsynchronous control interaction \(SSCI\) problems \(Irwin, Jindal, and Isaacs \[B13\]\).](#)

4.2.7 System unbalance

A protection function that detects phase unbalance can be used as a backup to the primary detection of MOV failure, prolonged gap conduction, platform fault, and bypass switch phase disagreement. All these conditions result in capacitor current differences among the three phases. The line unbalance specific to the system conditions must be known for the coordination of all these functions. Special coordination is required if single-phase reclosing is a common practice. The control and protection engineer should also evaluate the degree of unbalance the operation of these functions can generate into the adjacent lines to prevent a cascading-bypass action to the other lines.

4.2.8 Required speed for reinsertion

Stability during transients depends on speed of reinsertion. The protection system should be designed to meet the required reinsertion time, which can be determined by stability simulations. However, reinsertion might not be permitted if the temperature in the MOV is still above the acceptable threshold. Therefore, it is important for the protection and control engineer to ~~insure~~ [help ensure](#) that the MOV temperature model is adequate and well validated.

⁴ ⁵The numbers in brackets correspond to those of the bibliography in Annex ⁵.

4.3 Duty cycle

The duty cycle that the bank is designed to withstand will depend on local utility practices, the power system configuration, and the nature of the disturbance.

In order to specify the MOV rating for a particular power system, extensive EMTP ~~study~~ [studies](#) should be done. The EMTP model of an MOV can be obtained from the manufacturer. The following scenarios should be considered:

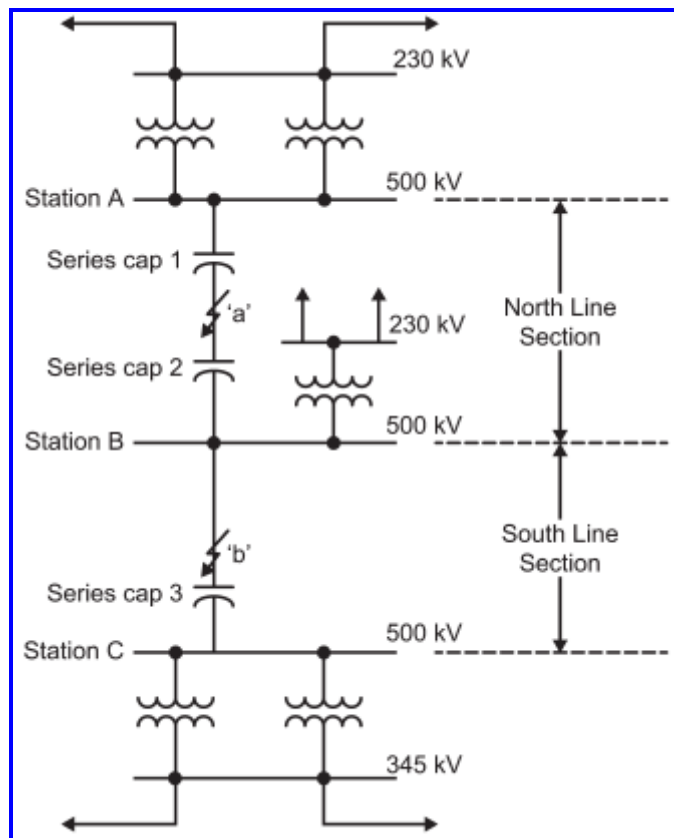
- Maximum power flow in both ~~direction~~ [directions](#) of the line
- Relay and breaker operating times
- Faults at definite intervals on the line (0% to 100%)
- Single- and multi-phase faults
- DC offset due to the fault on point of voltage waveform
- Reclosing
- Breaker failure
- Gap firing (if bypass gap is included)
- Bypass switch closing (if desired)

A typical example of a 500 kV line consisting of two segments, North and South, is shown in Figure 9.

