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IEEE Guide for the Protection of Shunt Capacitor Banks

IEEE Power and Energy Society

Sponsored by the
Power System Relaying Committee

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Abstract: The protection of shunt power capacitor banks and filter capacitor banks are discussed in this guide. The guidelines for reliable application of protection methods intended for use in many shunt capacitor bank designs are included. Also, a detailed explanation of the theory of unbalance protection principles is provided. Discussions on the protection of pole-mounted capacitor banks on distribution circuits or capacitors connected to the terminals of rotating machines are not included as they are outside the scope of this standard.
Keywords: bank configuration, externally fused, filter bank, fuseless, IEEE C37.99™, internally fused, overcurrent, overvoltage, relay, shunt capacitor bank, unbalance protection

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Introduction

This introduction is not part of IEEE Std C37.99-2012, IEEE Guide for the Protection of Shunt Capacitor Banks.

IEEE Std C37.99-2012 incorporates significant additions and changes since the last revision in 2000. These additions include the theory of unbalance protection methods, impedance measurement techniques, and settings examples as Annex E. Detailed discussion on grounding has now been reduced to address concerns related to protection, and the reader has been directed to refer to IEEE Std 1036™-2010[a] for more details.

This guide was revised by the shunt capacitor bank protection revision working group of the substations protection subcommittee of the Power Systems Relaying Committee of the IEEE Power and Energy Society.

[a] Information on references can be found in Clause 2.

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IEEE Guide for the Protection of Shunt Capacitor Banks

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1. Overview

1.1 Scope

This guide applies to the protection of shunt power capacitor banks and filter capacitor 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 the protection of pole-mounted capacitor banks on distribution circuits or capacitors connected to the terminals of rotating machines.

1.2 Purpose

This guide has been prepared to assist protection engineers 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 including the latest protection techniques. Additionally, this guide covers the protection of filter capacitor banks and large extra-high-voltage (EHV) shunt capacitor banks.

2. Normative references

The following referenced document is indispensable for the application of this document (i.e., it 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.

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

IEEE Std 18™, IEEE Standard for Shunt Power Capacitors.[2,3]

IEEE Std 469™, IEEE Recommended Practice for Voice-Frequency Electrical-Noise Tests of Distribution Transformers.

IEEE Std 525™, IEEE Guide for the Design and Installation of Cable Systems in Substations.

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

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

IEEE Std 1531™, IEEE Guide for Application and Specification of Harmonic Filters.

IEEE Std C37.012™, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers.

IEEE Std C37.04™, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.

IEEE Std C37.2™, IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations.

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

IEEE Std C37.66 ™, IEEE Standard Requirements for Oil-Filled Capacitor Switches for AC Systems (1 kV to 38 kV).

IEEE Std C37.90.1™, IEEE Standard for Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus.

IEEE Std C57.13.3™, IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases.

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

IEEE Std C62.2™, IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating Current Systems.

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

NEMA CP1, Shunt Capacitors.[4]

3. 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.[5]

back-to-back capacitor bank switching (or back-to-back switching or back-to-back capacitor switching): Switching a capacitor bank in close enough electrical proximity to one or more other energized capacitor banks and/or cables to influence the inrush current significantly.

capacitor bank: An assembly at one location of capacitor(s) and all necessary accessories (such as switching equipment, protective equipment, controls, etc.) required for a complete operating installation.

capacitor control: The device required to operate the switching device(s) automatically to energize and deenergize shunt power capacitor banks.

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

capacitor inrush current (or inrush current): The transient charging current that flows in a capacitor when a capacitor is initially connected to a voltage source.

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

capacitor outrush current (or outrush current): The transient discharge current that flows when an energized capacitor bank is initially connected to an external short circuit.

capacitor unit (capacitor, 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.

