

IEEE Guide for the Protection of Shunt Capacitor Banks

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Abstract: The protection of shunt power capacitor and filter banks are covered. Guidelines for reliable applications of protection methods intended for use in many shunt capacitor applications and designs are included. The protection of pole-mounted capacitor banks on distribution circuits and the application of capacitors connected directly to routing apparatus are not included.

Keywords: capacitor, fuseless, power capacitor, protection, relaying, shunt, unbalance protection

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Introduction

(This introduction is not a part of IEEE Std C37.99-2000, IEEE Guide for the Protection of Shunt Capacitor Banks.)

IEEE Std C37.99-2000 incorporates a significant number of additions and changes since the guide was issued in 1990. Significant changes were made in the clauses dealing with capacitor bank and filter bank protection, unbalance relaying methods, and calculations. The annexes underwent significant changes. Other changes put this guide in line with present-day technologies related to the protection of externally fused, internally fused, fuseless, and unfused capacitor banks.

This guide was revised by the Shunt Capacitor Bank Protection Guide Revision Working Group of the Substation Protection Subcommittee of the Power System Relaying Committee of the IEEE Power Engineering Society. The working group membership at the time of completion of this revision was as follows:

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IEEE Guide for the Protection of Shunt Capacitor Banks

1. Overview

1.1 Scope

This guide applies to the protection of shunt power capacitor and filter banks. Included are guidelines for reliable applications of protection methods intended for use in many shunt capacitor applications and designs. The guide does not include a discussion of pole-mounted capacitor banks on distribution circuits or application of capacitors connected to rotating apparatus.

1.2 Purpose

This guide has been prepared to assist in the application of relays and other devices for the protection of shunt capacitor banks used in substations. It covers methods of protection for many commonly used shunt capacitor bank configurations. Capacitor bank design trade-offs are also discussed because bank design influences the protection. Additionally, this guide covers the protection of filter banks and large extra-high voltage (EHV) shunt capacitor banks.

2. References

This guide shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply:

ANSI C37.06-1997, American National Standard AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.¹

ANSI C37.66-1969 (Reaff 1988), American National Standard for Requirements for Oil-Filled Capacitor Switches for Alternating-Current Systems.

IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors.²

¹ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (<http://www.ansi.org/>). The ANSI documents listed in Clause 2 are also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

IEEE Std 469-1988 (Reaff 1994), IEEE Recommended Practice for Voice-Frequency Electrical-Noise Tests of Distribution Transformers.

IEEE Std 525-1992 (Reaff 1999), IEEE Guide for the Design and Installation of Cable Systems in Substations.

IEEE Std 1036-1992, IEEE Guide for Application of Shunt Power Capacitors.

IEEE Std 1143-1994, IEEE Guide on Shielding Practice for Low Voltage Cables.

IEEE Std C37.012-1979 (Reaff 1988), IEEE Application Guide for Capacitance Current Switching of AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.04-1979 (Reaff 1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.2-1996, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.

IEEE Std C37.48-1997, IEEE Guide for Application, Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.90.1-1989 (Reaff 1994), IEEE Standard for Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems.

IEEE Std C57.16-1996, IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

IEEE Std C62.2-1987 (Reaff 1994), IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems.

IEEE Std C62.22-1997, IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems.

3. Definitions

For the purposes of this guide, the following terms and definitions apply:

3.1 back-to-back capacitor bank switching: Switching a capacitor bank with and in close electrical proximity to one or more other capacitor banks.

3.2 capacitor bank: An assembly at one location of capacitors and all necessary accessories, such as switching equipment, protective equipment, controls, etc., required for a complete operating installation. It may be a collection of components assembled at the operating site or may include one or more piece(s) of factory-assembled equipment.

3.3 capacitor control: The device required to automatically switch shunt power capacitor banks.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

3.4 capacitor element (or element): A device consisting essentially of two electrodes separated by a dielectric.

3.5 capacitor inrush current: The transient charging current that flows in a capacitor when a capacitor bank is initially connected to a voltage source.

3.6 capacitor line fuse (capacitor group fuse): A fuse applied to disconnect a faulted phase of a capacitor bank from a power system.

3.7 capacitor outrush current: The high-frequency, high-magnitude current discharge of one or more capacitors into a short circuit, such as into a failed capacitor unit connected in parallel with the discharging units, or into a breaker closing into a fault.

3.8 capacitor unit (power capacitor): 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.

3.9 discharge device: An internal or external device intentionally connected in shunt with the terminals of a capacitor for the purpose of reducing the residual voltage after the capacitor is disconnected from an energized line.

3.10 filter capacitors: Capacitors utilized with inductors and/or resistors for controlling harmonic problems in the power system, such as reducing voltage distortion due to large rectifier loads or arc furnaces.

3.11 fixed bank: A capacitor bank that does not have a capacitor control and must be manually switched.

3.12 fused capacitor: A capacitor having fuses mounted on its terminals, inside a terminal enclosure, or inside the capacitor case, for the purpose of interrupting a failed capacitor.

3.13 fuseless capacitor bank: A capacitor bank without any fuses, internal or external, which is constructed of parallel strings of series-connected capacitor units between line and neutral (wye connection) or between line terminals (delta or single-phase). *See also:* **unfused capacitor bank.**

3.14 individual capacitor fuse: A fuse applied to disconnect an individual faulted capacitor from its bank.

3.15 internal fuse of a capacitor: A fuse connected inside a capacitor unit, in series with an element or a group of elements.

3.16 internally fused capacitor (unit): A capacitor unit that includes internal fuses.

3.17 kilovar (1000 vars): The practical unit of reactive power, equal to the product of the root-mean-square (rms) voltage in kilovolts (kV), the rms current in amperes (A), and the sine of the angle between them.

3.18 parallel-(element)-connected capacitor (unit): A capacitor unit with the elements connected in parallel groups, with the parallel groups connected in series between the line terminals. A capacitor unit that has only one string of capacitor elements between the capacitor terminals is considered to be parallel-connected.

3.19 series-(element)-connected capacitor (unit): A capacitor unit with the elements connected in series with each other between the line terminals, with more than one such series strings within a capacitor unit (see Figure 1).

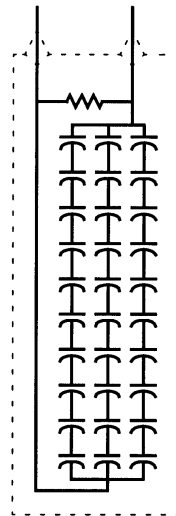


Figure 1—Series-connected capacitor unit with three strings of 10 elements (showing two shorted elements in one string)

3.20 string (string of capacitors) (string of capacitor elements): Capacitors connected in series between the line terminals.

3.21 switched bank: A capacitor bank designed for controlled operation.

3.22 thyristor-controlled reactor (TCR): The effective value of the reactor is changed by using thyristors to control the flow of current by phase-controlling the turn-on signal to the thyristors.

3.23 thyristor-switched capacitor (TSC): A capacitor switched on and off by thyristor control action.

3.24 unfused capacitor bank: Any capacitor bank without fuses, internal or external.

3.25 unfused capacitor (unit): A capacitor without any internal fuses.

4. Basic considerations

Relay protection of shunt capacitor banks requires an understanding of the terminology (see Figure 2), capabilities, and limitations of the individual capacitor units and associated electrical equipment. Four types of shunt capacitor bank connections or designs may affect the relay selection for the protection scheme

- a) Externally fused, with individual fuses for each capacitor unit.
- b) Internally fused, with each element fused inside the capacitor unit.
- c) Fuseless, with capacitor units connected in series strings between line and neutral (or between line terminals).
- d) Unfused, with the capacitor units connected in a variety of series and parallel arrangements.

See Figure 2 for examples of grounded wye-connected banks.

See Clause 2 for the applicable standards for the associated electrical equipment for the individual capacitor units, individual capacitor-unit fuses, bank switching devices, power fuses, voltage- or current-sensing devices, surge arresters, and reactors.