The North segment is 547 km (340 mi) from station A to B and contains two series capacitors (series cap 1, series cap 2) located in the middle of the line. The south segment is 215 km (134 mi) long from station B to station C. On the south segment, the series capacitor is located at station C. The series capacitors are protected by MOVs. Table 1 shows the maximum energy the MOV needs to absorb for the type of fault with breaker failure at maximum load transfer. The number in parentheses includes a 30% to 35% margin. Note that maximum energy for a phase-to-phase fault occurred at fault location 'a,' and occurred at fault location 'b' for a three-phase fault.

Table 1—MOV energy requirements without bypass gap

Description	Fault location	Type of fault	Energy
Series cap 1	'a'	phase-phase	108 MJ (140 MJ)
Series cap 2	'a'	phase-phase	101 MJ (130 MJ)
Series cap 3	'b'	three-phase	342 MJ (445 MJ)



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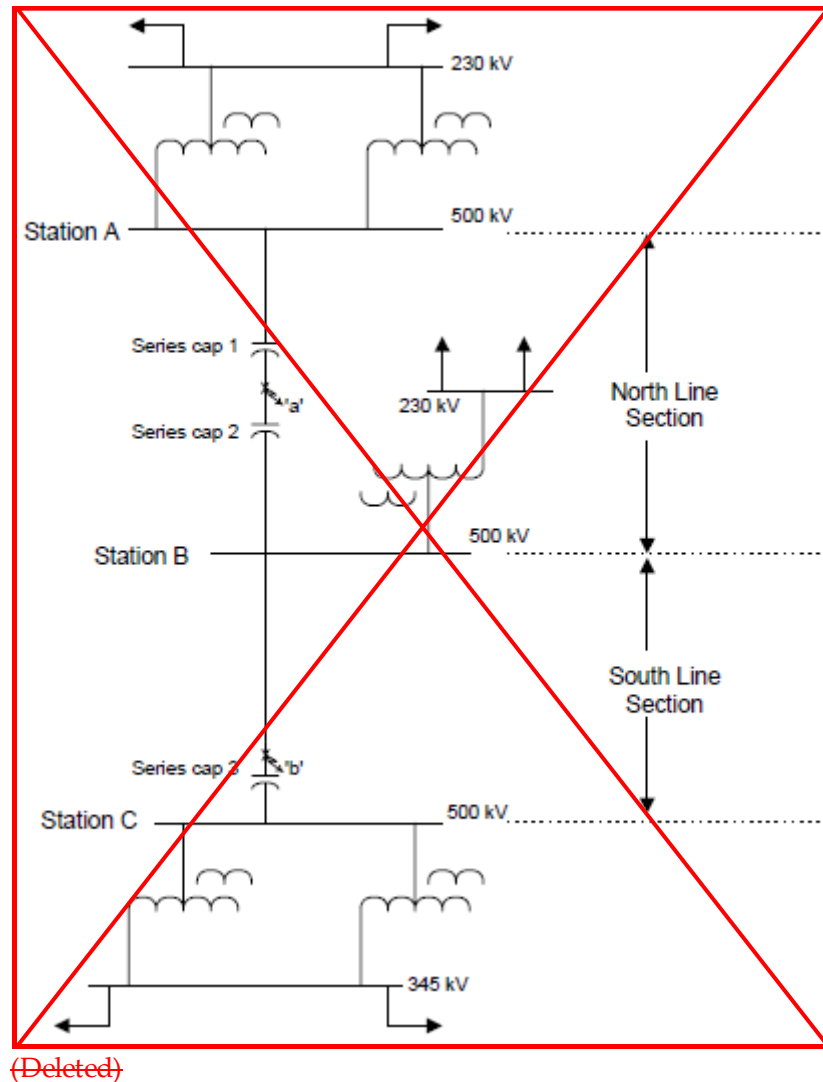


Figure 9—Example of a 500 kV system

The energy requirement can be reduced if a bypass gap is used across the MOV. At certain energy levels or high fault currents, the gap can be triggered to reduce MOV energy requirements. Table 2 shows the energy requirements with a bypass gap.