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

externally fused capacitor bank: A capacitor bank with fuses external to the (power) capacitor units.

filter capacitor: Capacitor(s) utilized with inductors and/or resistors for controlling harmonic voltages and currents in the power system.

fixed capacitor bank: A capacitor bank not designed for automatic or frequent switching.

fused capacitor: A capacitor having fuses mounted on its terminals, inside a terminal enclosure, or inside the capacitor case, for the purpose of disconnecting a failed capacitor element, unit, or group.

fuseless capacitor bank: A capacitor bank without any fuses, internal or external, which is constructed of (parallel) strings of series-connected capacitor units.

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[4] NEMA publications are available from Global Engineering Documents (http://global.ihs.com/).
[5] The *IEEE Standards Dictionary Online* subscription is available at http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

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

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

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

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.

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 (Figure 1).

phase-over-phase: A capacitor bank construction on one structure, with the individual phases (or legs for delta connected capacitor banks) of the capacitor bank installed above each other and insulated from each other.

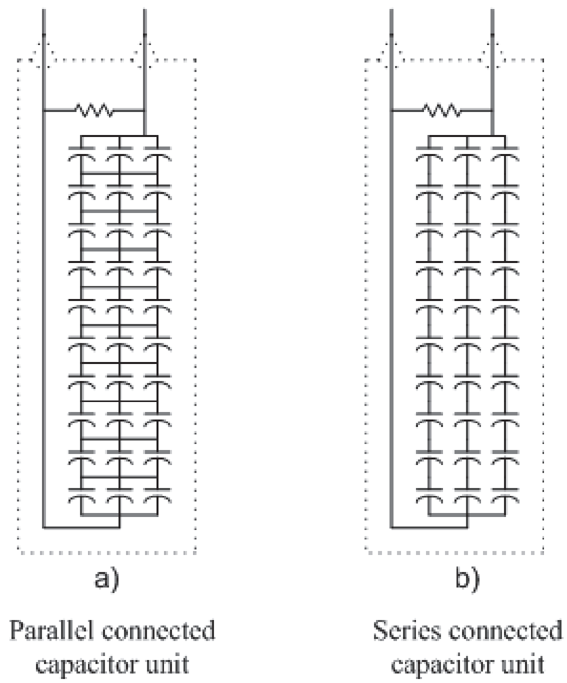


Figure 1—Capacitor unit design

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

switched capacitor (switched capacitor bank): A capacitor bank designed for controlled operation and/or frequent switching.

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

thyristor-switched capacitor (TSC): A capacitor switched ON and OFF by thyristor control action.