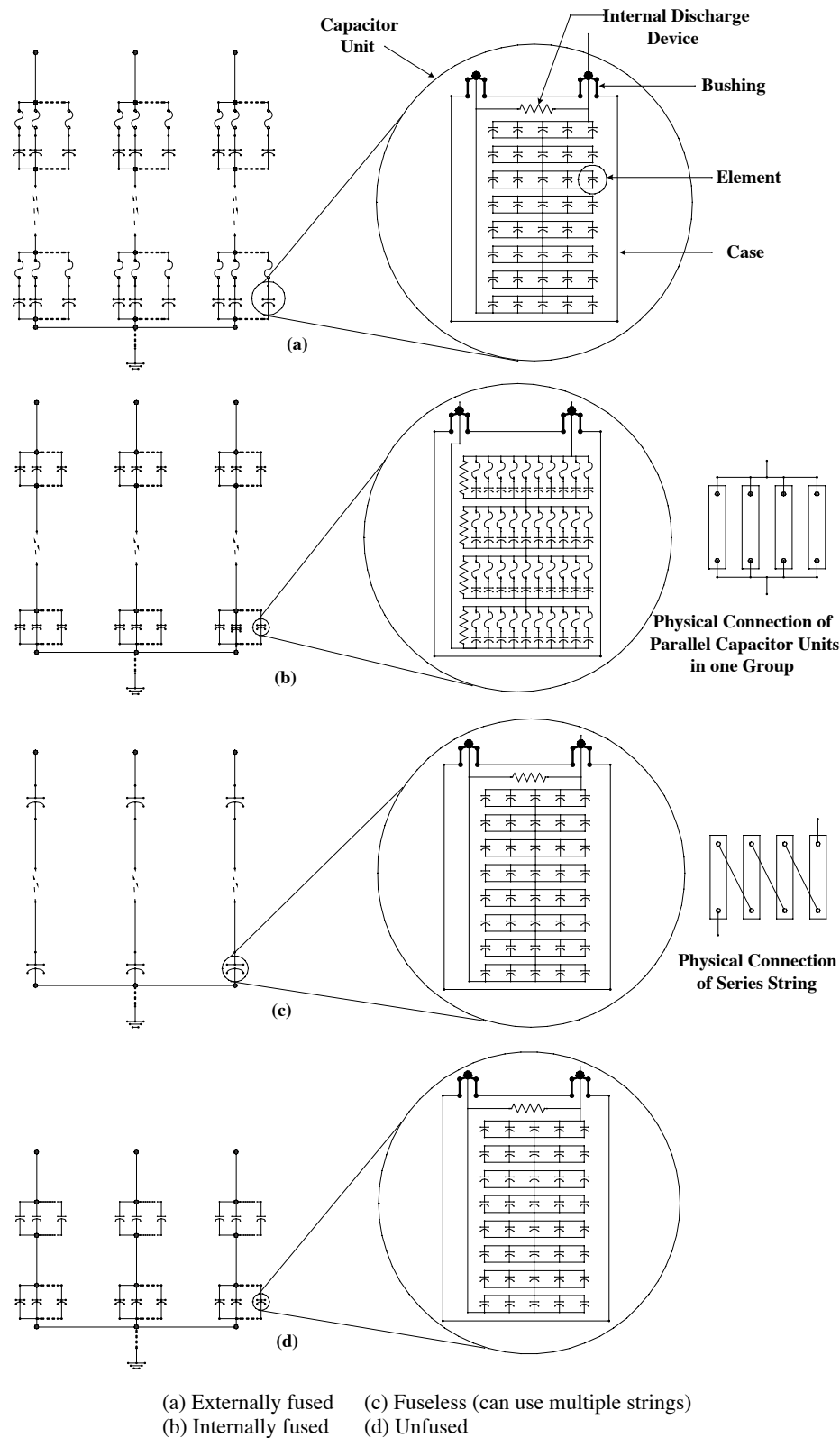


Figure 2—Wye-connected capacitor bank

4.1 Capacitor unit capabilities

IEEE Std 18-1992³ specifies the standard ratings of the capacitors designed for shunt connection to ac transmission and distribution systems. IEEE Std 1036-1992 gives application guidelines for these capacitors. Capacitors are intended to be operated at or below their rated voltage and frequency. Capacitors are capable of continuous operation under contingency system and bank conditions, provided the following limitations are not exceeded:

- a) Capacitor units should be capable of continuous operation including harmonics, but excluding transients, to 110% of rated terminal root-mean-square (rms) voltage and a crest voltage not exceeding $1.2 \times \sqrt{2}$ of rated rms voltage. The capacitor should also be able to carry 135% of nominal current. The voltage capability of any series element of a capacitor unit shall be considered to be its share of the total capacitor unit voltage capability.
- b) Capacitor units should not give less than 100% nor more than 115% (110% for capacitor units manufactured in conformance with IEEE Std 18-1992 after the year 2000) of rated reactive power at rated sinusoidal voltage and frequency, measured at a uniform case and internal temperature of 25 °C.
- c) Capacitor units mounted in multiple rows and tiers should be designed for continuous operation for a 24 h average temperature of 40 °C during the hottest day, or –40 °C during the coldest day expected at the location.
- d) Capacitor units should be suitable for continuous operation at up to 135% of rated reactive power caused by the combined effects of
 - 1) Voltage in excess of the nameplate rating at fundamental frequency, but not over 110% of rated rms voltage.
 - 2) Harmonic voltages superimposed on the fundamental frequency.
 - 3) Reactive power manufacturing tolerance of up to 115% of rated reactive power.
- e) Capacitor units rated above 600 V shall have an internal discharge device to reduce the 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). Capacitor units designed for special applications can exceed these ratings (see IEEE Std 18-1992). See IEEE Std 1036-1992 for capacitor short-time overvoltage capability.

4.2 Arrangement of capacitor units

Depending on the application, any of the four connections (i.e., externally fused, internally fused, fuseless, unfused) may be suitable.

4.2.1 Externally fused shunt capacitor banks

Externally fused substation shunt capacitor banks are configured using one or more series groups of parallel-connected capacitor units per phase. Each capacitor unit is typically protected by an individual fuse, externally mounted between the capacitor unit and the capacitor bank fuse bus. See Figure 2(a). The capacitor unit can be designed for a relatively high voltage because the external fuse is capable of interrupting a high-voltage fault. However, the kilovar rating of the individual capacitor unit may be smaller because a minimum number of parallel units are required to allow the bank to remain in service with one fuse or unit out.

³Information on references can be found in Clause 2.

4.2.2 Internally fused shunt capacitor banks

Figure 2(b) illustrates a typical capacitor bank utilizing internally fused capacitor units. In general, banks employing internally fused capacitor units are configured with fewer capacitor units in parallel and more series groups of units than are used in banks employing externally fused capacitor units. The capacitor units are normally large because a complete unit is not expected to fail.

An internal fuse is connected in series with each capacitor element. Each internally fused capacitor unit is constructed with a large number of elements connected in parallel to form a group and with only a few groups connected in series. This construction is the opposite to that found in externally fused capacitors, which normally employ a large number of series groups made up of parallel connected elements, with correspondingly fewer elements connected in parallel per series group. With internally fused capacitors, when a capacitor element fails, the current through its individual fusible link will be considerably higher than the normal current. This higher current will blow the fusible link, thereby isolating the failed element.

4.2.3 Fuseless shunt capacitor banks

Fuseless shunt capacitor banks are normally used for applications at or above 34.5 kV. The capacitor units are normally designed with two bushings with the elements insulated from the case. The capacitor units are connected in series strings between phase and neutral (or between line terminals for delta-connected or single-phase installations). The protection is based on the capacitor element's failing in a shorted mode. The discharge energy is small because no capacitor units are connected directly in parallel. Another advantage is that the unbalance protection does not have to be delayed to coordinate with the fuses. See Figure 2(c).

4.2.4 Unfused shunt capacitor banks

The unfused shunt capacitor approach uses a series/parallel connection of the capacitor units. The voltage across the remaining elements will increase more than in the fuseless design. The unfused approach would normally be used on banks below 34.5 kV (where series strings are not practical) or on higher voltage banks with modest parallel energy. This design does not require as many capacitor units in parallel as an externally fused bank. See Figure 2(d).

4.3 Capacitor bank design

4.3.1 Externally fused

An externally fused shunt capacitor bank of a given size and voltage rating may be made up of a number of series and parallel groups. Use of capacitors with the highest possible voltage rating will result in a capacitor bank with the fewest number of series groups. This arrangement generally provides the simplest rack structure and the greatest sensitivity for unbalance detection schemes. The available unbalance signal level decreases significantly 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 number of capacitor units in parallel per series group is governed by both a minimum and maximum limitation. The minimum number of capacitor units per group is determined by the overvoltage considerations upon isolation of one capacitor unit in the group and also having sufficient overcurrent through a fuse on a faulted capacitor unit to blow the fuse in a reasonably short time (so that the unbalance protection does not require a long time delay). The general rule is that isolation of one capacitor unit in a group should not cause voltage unbalance sufficient to place more than 110% of rated voltage on the remaining capacitors in the group. The value of 110% is the maximum continuous overvoltage capability of capacitor units as per IEEE Std 18-1992.

The minimum recommended number of capacitor units in parallel per series group may limit the maximum capacitor-unit kilovar rating that can be used for relatively small banks. Capacitor units with the highest possible voltage rating and minimum number of series groups are used in order to obtain an adequate number in each group.

The maximum number of capacitor units that may be placed in parallel per series group is governed by a different consideration. When a capacitor unit fails, other capacitors in the same parallel group will contain some amount of charge. This charge will drain off as a high-frequency transient current that flows through the failed capacitor unit and its fuse. The fuse holder and the failed capacitor unit should withstand this discharge transient.

For a large number of parallel externally fused capacitors, to minimize the probability of failure of the expulsion fuse holder or rupture of the capacitor case, or both, NEMA CP1-1988 [B11]⁴ recommends that the total energy stored in a parallel connected group of capacitors should not exceed 15 000 J for all-film dielectric capacitor units (10 000 J for older all-paper or paper-film dielectric capacitor units) at maximum peak voltage (rated voltage $\times 1.1 \times \sqrt{2}$). For 60 Hz applications, NEMA CP1-1988 recommends a total parallel kilovar limit of 4650 kvar for all film dielectric capacitor units (3100 kvar for older capacitor units). All film dielectric capacitor banks have been applied up to 9600 kvar in parallel with expulsion fuses (Mendis et al. [B9]). Consult the capacitor and fuse manufacturer before exceeding the 4650 kvar limit to ensure that the total available discharge energy (including energy from capacitors in a parallel wye and/or in parallel banks) does not exceed the discharge energy capability of the fuse or the faulted capacitor.

If a capacitor bank having the minimum number of series groups has more than 4650 kvar per series group, capacitors of a lower voltage rating requiring more series groups and fewer units in parallel per group may be a suitable solution. However, this arrangement will reduce the sensitivity of the unbalance detection scheme. The bank may be removed from service (for a reduced number of isolated capacitor units) because the voltage across the remaining units exceeds 110% of their rated voltage. Splitting the bank into two sections, as a double wye, may be a preferred arrangement and may permit a better unbalance detection scheme. Failure of fewer capacitor units can result in the removal of the bank. Another possibility is the use of current-limiting fuses in a single wye configuration.