Table 2—MOV energy requirements with bypass gap

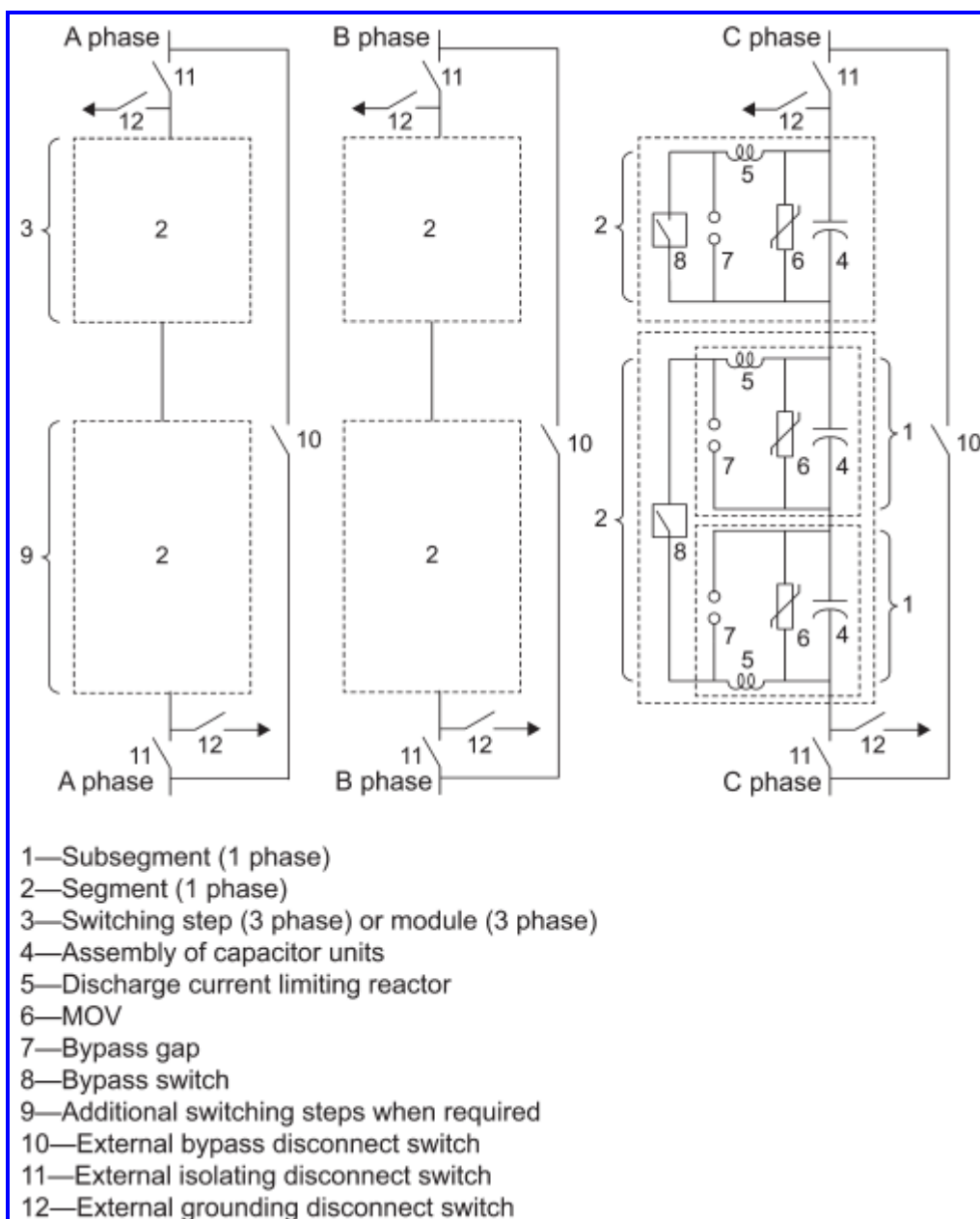
Description	Fault location	Type of fault	Energy
Series cap 1	'a'	phase-phase	20 MJ (30 MJ)
Series cap 2	'a'	phase-phase	15 MJ (25 MJ)
Series cap 3	'b'	three-phase	25 MJ (40 MJ)