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

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

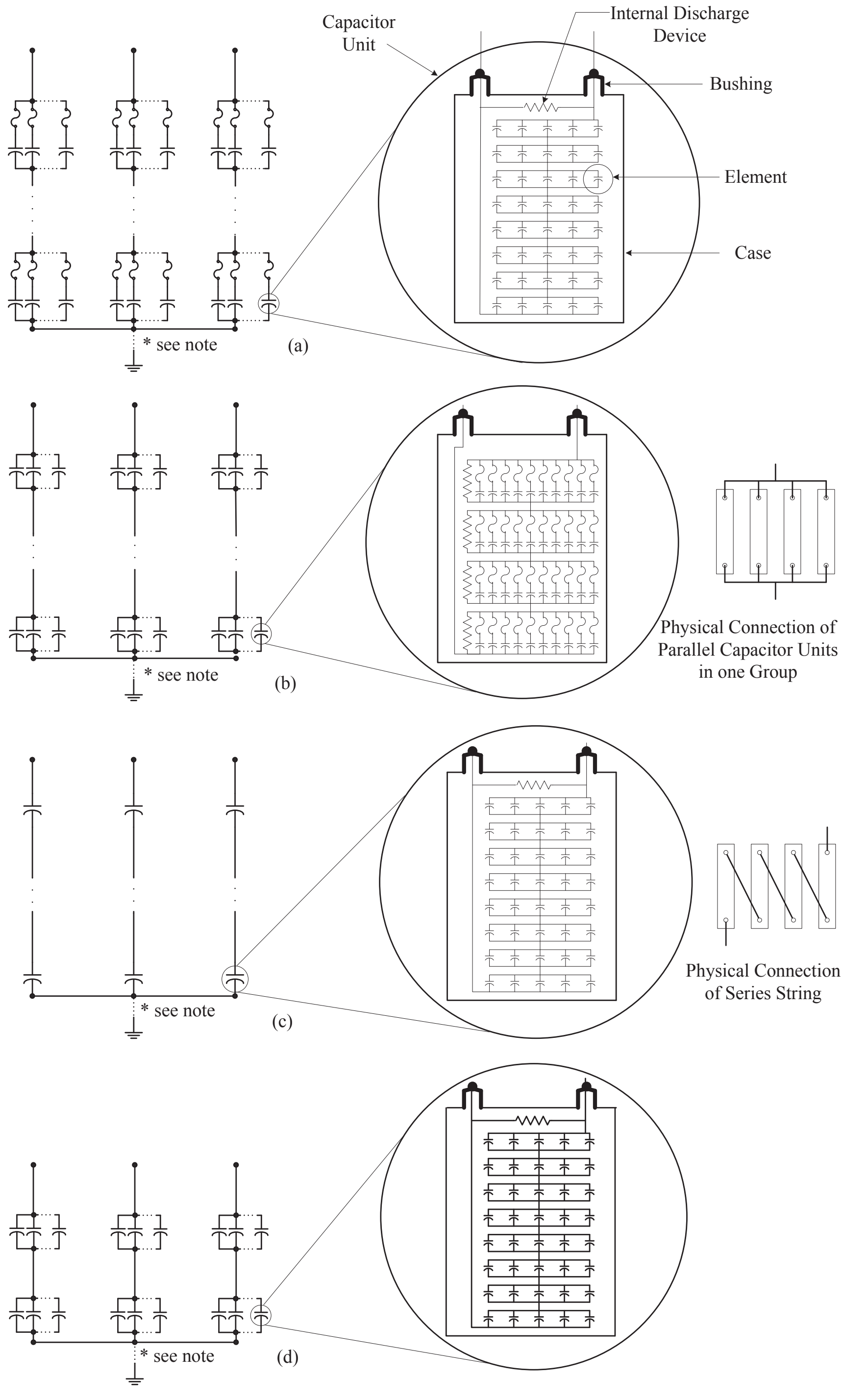
4. Basic considerations

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 capacitor units and their respective connections may affect the relay function 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 capacitor units connected in a variety of series and parallel arrangements

Figure 2 shows the basic terminology and examples of wye-connected banks (grounded or ungrounded) with these four types of capacitor units.

Clause 2 shows 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.



(a) Externally-fused
(b) Internally-fused
(c) Fuseless (may use multiple strings per phase)
(d) Unfused

*Note - Capacitor banks may be grounded

Figure 2—Wye connected capacitor bank—grounded or ungrounded

4.1 Capacitor unit capabilities

When protecting capacitor banks, it is important to realize the capabilities of capacitor units so that the protection system can be applied to guard the capacitor units against system-induced events and upon failures of some units in the bank. IEEE Std 18™ specifies the standard ratings of the capacitors designed for shunt connection to ac transmission and distribution systems.[6] IEEE Std 1036™ gives application guidelines for these capacitors. As per IEEE Std 18, the following is specified:

a) Capacitors are intended to be operated at or below their rated voltage. Capacitors shall be capable of continuous operation under the contingency system and bank conditions provided none of the following limitations are exceeded:
   1) 110% of rated RMS voltage
   2) 120% of rated peak voltage (i.e., peak voltage not exceeding $1.2\sqrt{2}$ times the rated RMS voltage, including harmonics, but excluding transients)
   3) 135% of nominal RMS current based on rated kvar and rated voltage
   4) 135% of rated kvar

b) The capacitance of a unit shall not vary more than –0% to +10% of the nominal value based on rated kvar, voltage, and frequency, measured at 25 °C uniform case and internal temperature.

c) Capacitor units mounted in multiple rows and tiers should be designed for continuous operation for a maximum 4 h average ambient air temperature of 40 °C during the hottest day. Capacitors shall be capable of both continuous operation and switching operations at a minimum ambient temperature of −40 °C.

d) 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 (216 V to 24 940 V) and sizes (2.5 kvar to about 800 kvar). Capacitor units designed for special applications can exceed these ratings (see IEEE Std 18). See IEEE Std 1036 for capacitor short-time overvoltage capability.