4.3.2 Internally fused

An internally fused shunt capacitor bank of a given size and voltage rating may be made up of a number of series and parallel groups.

Use of capacitors with the highest possible kilovar rating will result in a capacitor bank with the fewest number of capacitor units. This arrangement generally provides the simplest rack structure and the largest number of element failures before unbalance tripping is required.

It is usually desirable to have at least two units in parallel in each series group. In the event of a large number of internal fuse operations in one capacitor unit, the other capacitor helps keep the terminal voltage of the affected capacitor down.

The maximum number of capacitor units that may be placed in parallel per series group is governed by the parallel energy capability of the internal fuses. Placing too many capacitor units in parallel can jeopardize the operation of the fuses. The manufacturer of the capacitor units should recommend the maximum number of capacitor units to be connected directly in parallel.

If a proposed capacitor bank having the minimum number of series groups has too many capacitor units in parallel, it may be possible to reduce the parallel energy by changing the number of series groups or by rearranging the bank into multiple wyes.

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

4.3.3 Fuseless banks

Fuseless banks require a high system voltage (about 34.5 kV minimum). Capacitor units are connected in series strings. The capacitor units usually have two bushings and may have additional insulation between the capacitor elements and the case. Each string usually has more than 10 elements in series to ensure that the remaining elements do not exceed 110% rating if an element in the string shorts. If a large fuseless bank is required, several strings can be connected in parallel.

4.3.4 Unfused banks

An unfused bank would have a series/parallel arrangement. Relay settings normally require the bank to trip when the voltage on remaining capacitor units exceeds 110% of rated voltage or the overvoltage on remaining elements in a faulted capacitor unit is high enough that cascading failure on system transient overvoltage is likely. On smaller banks, tripping may be based on the failure of a single element. (For small banks, the probability of element failure may be small, given the small total number of elements.)

4.4 Overvoltage on remaining capacitor units

The overvoltages that occur when individual capacitor elements fail or internal or external fuses operate determine whether the bank should be removed from service. Usually the larger the kilovar rating of an individual capacitor unit, the simpler the bank design, but the unit size will affect the resulting overvoltages following fuse operation or element shorting.

4.4.1 Externally fused bank

For an externally fused bank of a given size, use of a larger individual capacitor-unit kilovar rating decreases the number of parallel capacitor units per group and increases the overvoltage change due to isolation of a single capacitor. Failure of additional capacitors is likely to occur in the same parallel group as the first failure because these remaining capacitor units have the highest voltage stress. However, if two capacitors fail in different parallel groups, the overvoltage percentage is less than that of the two capacitors failing in the same parallel group.

4.4.2 Internally fused bank

An internally fused bank can connect the capacitor elements inside the capacitor unit in various series and parallel configurations to minimize the overvoltage stress on the remaining internal elements and unaffected capacitor units when fuses operate.

4.4.3 Fuseless bank

Fuseless bank design depends on the capacitor elements being connected in series, and the expected failure mode of the capacitor element will be a short circuit. The higher the voltage for the bank, the more capacitor elements in series. If an element shorts, the remaining capacitor elements will absorb the additional voltage. The additional voltage on each element will be approximately equal to $E/(E - 1)$ where E is the original number of capacitor elements in the string.⁵ The continuous and overvoltage capability of the elements is equal to the capability of the capacitor unit divided by the number of elements in series within the capacitor unit.

⁵Many of the variables in this guide have not been specially formatted (i.e., using italics or superscripting and subscripting). This has been done intentionally to match the appearance of the variables in the spreadsheets presented herein.

4.4.4 Unfused bank

The unfused capacitor bank has no fuses. Unbalance protection should be applied so that following failures, the resulting voltage on the remaining healthy capacitor units does not exceed 110% of their rating or the recommended level specified by the manufacturer.

5. Bank connections

Five capacitor bank connections are common. The optimum connection depends on the best utilization of the available voltage ratings of capacitor units, fusing, and protective relaying. These connections can be used for externally fused capacitor bank design, internally fused capacitor bank design, fuseless capacitor bank design (if enough elements are connected in series for a protection scheme to be applied), and unfused capacitor bank design. Virtually all substation banks are connected wye. Distribution capacitor banks, however, may be connected wye or delta. Some banks use an H configuration on each of the phases with a current transformer in the connecting branch to detect the unbalance.

The various types of connections are illustrated in Figure 3.

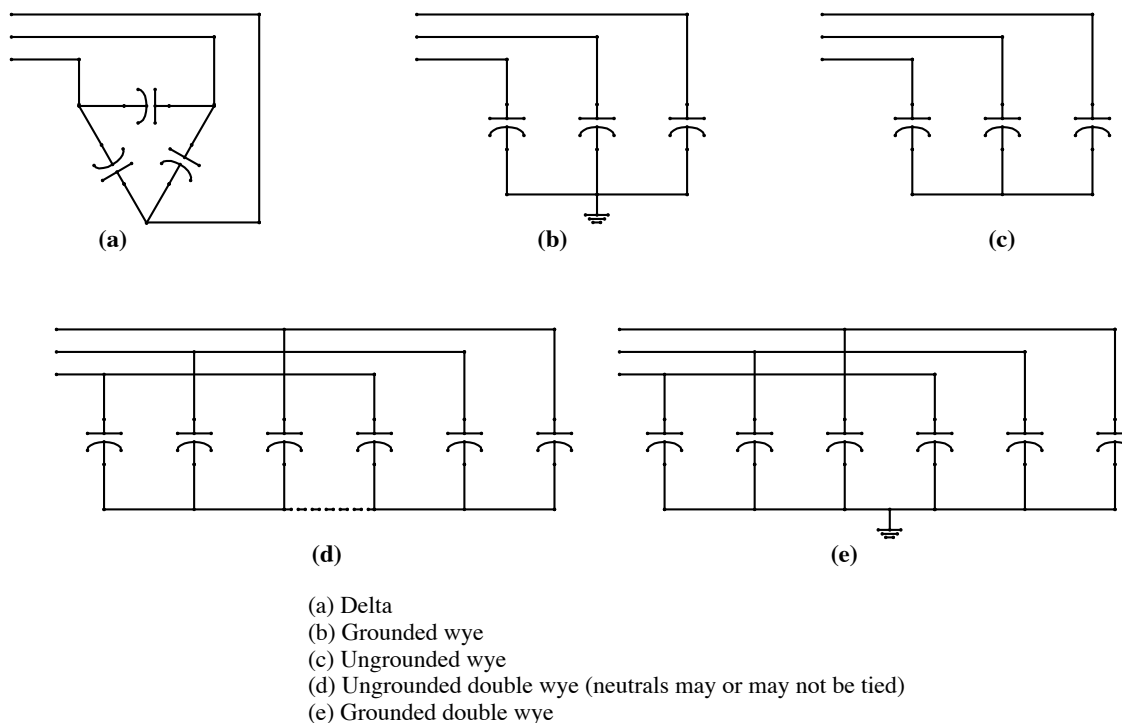


Figure 3—Basic capacitor bank connections

5.1 Grounded wye-connected banks

Grounded wye capacitor banks, composed of series- and parallel-connected capacitor units per phase, may require overvoltage/unbalance protection. Figure 2 shows typical bank arrangements.

Grounded capacitor banks provide a low-impedance path to ground for lightning surge currents and give some protection from surge voltages. Some banks may be operated without surge arresters, taking advantage of the capability of the capacitors to absorb the surge.

Grounded capacitor banks also provide a low-impedance path to ground for triplen harmonic currents. These harmonic currents may cause communication facility interference, if such circuits parallel power lines. Additionally, an open phase produces zero sequence currents that may cause ground relay operations. Harmonic resonance may also be a problem.

When the neutral is grounded, recovery voltages encountered during switching are reduced; however, careful consideration should be given to the effect of inrush current on protective relay performance (see Clause 11) and the method of grounding (see 6.2).

5.1.1 One unit phase to ground

There is no overvoltage across the remaining capacitor units if a failed, externally fused capacitor unit is isolated with a fuse; therefore, unbalance relay protection is not required. The individual external capacitor fuses shall be capable of interrupting the system available fault current.

Internally fused and unfused capacitor banks should have unbalance protection to avoid excessive element voltages and to trip the bank for severe unbalance conditions.

5.1.2 Multiple units in series phase to ground—single wye

Grounded wye externally fused capacitor banks above 34.5 kV are commonly composed of two or more series groups of parallel connected capacitor units per phase. The presence of multiple series groups of units limits the maximum fault current so that individual current-limiting fuses are usually not required unless the parallel kilovar exceeds 4650 kvar or the level specified by the manufacturer.

Internally fused capacitor units should be arranged in the bank design to ensure that energy in the parallel group does not exceed the interrupting capability of the internal fuses. Relatively small banks can be designed with internally fused capacitor units and still use large capacitor units for a simple design.

The fuseless design is not usually applied for system voltages less than about 34.5 kV. The reason is that there shall be more than 10 elements in series so that the bank does not have to be removed from service for the failure of one element because the voltage across the remaining elements would increase by a factor of about $E/(E - 1)$ where E is the number of elements in the string.

5.1.3 Multiple units in series phase to ground—double wye

When a capacitor bank becomes too large, making the parallel energy of a series group too great for the capacitor units or fuses, the bank may be split into two wye sections. The characteristics of the grounded double wye are similar to a grounded single wye bank. The two neutrals should be directly connected with a single connection to ground.