4.4 Multiple segment series capacitors

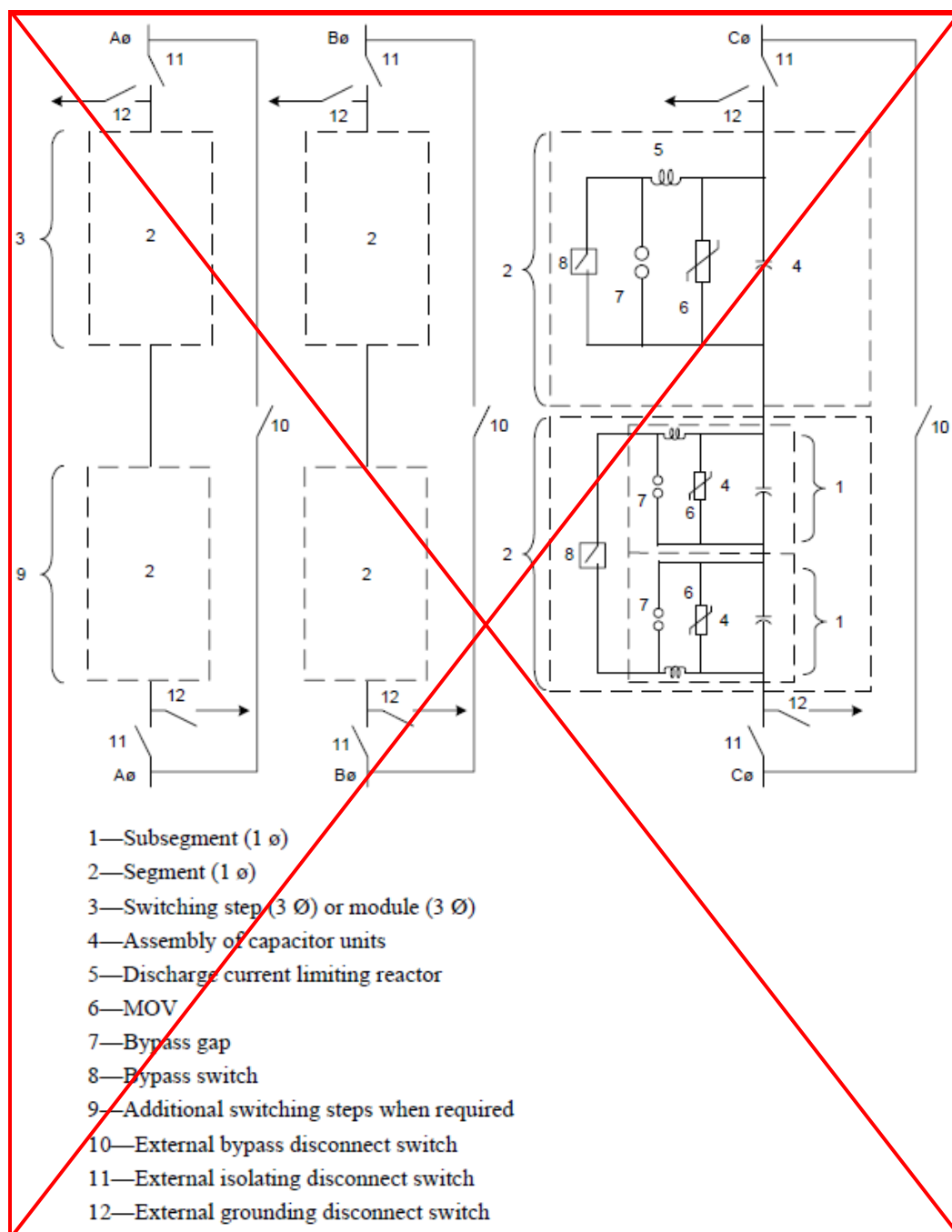
Typically, the series capacitive compensation in a transmission line is selected as a fixed percentage of the line inductive reactance, having a value anywhere between 20% and 80%.