4.2 Capacitor unit connections

Depending on the application, any of the four types of capacitor units (i.e., externally fused, internally fused, fuseless, and unfused) may be suitable for the capacitor bank design.

4.2.1 Externally fused shunt capacitor banks

Externally fused shunt capacitor banks are configured using one or more series groups of parallel connected capacitor units per phase. An individual fuse, externally mounted between the capacitor unit and the capacitor bank fuse bus, typically protects each capacitor unit. Figure 2(a) illustrates a typical capacitor bank utilizing externally fused capacitor units. 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 is required to allow the bank to remain in service with one unit out.

4.2.2 Internally fused shunt capacitor banks

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.

[6] Information on references can be found in Clause 2.

Figure 2(b) illustrates a typical capacitor bank utilizing internally fused capacitor units. The capacitor units normally have a large kvar rating, and a complete unit is not expected to fail due to operation of fuses on failed internal elements.

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 of 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 where the failure (short circuiting) of one capacitor element will not cause excessive voltage on the remaining elements in that string. This is usually 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. Figure 2(c) illustrates a typical capacitor bank utilizing fuseless capacitor units.

4.2.4 Unfused shunt capacitor banks

The unfused shunt capacitor approach uses a series/parallel connection of the capacitor units, similar to externally or internally fused capacitor banks. This type of capacitor bank has not been widely used. Some users have removed fuses from externally fused capacitor banks because of excessive nuisance operations and have ended up with an unfused capacitor bank. The unfused approach may be useful on banks below 34.5 kV (where series strings are not practical) or on higher voltage capacitor banks with modest parallel energy. This design may not require as many capacitor units in parallel as an externally fused bank because the voltage on the fuse during operation is not a consideration. Figure 2(d) illustrates a typical capacitor bank utilizing unfused capacitor units.

4.3 Capacitor bank design

4.3.1 Externally fused shunt capacitor banks

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 a 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 has 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.

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 safely until the fuse blows.

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 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 × 1.1 × √2). For 60 Hz applications, NEMA CP1 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. [B10][7]). Consult the capacitor and fuse manufacturer before exceeding the 4650 kvar limit to assist in ensuring 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, then 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 have to 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. In a “double-wye” arrangement, the failure of fewer capacitor units will also result in the removal of the bank. The use of current-limiting fuses in a single wye configuration would be another option.

4.3.2 Internally fused shunt capacitor banks

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 permits 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 typically recommends the maximum number of capacitor units to be connected directly in parallel.

[7] The numbers in brackets correspond to those of the bibliography in Annex A.

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

4.3.3 Fuseless shunt capacitor banks

A fuseless capacitor bank is arranged with individual capacitor units in series (called a “series string”) connected between the phase terminals and the ground or neutral. The sum of the individual capacitor unit rated voltages in a string should equal or exceed the normal phase-to-ground or phase-to-neutral voltage of the capacitor bank. The desired three-phase kvar of the capacitor bank is accomplished by adding series strings of capacitor units in parallel.

Fuseless banks are usually used at a higher system voltage (at or above 34.5 kV). 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 assist in ensuring that the remaining elements do not exceed 110% of the nominal rating if an element in the string shorts.

4.3.4 Unfused shunt capacitor banks

An unfused bank would have a series/parallel arrangement. Relay unbalance functions are normally set to trip the bank 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 shunt capacitor banks

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, then the overvoltage percentage is less than that of the two capacitors failing in the same parallel group.

4.4.2 Internally fused shunt capacitor banks

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. When a puncture or a short-circuit occurs in a capacitor element, the current through the fuse increases in proportion to the number of elements connected in parallel. This increase is sufficient to melt the fuse within a very short time. The capacitor units are designed with a large enough number of elements in parallel so that the operation of one fuse does not result in too much increase in voltage on the remaining parallel elements. Further failures of elements causes overvoltage on the healthy units, and unbalance protection should ultimately operate when overvoltage exceeds design level.