The double wye design allows a secure and faster protection with a simple uncompensated relay because any system zero sequence unbalance affects both wyes equally, but a failed capacitor unit will be detected in the neutral unbalance. Time coordination may be required to allow a fuse to blow in or on a failed capacitor unit. If it is a fuseless design, the time delay can be set short because no fuse coordination is required. If the current through the string exceeds the continuous current capability of the capacitor unit, more strings shall be added in parallel (for example, wye wye-wye wye).

5.2 Ungrounded wye-connected banks

Ungrounded wye banks do not permit zero sequence currents, third harmonic currents, or large capacitor discharge currents during system ground faults. (Phase-to-phase faults may still occur and will result in large discharge currents.) The neutral, however, should be insulated for full line voltage because it is momentarily

at phase potential when the bank is switched or when one capacitor unit fails in a bank configured with a single group of units.

5.2.1 One unit phase to neutral

For systems with line-to-neutral voltages corresponding to available capacitor ratings, wye-connected capacitor banks with a single series group per phase may be used. The capacitor bank neutral may be ungrounded in order to avoid the need for power fuses to interrupt the system short-circuit fault current or to minimize the flow of triplen harmonics, which can cause telephone interference. This design requires that single-bushing capacitor units be mounted on an insulated rack. If two-bushing capacitor units are used with a grounded rack, a fault to the case will be a system line-to-ground fault. High system fault currents may lead to case rupture. For externally fused capacitor banks, the fuses should be selected to interrupt the available phase-to-ground short-circuit current. If lower rated fuses are used, a fault to the capacitor case may not be cleared by the capacitor-unit fuse and will require that the fault be cleared by the capacitor bank overcurrent protective devices. Ungrounded wye capacitor banks usually do not require current-limiting capacitor-unit fuses because current through a faulted capacitor unit is limited to three times normal phase current. However, caution needs to be exercised when re-fusing a bank of this type because faulted capacitors in different phases could result in a phase-to-phase system fault.

5.2.2 Multiple units in series phase to neutral—single wye

Wye banks with multiple series groups may also be ungrounded. Such a bank does not provide a path to ground for a surge voltage and provides no path to ground for third harmonic currents. The entire bank, including the neutral, should be insulated for full line voltage.

Capacitor units with external fuses, internal fuses, or no fuses (fuseless or unfused design) can be used to make up the bank. For unbalance protection schemes that are sensitive to system voltage unbalance, either the unbalance protection time delay shall be set long enough for the line protections to clear the system ground faults or the capacitor bank may be allowed to trip off for a system ground fault.

5.2.3 Multiple units in series phase to neutral—double wye

When a capacitor bank becomes too large for the 4650 kvar per group maximum for expulsion fuses and is large enough to meet the minimum units per group requirement as outlined in 4.2, the bank may be split into two wye sections. When the two neutrals are ungrounded, the bank has some of the characteristics of the ungrounded single-wye bank. These two neutrals may be tied together through a current transformer or a voltage transformer. As for any ungrounded wye bank, the neutral instrument transformers should be insulated from ground, as should the phase terminals, for full line-to-ground voltage.

5.3 Delta-connected banks

Delta-connected banks are generally used only at distribution voltages and are configured with a single series group of capacitors rated at line-to-line voltage. Delta-connected banks require a two-bushing capacitor or single-bushing units with insulated racks. Delta-connected banks are frequently used at 2400 V because capacitor units for wye connection at 2400 V are not readily available.

With only one series group of units, no overvoltage occurs across the remaining capacitor units from the isolation of a faulted capacitor unit. Therefore, unbalance detection is not required for protection, but may be used to detect the outage of units within the bank. No zero-sequence or third harmonic currents can flow into a delta-connected capacitor bank.

Where one series group per leg is used, the individual capacitor fuses shall be capable of interrupting the system short-circuit phase-to-phase fault current. This design may necessitate current-limiting fuses.

If internally fused capacitor units are used, unbalance detection is required to detect a capacitor with failed elements. There is no visible indication of a blown fuse. Two or more series groups are normally required in each capacitor unit to enable the internal fuses to interrupt the fault current.

Static var compensators usually use the delta connection for the thyristor-switched capacitors (TSCs) to simplify the controls and optimize the use of the thyristor valve.

5.4 H configuration

Some larger banks use an H configuration in each phase with a current transformer connected between the two legs to compare the current down each leg. As long as all the capacitors are normal, no current will flow through the current transformer. If a capacitor fuse operates, some current will flow through the current transformer. This bridge connection can be very sensitive. This arrangement is used on large banks with many capacitor units in parallel.

6. Other considerations

The performance of the protection method can be influenced by the design of the capacitor bank. Therefore, protection begins with bank design (see 4.3). In general, shunt capacitor bank design requirements necessitate an increase in minimum bank size with system voltage. The higher the system voltage, the larger the bank investment and risk of costly damage. Although capacitors having large kilovar ratings may reduce the overall cost of the bank, they may also reduce the choice of different capacitor combinations.

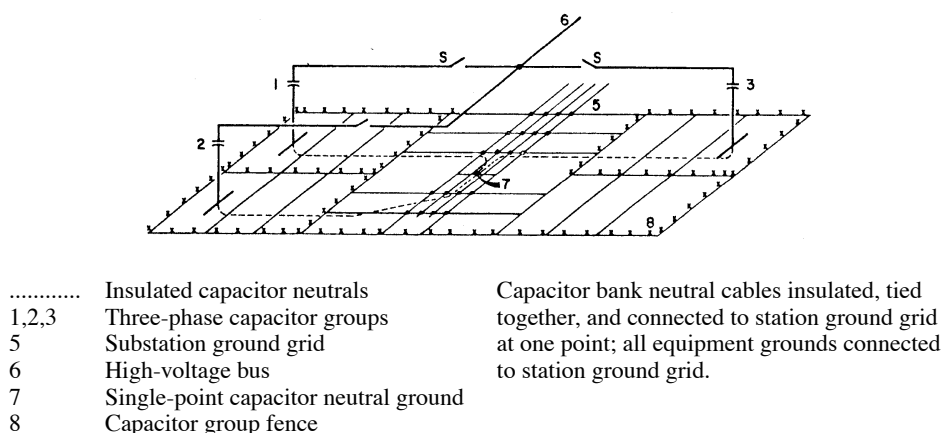
6.1 Single-point and peninsula grounding

Where two or more grounded wye banks are at the same location, the neutrals should be directly connected, with a single connection to ground (single-point grounding). The design of the substation ground grid and the connections of the respective bank neutrals to the substation grid is of prime importance. Improper grounding can result in neutral current transformer, voltage transformer, or control cable failures. Two methods of neutral grounding have been successfully used: single-point grounding and peninsula grounding. See Figure 4.

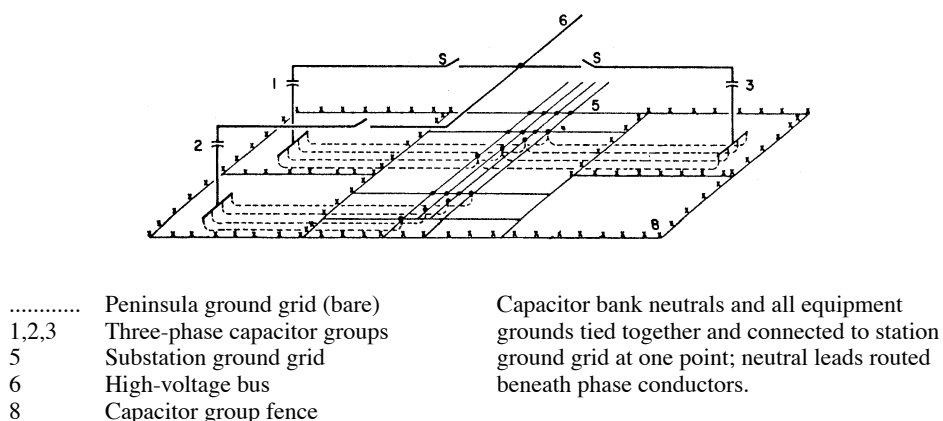
With single-point grounding, the neutrals of all capacitor banks of a given voltage are connected together with insulated cable, or an isolated bus, and tied to the substation ground grid at only one point. This arrangement prevents high-frequency currents that flow between banks during back-to-back switching from flowing in the ground grid. In the event of a nearby ground fault, however, this arrangement does not eliminate high-frequency currents that flow back into the power system via the substation ground grid.

With peninsula grounding, one or more ground grid conductor(s) are carried underneath the capacitor rack of each phase of each group and tied to the main station ground grid at one point at the edge of the capacitor area. All capacitor bank neutral connections are made to this isolated peninsula ground grid conductor(s) only (Rogers and Gillies [B12]). Although this arrangement allows the capacitor bank neutral potential (and associated current transformers and voltage transformers) to rise during capacitor bank switching, it does help reduce these transients in the rest of the substation. See Figure 4.

If single-point grounding is used, the voltage will be substantial (tens of kilovolts) between the ends of the neutral bus and the single-point ground during switching. As a result, the primary-to-secondary insulation of neutral current transformers, or voltage transformers, will be subjected to this voltage, increasing the possibility of failure. A voltage transformer with two bushings should be used with the primary connected to the capacitor bank neutral and to the station ground grid.



(a) Single-point grounding



(b) Peninsula grounding

Figure 4—Single-point and peninsula grounding

This does not occur with peninsula grounding because all equipment at the neutral tends to rise to the same potential. Peninsula grounding coordinated with control cable shielding and grounding will keep common mode voltages, appearing on control cables in the control house, to safe levels.

Single-point grounding and peninsula grounding may be used together. It is desirable for all capacitor banks of the same system voltage to use the same grounding scheme in the same substation.