This series capacitive reactance is generally installed as two banks, one at each line terminal, as a single bank at one terminal, or in the middle of the line. Series capacitor banks can be designed to be divided in several segments, each of which can either be in operation or bypassed. A range of reactance values can be the result. There are several reasons to use this type of design; the most important being the limited overvoltage capabilities of the bypass element. Others include control of the inserted capacitance.

A “segment” is defined as a single-phase assembly of capacitor units and associated protective device, discharge current limiting reactor, protection and control functions, and one phase of a bypass switch. Segments are not normally separated by isolating disconnect switches. More than one segment can be on the same insulated platform, as shown in Figure 10. Rated segment voltage (V_R) is the rated root-mean-square (rms) voltage across a segment when the segment is carrying rated current.



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Source: IEEE Std 824-2004.

Figure 10—Nomenclature for a typical series capacitor installation

A “subsegment” is a portion of a segment that includes a single-phase assembly of capacitor units and associated protective device, discharge current limiting reactor, and selected protection and control functions; but does not have a dedicated bypass switch.

A “switching step” is the three-phase assembly that consists of one segment per phase, with a three-phase operating bypass switch for bypassing or inserting the capacitor segments. This is sometimes referred to as a capacitor module.

The number of switching steps in a capacitor banks depends on several factors, such as: protection against overvoltages, amount of reactive capacitance needed to be switched in and out of service, [and](#) limitation and damping of high-amplitude, high-frequency discharge currents. Basically, the intent is to maintain the bank rms voltage and transient voltages to a manageable design level.

In the late ~~60s~~ [1960s](#) and early ~~70s~~ [1970s](#), when the series capacitors banks were first installed, the series capacitor bypass and insertion technology used spark gaps, which some manufacturers utilized to limit each bypassing step to 15 kv to 18 kV rms or 70 kv to 75 kV peak transient voltage across the switching step. This was necessary to meet the performance requirements of the spark gap and to [help](#) ensure that the series capacitors would reinsert successfully when a line fault on an adjacent line is cleared.

Today, improvements and developments in the bypass technology enable the design of series capacitor banks with bank voltages of up to 100 kV rms and 300 kV peak transient voltages. This allows designing the majority of series capacitor banks as a single switching step bank and has resulted in substantially reduced costs and superior performance.

4.5 Single-phase trip/reclose considerations

When looking at single-phase tripping and reclosing considerations for a series capacitor bank, the appropriate bank controls should be specified. These control requirements are related to the system aspects, as well as the line protection aspects of the project.

For a transmission line that is only switched three-phase, bank control is reasonably straightforward. All switching, whether for fault tripping, bank tripping, automatic bank control, or routine switching from the control center, is applied on a three-phase basis.

Various options are available when the associated transmission line is switched single-phase, depending upon the system, bank, and line protection requirements.

4.5.1 System requirements

To aid secondary arc extinction, it is beneficial to bypass at least the faulted phases of the series capacitor bank. Considering this aspect, either the faulted phase or all three phases can be bypassed.

The primary benefit of single-phase tripping and reclosing is to maintain transmission capability during system single-line-to-ground faults. Thus, from this point of view, it is desirable not to bypass the unfaulted phases of the series capacitor to be able to maintain as high a load transfer as possible.