4.4.3 Fuseless shunt capacitor banks

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 number of capacitor elements in series increases with the increase in the nominal voltage rating of the capacitor bank. If an element shorts, then the remaining capacitor elements will be subject to overvoltage. The voltage increase on each element will be approximately equal to $E / (E - 1)$, where E is the original number of capacitor elements in the string. 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.

4.4.4 Unfused shunt capacitor banks

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

Six common capacitor bank connections are shown in Figure 3. 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 wye connected. Distribution capacitor banks, however, may be wye or delta connected. Some banks use an H configuration on each of the phases with a current transformer in the connecting branch to detect the unbalance.

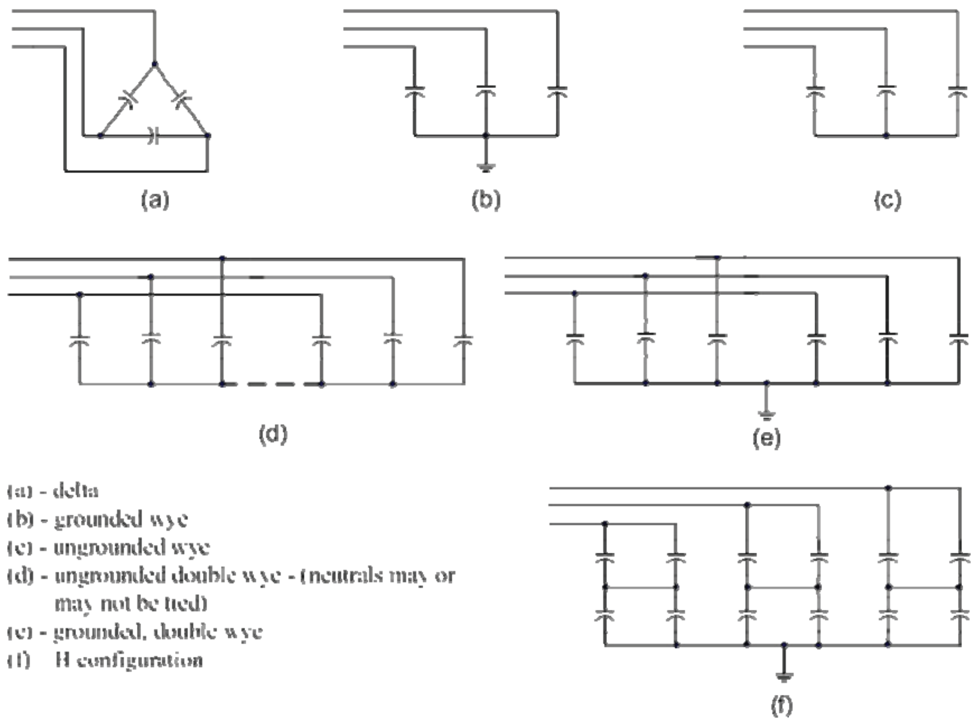


Figure 3—Common capacitor bank connections

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 in the vicinity of the capacitor bank produces zero sequence currents that may cause capacitor bank ground relay operations. Harmonic resonance may also be a problem because capacitor banks are in many cases part of a resonant loop, resulting in magnification of specific harmonic components.

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 current transformer (CT) circuits (see 10.6.1), communication circuits and bank protective relay performance (see 11.3), and the method of system grounding (see 6.1).

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 should be capable of interrupting the system available fault current.

Internally fused and unfused capacitor banks should have unbalance protection to avoid excessive element overvoltages 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 so that the 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 should 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

Large capacitor banks may be split into two wye sections, to maintain the parallel energy of a series group within the limits of capacitor units or fuses. 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.

In fuseless capacitor banks, double wye designs with voltage differential schemes also may mitigate nuisance alarms or trips caused by the unequal variation of capacitance due to solar radiation.

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 point of the bank, 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 or during close-in system ground fault.

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 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, then 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, then 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 1.73 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.