When energizing a capacitor bank, the magnitude of voltage disturbances on the system is greatly reduced by the presence of one or more additional banks of comparable size connected to the same bus. During a closing operation or a restrike, however, the transient inrush current through the switching device between the energized banks and the one being switched can be very large. These currents are oscillatory at very high frequencies. The peak current may be on the order of 50–100 times the normal peak of the capacitor bank current. Such a high instantaneous current can produce high forces in the interrupter of the switching device, and such forces may be damaging to the contacts or linkage.

Because the severity of parallel bank switching is caused by the very sudden high current, which initially is limited only by the very low resistance and inductance of the circuit between the banks, it can be reduced by the addition of inductance to the circuit. An inductance with a 60 Hz reactance as low as 0.5–1% of the 60 Hz capacitive reactance of the banks placed in series with them will greatly reduce both the rate of rise

and the peak value of the inrush current. This inductance greatly reduces the severity of the switching device duty. Additional inductance may be obtained by increasing the length of the bus between the capacitor banks or adding current-limiting reactors. The reactors may be air core or consist of magnetic cores surrounding the leads or bus.

Preinsertion resistors or inductors on the capacitor switching device, or synchronous (zero voltage) closing, can also effectively limit the inrush current. The use of insertion resistors or reactors or zero-crossing closing controls minimizes the switching transient on closing, but does not help reduce the outrush current for close in faults (McCauley et al. [B8]). Fixed reactors may be required to reduce the transient currents in order to

- Minimize the possibility of induced voltages affecting the relaying.
- Avoid damaging other equipment (Rogers and Gillies [B12]; Alexander [B2]; McCauley et al. [B8]).

6.2 Neutral grounding

The application of large shunt capacitor banks with switched parallel banks in high-voltage transmission systems involves a number of considerations, one of which is grounding. It is generally recommended that the neutral of capacitor banks be grounded only to systems that are effectively grounded. In the event of a phase-to-ground fault, a grounded capacitor bank neutral in an otherwise ungrounded system may lead to high transient overvoltages in the system and capacitor bank as a result of restriking of the arcing fault to ground.

One of the main advantages associated with neutral grounding concerns the severity of the recovery voltage across the first pole of the switch to clear, interrupting the charging current of the capacitor bank. The recovery voltage across the first pole to open consists of trapped charges on the capacitors and the variation in the 60 Hz voltage of the system. Due to system parameters and capacitor bank size, the recovery voltage can be approximately two times normal peak voltage when the bank is grounded. On an ungrounded bank, the magnitude of the first peak of the recovery voltage can be as high as three times the peak system line-to-ground voltage when the bank is switched.

Because recovery voltage is a critical factor in determining the capability of a switching device to switch capacitive reactive power, it may be desirable (in terms of switch performance) to ground the neutral of shunt capacitor banks. IEEE Std C37.04-1979 and ANSI C37.06-1997 recommend that both the shunt capacitor bank and the system be grounded at voltage levels of 121 kV and above. Many capacitor banks of higher voltage are installed ungrounded, but the circuit breaker manufacturer should be consulted for the application of a breaker if these conditions are not met.

While many shunt capacitor banks are directly connected to a high-voltage substation bus, switched capacitor banks may be applied to tertiary of power transformers that are connected to the line or possibly to the bus. Grounding the neutral of the wye-connected capacitor bank should be done only on an effectively grounded system. For instance, the delta tertiary of the auto transformer represents an isolated source; grounding the capacitor bank neutral makes this side of the transformer capacitively grounded. Overvoltages may be experienced during line-to-ground faults for certain ratios of X_0/X_1 , depending on system, transformer, and capacitor bank parameters. If the neutral is to be grounded on a system that is not effectively grounded, the application should be thoroughly analyzed for proper application of surge arresters, bank configuration, bank switching devices, etc.

7. Introduction to bank and system protection

The protection of shunt capacitor banks involves both bank and system protection schemes.

Bank protection schemes are provided for faults within the capacitor bank itself. Bank protection may include items such as a means to disconnect a faulted capacitor unit or capacitor element(s), a means to initiate a shutdown of the bank in case of faults that may lead to a catastrophic failure, and alarms to indicate unbalance within the bank.

System protection schemes are provided to protect the capacitor bank from stresses that may be caused by the system and to protect the substation and system from stresses that may be caused by the operation of the capacitor bank. System protection may include items such as a means to limit overvoltage and excessive transient overcurrents, and to disconnect the bank in the event of a major fault within the capacitor installation. System protection may also include alarms and/or a method to disconnect the entire shunt capacitor bank in order to prevent further damage to the capacitors due to abnormal system conditions.

Table 1 lists various bank and system protection schemes typically applied to shunt capacitor banks. Each of the conditions listed should be considered when providing protection for a shunt capacitor bank.

Table 1—Bank and system protection

Bank protection		
Condition	Type of protection	Remarks
Faulted capacitor element.	External or internal fuse for fused banks; weld, which occurs at the failure, for banks without fuses.	Fuses should be fast to coordinate with fast unbalance relay settings, but should not operate during switching or external faults.
Fault from capacitor elements to case, bushing failure, faulty connection in capacitor unit.	Fuse for externally fused capacitor; unbalance protection for internally fused banks or banks without fuses.	For externally fused capacitor banks, fuses should be fast to coordinate with fast unbalance relay settings, but should not operate during switching or external faults. For internally fused banks or banks without fuses, the unbalance protection should be fast to avoid case rupture, but should not operate during switching or external faults.
Fault in capacitor bank other than in unit (arcing fault in bank).	Unbalance protection. Relay should have a band-pass filter for the fundamental current or voltage for security.	Unbalance protection should be fast to minimize damage to other units during a major fault. See 7.1.4.
Continuous overvoltage on capacitor elements or units due to faulted elements or fuse operations within the bank.	Unbalance protection. Relay should have a band-pass filter for the fundamental current or voltage for security.	Bank should be tripped for voltages > 110% of rated voltage or as recommended by manufacturer on healthy capacitor units. An alarm may be added for 5% unbalance or one unit out. (In some critical applications an alarm with delayed tripping above 110% of rated voltage is used; see 7.1.4.)
Rack-to-rack flashover in two series group phase-over-phase single wye banks.	Phase overcurrent or negative sequence relay; unbalance current for wye-wye capacitor banks.	Fast operation is required to minimize damage. See 7.1.4 and 7.1.5.
System protection		
Condition	Type of protection	Remarks
System surge overvoltage.	Surge arresters.	Selection of surge arrester may require consideration of bank energy, particularly for larger capacitor banks.
Power frequency system overvoltage.	Phase voltage relays.	For a distorted voltage waveform, the capacitor dielectric is sensitive to the peak voltage.

Table 1—Bank and system protection (continued)

System protection (continued)		
Condition	Type of protection	Remarks
Harmonic current overloading.	Relay sensitive to harmonic current.	Where excessive harmonic currents are anticipated, harmonic relaying may be required.
Bus fault in capacitor installation or major capacitor bank failure.	a) Circuit breaker or circuit switcher with conventional relays, or b) Power fuses.	Relays or power fuses should be as fast as possible without nuisance operations due to outrush currents into nearby faults.
Fault in or near substation, but outside capacitor installation.	Inrush and outrush limiting reactors.	Reactors may be required to protect circuit breakers, current transformer circuits, and other components against excessive currents or induced voltages.
Excessive inrush current.	a) Insertion resistor or reactor in switch, breaker, or circuit switcher, or b) Inrush and outrush limiting reactors between capacitor banks, or c) Synchronous (zero voltage) closing of the switch or circuit breaker.	Energizing a capacitor bank in close proximity to an energized capacitor bank may result in excessive inrush currents, damaging circuit breakers or switches, causing undesired fuse operations, causing excessive voltages in current transformers and relays, causing arcing at gate latches, etc.
System outage.	Undervoltage relays.	Capacitor banks (which may be) energized through a transformer without load on the transformer may need to be switched off before re-energizing the system.
Transmission line tripping (for capacitor banks connected to a transmission line segment).	a) Transfer tripping of the capacitor bank switch, or b) Undervoltage relays.	Capacitor banks directly connected to a transmission line with no connected load may need to be disconnected from the line before reclosing the line.
Breaker failure.	Conventional breaker failure relays.	Local or remote breakers should have capacitor switching capability if they trip the bank without parallel load due to breaker failure considerations.

7.1 Bank protection

In externally fused capacitor banks, several capacitor element breakdowns may occur before the fuse removes the entire unit. The external fuse will operate when a capacitor unit becomes (essentially) short circuited, isolating the faulted unit. Unbalance protection removes the bank from service when the resulting overvoltage becomes excessive on the remaining healthy capacitor units.

Internally fused capacitors have individual capacitor elements within a capacitor unit that are disconnected when an element breakdown occurs. The risk of successive faults is minimized because the fuse will isolate the faulty element within a few cycles. Unbalance protection removes the bank from service when the resulting unbalanced voltage becomes excessive on the remaining healthy capacitor elements or units.

For fuseless or unfused capacitor banks, a failed element is short-circuited by the weld that naturally occurs at the point of failure. Unbalance protection removes the bank from service when the resulting voltage becomes excessive on the remaining healthy capacitor elements or units.

7.1.1 General fuse requirements (for banks with fuses)

The fuse selection should provide sufficient safety margins to ensure the availability of the capacitor banks. The fuses shall be selected to quickly isolate dielectric failures and interrupt the available energy developed at the fault location.

Capacitor fusing requires the careful protection considerations given in 7.1.2 and 7.1.3 for externally and internally fused capacitor banks.

7.1.2 External fuse selection and operation

IEEE Std C37.48-1997 covers in detail the application guidelines for high-voltage external capacitor fuses.