4.5.2 Bank requirements

The capacitor bank must be protected against system faults and bank faults. Bank protection is discussed in [4.2.5.1](#) to [4.5.7](#) of this guide. For certain protection provided for system faults, such as MOV protection, bypass may or may not be on a three-phase basis. For example, MOV temperature overload protection (see [4.5.2.2.3](#)) would initiate a three-phase bypass and insertion of the bank in all cases, due to the requirement to remain bypassed for a relatively long period to allow the MOVs to cool down. However, the MOV high current protection (see [4.5.2.2.2](#)) could bypass and insert on a single-phase basis.

4.5.3 Line protection requirements

Line protection of the associated transmission line should be tested to confirm performance and [help](#) avoid problems ~~such as~~ [associated with](#) voltage inversion or current reversals [affecting both distance and ground directional elements](#) (see Appendix III of *Series Capacitor Bank Protection*, IEEE Special Publication).

If single-phase bypassing and insertion for some bank protection functions is enabled, there is a possibility that a spurious bypass can occur for an external line fault. Depending upon the applied line protection, the series unbalance that occurs (due to one phase of the bank that is bypassed, two that are inserted) may present a problem for the applied line protection. For current-only based protection, such as phase comparison or line current differential, this should not be a problem. For directional comparison-based schemes, particularly where sensitive ground directional fault detectors are applied, this may present a problem. In some instances, the requirement for sensitive ground directional fault protection may mean that the line protection may operate during the spurious bypass condition. Solutions to this problem are beyond the scope of this publication. However, to allow flexibility if these problems occur in the future, the benefit of specifying the requirement for single-phase or three-phase operation of the bank (via a local control/remote control switch) cannot be underestimated.

4.6 Impact on line protection

The impact that a series capacitor application has on line protection is well discussed in the literature ([Alexander, et al. \[B1\]](#), ~~[\[B4\]](#)~~, ~~[\[B9\]](#)~~, ~~[\[B11\]](#)~~ [Kasztenny \[B14\]](#), [IEEE Std C37.113™-2015 \[B10\]](#), [Bakie and Westhoff, et al. \[B5\]](#), and [Altuve, Mooney, and Alexander \[B2\]](#)) and also summarized in Appendix III of *Series Capacitor Bank Protection*, IEEE Special Publication. In ~~34~~.5 of this guide, there is a brief summary of the issues related to switching a capacitor bank on a single-phase basis.

4.7 Line protection and series capacitor protection/control interaction

From a series capacitor bank perspective, the following aspects should be well known, documented, and specified to ~~ensure~~ make sure that those responsible for applying the line protection have the necessary information to evaluate performance:

- a) Identify if the bank is switched single-phase or three-phase (also for which protection and control function).
- b) Determine if a bank control switch has been specified to allow the bank to be switched three-phase instead of single-phase.

- c) For a spurious bypass or automatic bank insertion condition, determine the time that the unbalance will persist.
- d) Identify how the bank is switched for low magnitude faults, which precludes bank protection operation in one of the following ways:
 - 1) Bank remains in the circuit ~~at all times~~ permanently.
 - 2) Bank is switched out on faulted phases by local low current/low voltage detection or by receipt of transfer trip information from the line ends. Similarly, the bank can be reinserted by similar logic.
- e) For any switching logic applied, determine the applicable time delays for insertion or bypass relative to the opening and closing of the line circuit breakers.
- f) Opportunities may exist to communicate bank information to the line ends to resolve potential problems with spurious series unbalances and other bank problems. Determine the speed of response in communicating this information to the line ends.
- g) Coordinating line protection and capacitor bank protection during internal and external faults, during autoreclose cycle, line energization, and de-energization.

4.7.1 Capacitor ~~deenergize/energize~~ bank bypass and insert logic

Depending upon utility practice and philosophy, there may be a requirement to automatically bypass the bank upon line de-energization and automatically insert the bank (after a small-time delay) after the last line terminal has closed. The reasons such a philosophy may be applied include the following:

- Mitigating dc current component in line shunt reactors
- Easing line circuit breaker duty requirements
- Mitigating secondary arc during reclose dead time (applicable for single-phase trip and reclose schemes only)