The energy stored in the healthy capacitors of one series group of parallel-connected capacitors will discharge into the failed capacitor unit of that group and its fuse. The fuse shall be able to interrupt the energy supplied by the parallel group of capacitor units when they are charged to their peak voltage.

If the capacitor bank design has an available discharge energy higher than the capacitor units or expulsion fuses can withstand, current-limiting fuses with adequate energy rating should be considered.

When ungrounded wye capacitor banks are supplied in an enclosure, current-limiting fuses shall be used to eliminate the arc products that occur with the use of an expulsion fuse. These arc products in the confined enclosure could cause further evolution of the fault. Current-limiting fuses may also be required on enclosed single-group ungrounded wye banks that are designed with two bushing units. In this design, the first bushing is used for the phase connection, the second bushing used for the neutral connection, and the case connected to ground. This arrangement requires the capacitor fuses to interrupt system fault current in the event of a failure of the unit insulation near the phase bushing.

NEMA CP1-1988 [B11] suggests a parallel energy limit of 15 kJ (4650 kvar) for all film dielectric capacitors. Expulsion fuses are frequently applied with higher parallel energy (to 30 kJ) (Mendis et al. [B9]). This higher energy application is acceptable if the total available discharge energy of the bank does not exceed the discharge energy rating of the fuse or the capability of the faulted capacitor unit.

To determine proper fuse selection, the capacitor unit case rupture curve shall be available from the manufacturer. Case rupture curves are different for different capacitor unit constructions and designs. The total clearing curve of the fuse or fuse link is then compared to the case rupture curve; adequate protection is assured if the total clearing curve of the fuse is to the left of and below the rupture curve of the capacitor unit.

Other important considerations for external fuse selection and operation include the following:

- Fuses should be designed and rated for the externally fused capacitor bank application.
- Fuses should provide for the fast isolation of a faulted capacitor unit.
- Voltage interruption capability of the fuse shall be coordinated with the voltage withstand capability of the capacitor unit.
- Fuses shall handle the transient inrush and outrush current.
- Fuses shall be designed for the current loadability requirements, including harmonics and adequate allowance factors.
- Fuses shall be designed for the inductive and capacitive current interruption capability.
- Fuse characteristics shall coordinate between the different shunt bank protection schemes and the characteristics of the fuses (that is, expulsion, current-limiting, or a combination of both).

7.1.3 Internal fuse operation

The optimum performance of an internally fused capacitor bank relies on the design and selection of fuses. Adequate fuse operation shall be assured in case of capacitor element breakdown. Element fuses in internally fused capacitor banks have current-limiting properties that are mainly dependent on the available fault current, the discharge energy (≈ 1 kJ) from the elements connected in parallel with the faulty element, and the voltage across the faulted element at the instant of failure.

The fuses shall properly isolate the faulted element after fuse operation. Fuses shall be designed with sufficient overvoltage interruption capability to ensure reliable and safe operation under extreme transient element overvoltage conditions, considering both the system transient overvoltage and the unbalance within the capacitor unit resulting from previously blown fuses. Fuse selection shall consider the following:

- Overvoltage interruption capability.
- Transient conditions due to external faults where the fuse shall not operate.
- Inrush and outrush currents over the life of the capacitor units.

The fastest appropriate element fuse that meets the above requirements shall be selected. The remaining healthy fuses in a faulted capacitor unit shall be capable of safely interrupting other internal element failures.

7.1.4 Capacitor unbalance protection

Unbalance protection normally provides the primary protection for arcing faults within a capacitor bank and other abnormalities that may damage capacitor units and or fuses. Arcing faults may cause substantial damage in a small fraction of a second. The unbalance protection should have minimum intentional delay in order to minimize the amount of damage to the bank in the event of external arcing.

Capacitor unbalance protection is provided in many different ways, depending on the capacitor bank arrangement. The variety of unbalance protection schemes that are used for internally fused, externally fused, fuseless, or unfused shunt capacitor banks is illustrated in the figures of Clause 8 along with examples of the required calculations.

Unbalance protection normally senses changes associated with capacitor element or unit failure and/or fuse operation. It is not generally sensitive enough to detect a defective connection. Defective connections may deteriorate until a fault occurs within the capacitor bank, causing the unbalance protection to operate. A defective connection within a capacitor unit (usually a rare occurrence) may result in a pressure buildup and capacitor unit rupture before the operation of the unbalance protection. The unbalance protection should operate quickly for the external arcing following case rupture.

7.1.5 Protection for rack faults (arc-over within the capacitor rack)

With a shunt capacitor bank constructed so that the individual phases are well separated on separate structures, an arc-over within the capacitor bank will begin as an arc-over of a single series group. Such a fault produces very little phase overcurrent. If an unbalance relay protection scheme fails to operate, more and more series groups of the same phase can become involved until the bank overcurrent relays trip the bank or fuses clear. This fault is accompanied by heavy damage to the bank, including many blown fuses and ruptured capacitor units. Instantaneous overcurrent relays are usually not effective for rack faults because of their required high setting.

The most effective protection for an arc-over within the capacitor bank is provided by a fast unbalance relay. A short time delay for the unbalance relays minimizes the damage caused by rack faults. Intentional delays as short as 0.05 s have been used. This short unbalance time delay, however, should not be less than the maximum clearing time of the capacitor-unit or element fuse.

An unusually long unbalance time delay may be required to coordinate with the line relays, unless the unbalance relay scheme is a type that does not respond to (or uses compensation for) system voltage unbalance (zero sequence voltage).

The setting of the unbalance trip relay shall be sensitive enough to protect the capacitor units or elements from continuous overvoltages that result from individual unit or element failure and resultant fuse operation. When set on this basis, the resultant sensitivity is quite adequate to detect the initial rack fault, assuming the initial fault is across one series section of one phase.

Although the unbalance trip relay is the most effective protection for arc detection of a series section, the neutral voltage type of unbalance relay [for instance, see Figure 12(b)] should not be relied upon for rack fault protection on capacitor banks where all three phases are not well separated. For example, consider an ungrounded single wye capacitor bank with two series groups per phase, where all three phases are installed upon a single steel structure. The individual phases are stacked over each other so that the initial fault may occur as a midrack phase-to-phase fault, as shown in Figure 5. This fault does not cause an unbalance of the neutral voltage (or neutral current, if grounded); therefore, a neutral unbalance relay does not respond. The initial fault may spread until it becomes severe enough to operate the time or instantaneous overcurrent relays. However, there may be considerable damage involving all three phases before the bank trips. Methods for protecting a midrack phase-to-phase arcing fault include the following:

- Using a fixed time overcurrent relay set at about 1.35 times normal phase current and using a short time delay (≈ 0.1 s). The overcurrent relay shall have a fast dropout time.
- Using a current unbalance or negative sequence current relay. Negative sequence relays as a backup protection can be set to be more sensitive than phase overcurrent relays, but tripping should be delayed to coordinate with the other relays in the system. A setting of 10% of the rated capacitor current, taking into consideration the maximum system voltage unbalance and the maximum capacitance variation together with a time delay setting of 15–25 cycles, may provide adequate coordination for faults external to the bank. However, it may not prevent damages due to arcing faults within the bank structure.

For wye-wye banks, the unbalance protection will operate for this type of fault, provided the correct groups are bonded to the rack (see 8.2.2).

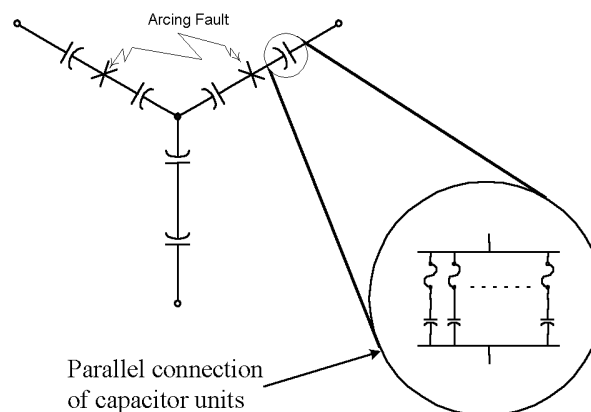


Figure 5—Midrack phase-to-phase arcing fault

7.2 System protection

In order to provide redundancy in the bank protection, system protection may help reduce stresses and minimize damage to capacitors upon the occurrence of the following events:

- External arcing
- Overvoltages, including harmonic distortions
- Bank overcurrent
- Loss of bus voltage
- System overvoltage
- Other considerations (such as loss of voltage transformer fuse, breaker failure protection, and surge arrester protection)

7.2.1 External arcing

External arcing without the prompt operation of the unbalance protection may cause case ruptures or other damage to capacitor units and may blow fuses. It may be desirable to provide the capacitor bank with redundant unbalance protection and/or current unbalance or negative sequence current protection to minimize damage. The overcurrent protection is not normally sensitive to arcing within a capacitor bank and, if it senses a disturbance, is normally too slow.

7.2.2 Overvoltages

The capacitor bank and other equipment in the vicinity may be subjected to overvoltages resulting from abnormal system operating conditions. If the system voltage exceeds the capacitor or equipment capability with the capacitor bank on line, the bank should be removed with minimum time delay. (Removing the capacitor bank from the system lowers the system voltage in the vicinity of the capacitor, reducing the overvoltage on other system elements.)

In some cases, inverse time overvoltage relays may be required to protect the capacitor units from severe system power frequency overvoltage conditions. In this case, a suitable overvoltage relay provided with adequate protection algorithms should be used, set according to the capabilities provided by IEEE Std 1036-1992 or the capacitor manufacturer. If the capacitors are exposed to overvoltages as a result of a combined fundamental and harmonic content, the manufacturer should be asked to provide the peak voltage stress levels as a function of time and temperature. Modern all-film capacitors are affected by crest voltage; therefore, peak overvoltage measuring relays are recommended for this application.

For very large EHV capacitor banks, it is advisable to install three-phase overvoltage relays (59B) to monitor the bus voltage. The 59B relays in Figure 6 may trip the bank quickly for extreme overvoltage conditions. To avoid nuisance tripping during transient overvoltage conditions, in some cases, tripping is delayed by a timer. Because this tripping is not due to a fault within the capacitor bank, the capacitor bank is not locked out.

7.2.3 Bank overcurrent protection

Each time a large grounded wye capacitor bank is energized, momentary capacitor charging currents in one phase and in the neutral may approach the ground fault trip level. Where a parallel bank is already energized, currents can be on the order of thousands of amperes (Abdulrahim et al. [B1]). Spurious relay operations, relay failures, current transformer failures, charged substation fences, and ground mat problems may result. The neutral connection between multiple banks should not be through the ground mat; instead single-point or peninsula grounding should be used.

Protecting the capacitor bank against a major fault, such as a line-to-line fault or a line-to-ground fault, generally requires external protection, such as power fuses, circuit breakers, or circuit switchers with associated relay circuits. For best protection, the relays should be set as low and fast as possible, with only enough delay to avoid tripping on external system disturbances.

Time-overcurrent relays can be applied with normal settings without encountering false operations due to inrush currents. The desirable minimum pickup is 135% of nominal phase current for grounded wye banks or 125% for ungrounded banks. Instantaneous relays, if used, should be set high to override inrush or out-rush transients.

Modern relays with fundamental frequency band-pass filters are not susceptible to inrush or outrush currents. Successful operation may be obtained by setting instantaneous relays at three to four times the capacitor rated current (or lower) to override back-to-back bank switching.

In some large capacitor banks, redundant overcurrent devices may protect for short circuits within the capacitor bank. Figure 6 illustrates two sets of three-phase overcurrent relays (50/51) with short-time overcurrent and instantaneous functions. A low burden for this neutral overcurrent relay, 51N, reduces high voltages across current transformer secondaries caused by high-frequency outrush currents from the bank during an external fault.

For ineffectively grounded systems with ungrounded capacitor banks, the neutral overcurrent relay, 51N, should be set to a low tap to detect and to provide fast clearing for ground faults of low magnitudes not detected by phase overcurrent relays.

For effectively grounded systems with grounded wye capacitor banks, the high-frequency outrush current into an external ground fault will not normally operate the 51N ground relay. The unbalanced capacitor bank load current caused by the external ground fault may be sufficient to cause the relay to pick up and trip the capacitor bank if the 51N is set too low. To prevent this inadvertent tripping, the trip of the 51N relay is normally set above the capacitor phase current.

Figure 6 illustrates one unbalance protection scheme in use on large EHV capacitor banks. Other schemes are also in use (for example, midpoint taps, H-bridges, and wye-wye arrangements). Refer to Clause 8 for unbalance protection schemes.

7.2.4 Loss of bus voltage

In some cases, it may be necessary to trip a shunt capacitor bank if the supply bus voltage is lost. Two conditions that may need to be considered are

- Re-energizing a bank with a trapped charge.
- Energizing a capacitor bank without parallel load through a previously unenergized transformer.

Circuit breaker reclosure schemes and capacitor voltage discharging means should be considered to avoid nuisance tripping or equipment damage upon loss of bus voltage with fast reclosing schemes.

Undervoltage relay, device 27B in Figure 6, will detect loss of system voltage and trip the capacitor bank after a time delay. This delay prevents tripping of the bank for system faults external to the bank. The undervoltage relay should be set so that the relay will not operate for voltages that require the capacitor bank to remain in service. Because this tripping, like system overvoltage tripping, is also not due to a fault within the capacitor bank, the bank is not locked out.

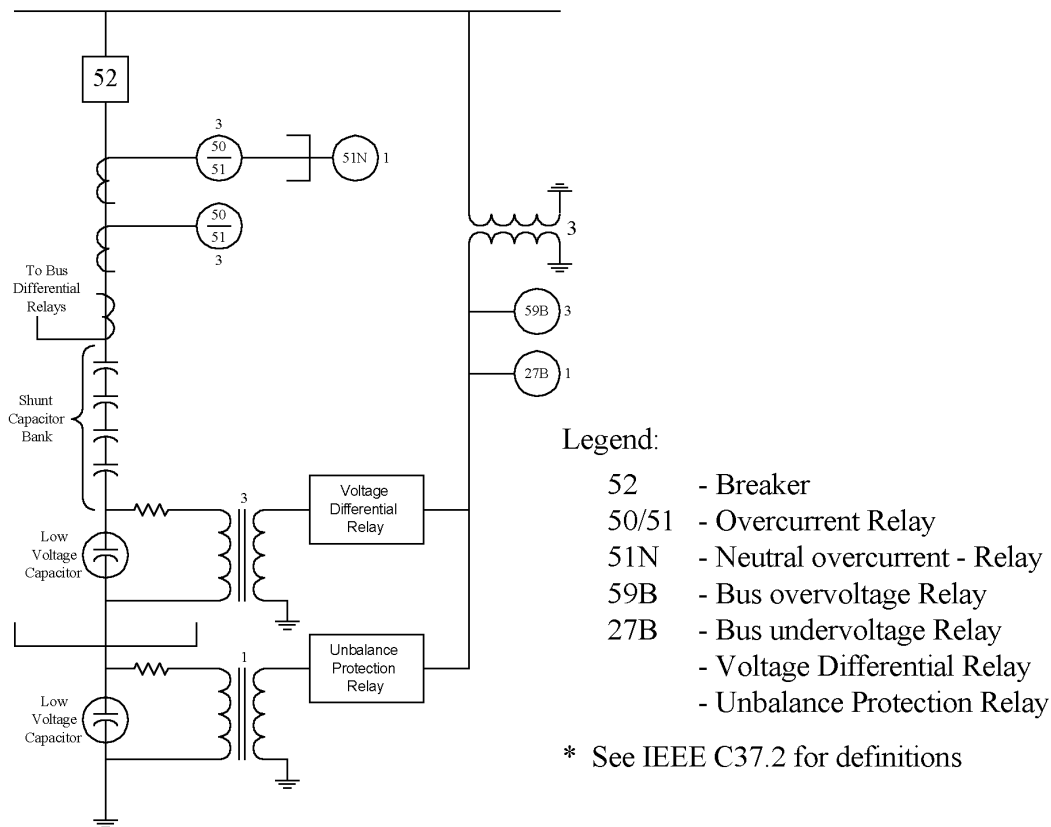


Figure 6—Sample protection scheme for a very large EHV capacitor bank

7.2.5 Fusing for capacitor bank relaying

Many of the protective schemes used on large capacitor banks are sensitive to loss of voltage. For this reason, primary fuses should not be installed on voltage transformers used for this purpose. In addition, the circuit supplying the potential for the protective relays should be brought directly from the voltage transformer to the relay panel with no other connected loads. This arrangement prevents cable voltage drops, especially from varying loads, from affecting the sensitive unbalance protection relays.

When other codes or standards require primary fuses to be installed, the fuse operation shall not cause the loss of protection. A voltage transformer with an open primary circuit may have a high impedance between the secondary terminals, inhibiting relay operation.

Secondary fuses usually do not present a problem because they are sized to protect the cable (usually 30 A) and the unbalance protection will trip before the fuses blow.

7.2.6 Capacitor bank breaker failure protection

If the capacitor switching device is a circuit breaker or a circuit switcher, a breaker failure protection scheme may be incorporated to provide a local backup protection if the switching device fails. If the device does fail, the capacitor bank is isolated from the system by tripping the adjacent breakers connected to the bank after a set time delay. In some cases, remote transfer tripping may be necessary. It is important to verify the capacitance switching capabilities of these adjacent devices for proper operation of the scheme.

The local breaker failure detection logic is initiated by auxiliary relays. Standard breaker failure schemes either have an overcurrent supervision logic to start a timer or have the output of the timer, supervised by overcurrent logic. These overcurrent elements are set to operate for all types of capacitor faults. (Some currents can be less than the nominal rated current.) A phase overcurrent setting of 50% of the capacitor bank normal rated current is generally considered adequate for both grounded and ungrounded banks.

7.2.7 Surge arrester protection

Lightning and switching transient overvoltages may be controlled by using standard overvoltage protection equipment, such as surge arresters. A capacitor bank generally absorbs overvoltages because it acts temporarily as a short circuit for step voltage changes. Overvoltages around capacitor banks are greatly reduced, but complete protection is not assured. The overvoltage on a bank depends upon the length of line between the shunt capacitor bank, the point at which the transient voltage is generated, and the surge duration.

8. Unbalance relaying methods

8.1 Introduction

Unbalance protection utilizes the unbalance that occurs in a normally balanced capacitor bank to detect an abnormality and initiate appropriate action. The most important function is to promptly remove the bank from service for any fault that may result in further damage. An external fault in a capacitor bank is likely to cause extensive damage (cascading failure) and may create a safety hazard if the bank is not tripped quickly. (An external fault in a capacitor bank is a fault within the zone of protection of the unbalance relaying, but external to a capacitor unit, for instance, across an insulator supporting a fuse rail or frame.)

The functions of unbalance relaying are normally to

- a) Trip the bank promptly if an unbalance indicates the possible presence of external arcing or a cascading fault within the capacitor bank.
- b) Provide early unbalance alarm signal(s) to indicate the operation of fuses (internally or externally fused capacitors) or failure of capacitor elements (fuseless or unfused capacitors).
- c) Trip the bank for unbalances that are large enough to indicate that continuing operation may result in
 - 1) Damage to remaining good capacitor units or elements from overvoltage.
 - 2) Fuse malfunction.
 - 3) Inappropriate filter operation (for capacitor banks that are a part of a harmonic filter).
 - 4) Other undesirable consequences.

Functions a) and c) are frequently combined by setting the trip level based on function c) and with a very short timing based on function a). This scheme works quite well for most applications.

Failure to provide adequate unbalance protection may lead to one or more of the following situations:

- Excessive damage to the capacitor bank.
- Adverse system effects.
- Spread of damage to adjacent equipment.
- Excessive period when the damaged equipment is unavailable.
- Possible case rupture and undesirable discharge of dielectric liquid and/or fire.

Unbalance protection systems do not operate fast enough to avoid catastrophic failure due to high system short-circuit currents within capacitor units. Single series group grounded wye capacitor banks or capacitor banks with grounded capacitor unit cases may have system short-circuit current for a single fault within a capacitor unit. External fusing may be desirable to avoid major damage for these banks.

Most installations will require an individual engineering analysis to determine the most appropriate protection scheme. Bank design, fuse coordination, and selection of a sensing device will directly affect sensitivity and the delay time requirements of the protection scheme. Selection of the bank configuration and design should include an analysis of the amount of inherent unbalance that can be expected and tolerated by the protection.

Unbalance protection normally senses changes associated with capacitor element or unit failure and/or fuse operation. It is not generally sensitive enough to detect a defective connection. Defective connections may deteriorate until a fault occurs within the capacitor bank, causing the unbalance protection to operate. A defective connection within a capacitor unit (usually a rare occurrence) may result in a pressure buildup and capacitor unit rupture before the operation of the unbalance protection. The unbalance protection should operate quickly for the external arcing following case rupture.

8.2 General unbalance relay considerations

The unbalance relays should be set on the basis of maximum continuous system operating voltage.

8.2.1 Schemes with ambiguous indication

Ambiguous indications may come from two or more different conditions of the bank, but provide the same indication. For instance, negligible current may flow through the current transformer between the neutrals of an ungrounded wye-wye capacitor bank for a balanced bank, and this condition is desirable. However, the same negligible current may flow through this current transformer if an equal number of units or elements are removed from the same phase on both sides of the bank. This condition is undesirable, and the indication is obviously ambiguous.

Where ambiguous indication is a possibility, it is desirable to have a sensitive alarm (preferably one fuse operation for fused banks or one faulted element for fuseless or unfused banks) to minimize the probability of continuing operation with canceling failures that result in continuing, undetected overvoltages on the remaining units.

It may also be desirable to set the trip level based on an estimated number of canceling failures in order to reduce the risk of subjecting capacitor units to damaging voltages and requiring fuses to operate above their voltage capability when canceling failures occur.

Common schemes with ambiguous indication are as follows:

- In wye-wye banks (see Figure 7), the operation of fuses or short-circuiting of elements in one wye may cancel the unbalance signal generated in the other wye.

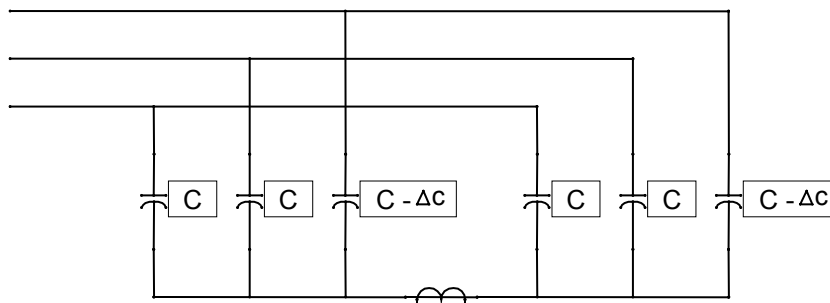


Figure 7—Wye-wye: Compensating failures result in no unbalance signal even though the bank is unbalanced

- In H-bridge banks (see Figure 8), the operation of fuses or short-circuiting of elements in one leg of the H may cancel the unbalance signal generated in another leg of the H.

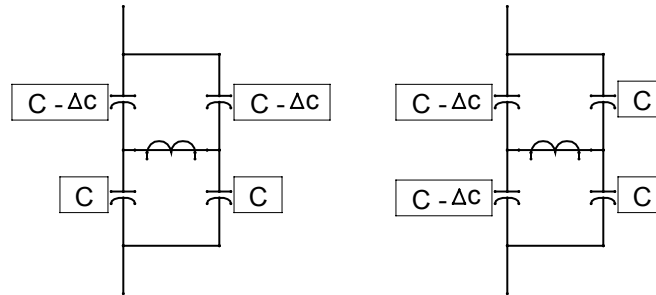


Figure 8—H-bridge: Compensating failures results in no unbalance signal even though the bank may be unbalanced

- In midpoint-tapped banks (see Figure 9), the operation of fuses or short-circuiting of elements above the tap point may cancel the unbalance signal generated below the tap point.

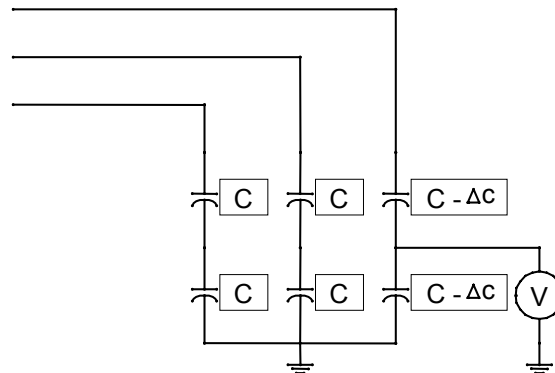


Figure 9—Midpoint taps: Compensating failures result in no unbalance signal even though the bank may be unbalanced

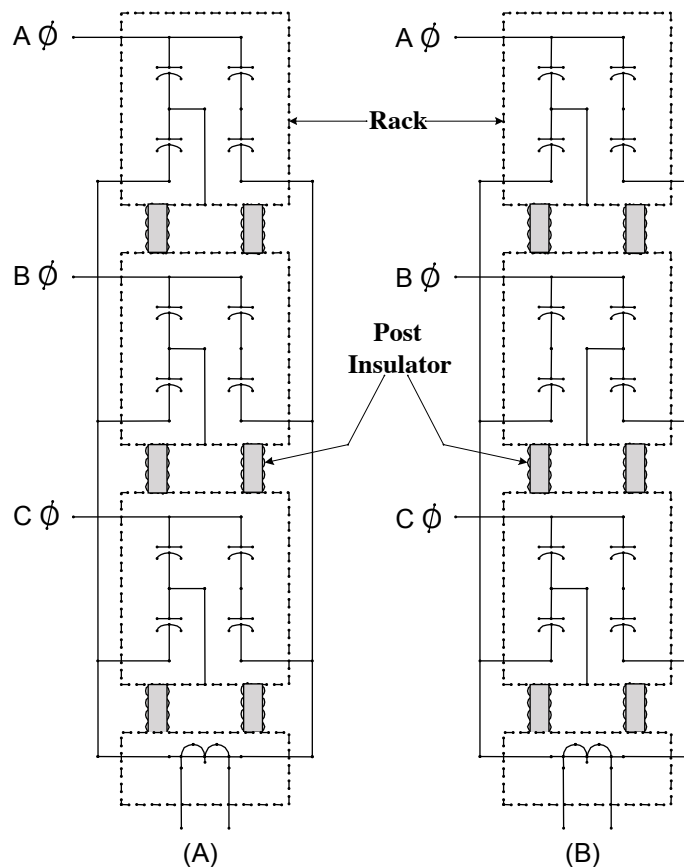
8.2.2 Undetectable failure modes

For certain capacitor bank configurations, some faults within the bank will not cause an unbalance signal, such as

- Rack-to-rack faults for banks with two series groups connected phase-over-phase and using neutral voltage or current for unbalance protection.
- Rack-to-rack faults for certain H-bridge connections.

Refer to 7.1.5 for a discussion of these conditions.

For phase-over-phase wye-wye and H-bridge banks, correct bonding of the racks is required in order that the unbalance protection will be responsive to rack-to-rack flashovers. See Figure 10 for an illustration of the bonding for a wye-wye bank.



(A) Incorrect rack bonding (all on same side); no neutral current through the current transformer for a rack-to-rack insulator flashover

(B) Correct rack bonding (on alternate sides); neutral current will flow through a current transformer for a rack-to-rack insulator flashover

NOTE—Bonding is similar for a grounded wye-wye bank for a phase-over-phase design.

Figure 10—Bonding of the frames of an ungrounded wye-wye bank

8.2.3 Inherent unbalance, system unbalance, and other sources of error

- a) In practice, the unbalance seen by the unbalance relay, due to loss of individual capacitor units or elements, is somewhat different from the calculated value because of inherent unbalance. The primary unbalance, which exists on all capacitor bank installations (with or without fuses), is due to system voltage unbalance and capacitor manufacturing tolerance. Secondary unbalance errors may be introduced by sensing device tolerance and variation and by relative changes in capacitance due to difference in capacitor unit temperatures in the bank.

The total inherent unbalance error will be a vectorial combination of the primary and secondary effects. The error may be in a direction to prevent unbalance relay operation, or to cause a false operation. The amount of inherent unbalance for various configurations may be estimated using equations in Annex C. A worst-case estimate can be made by assuming the unbalance errors to be additive.

If the inherent unbalance error approaches 50% of the alarm setting, compensation should be provided in order to correctly alarm for the failure of one unit or element as specified. In some cases, a different bank connection can improve the sensitivity without adding compensation.