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 4.3, the bank may be split into two wye sections. When the two neutrals are ungrounded, the bank has the same characteristics as the ungrounded single-wye bank outlined in 5.2.2. These two neutrals may be tied together through a current transformer or a voltage transformer to facilitate certain protection methods. As for any ungrounded wye bank, the neutral instrument transformers should be insulated from ground for full line-to-ground voltage.

5.3 Delta-connected banks

Delta-connected banks are generally used only at distribution voltages and are typically configured with a single series group of capacitors because banks are small, 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 of capacitors is used, the individual capacitor fuses should 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, then 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, then 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 consideration 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, if protection does not operate correctly. Although capacitors having large kilovar ratings may reduce the overall cost of the bank, they may also reduce the choice of different capacitor connections or combinations.

6.1 Bank grounding

With grounded wye capacitor banks, high-frequency, high-magnitude transient currents may flow from the capacitor bank neutral into the substation ground. Voltages induced by these ground currents may cause malfunction or damage to protection systems or other equipment, even in parts of the substation not directly related to the capacitor installation.

Some of the most onerous transient currents are caused by the following:

- Discharge of the capacitor bank from the peak of the operating voltage into a nearby line-to-ground fault
- Restriking capacitor switch with back-to-back capacitor switching
- Line-to-ground fault in the capacitor bank (large discharges may occur as series groups are shorted out)

These high-frequency ground mat transient currents are an important consideration in the design of the ground mat in substations that include grounded wye capacitor banks. The use of peninsula grounding can help keep the high-frequency transient currents out of parts of the substation not directly connected with the capacitor. Where there are multiple capacitor banks at the same voltage in a substation, the use of single point grounding will reduce the ground mat currents between capacitor banks associated with capacitor switching. The subject of capacitor bank grounding, including peninsula grounding and single point grounding, is discussed more fully in IEEE Std 1036.

These high-frequency ground currents are also an important consideration in the shielding and protection of relaying circuits associated with a capacitor bank. These considerations are discussed in 10.6. For instrument transformer secondary grounding considerations, refer to IEEE Std C57.13.3™.

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 in 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 main advantage associated with neutral grounding is less severity of the transient recovery voltage (TRV) 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 the 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™ and ANSI C37.06-2000 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 connected to tertiaries of power transformers that are connected to the line or possibly to the bus. Grounding the neutral of a 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 network; grounding the neutral of the capacitor bank connected to the tertiary winding makes this side of the transformer capacitively grounded. Overvoltages may be experienced during line-to-ground faults for certain ratios of X0/X1, depending on system, transformer, and capacitor bank parameters. If the neutral is to be grounded on a system that is not effectively grounded, then the application should be thoroughly analyzed for proper application of surge arresters, bank configuration, bank switching devices, and so on.

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 tripping 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 or on the substation bus to which the capacitor bank is connected. 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 condition 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 an appropriate filtering in currents and/or voltages for security.	Unbalance protection should be fast to minimize damage to other units during a major fault. Time delay of 0.05 s to 0.1 s has been used. See 7.1.4 and 8.3.4b)
Continuous overvoltage on capacitor elements or units due to faulted elements or fuse operations within the bank.	Unbalance protection. Relay should have an appropriate filtering in currents and/or voltages 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.
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 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. Use of reactors require mitigation methods to address high TRV issues on circuit breakers
Excessive inrush current.	(a) Insertion resistor or reactor in switch, breaker, or circuit switcher (b) Inrush and outrush limiting reactors between capacitor banks (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, and so on.

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 reenergizing the system.
Transmission line tripping (for capacitor banks connected to a transmission line segment).	(a) Transfer tripping of the capacitor bank switch (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.	Breaker failure relays.	Local or remote breakers should have capacitor switching capability if they trip the bank without parallel load during breaker failure conditions.

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 is typically designed to remove 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 is typically designed to remove the bank from service when the resulting overvoltage 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 is typically designed to remove the bank from service when the resulting overvoltage 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 assist in ensuring the availability of the capacitor banks. The fuses should be selected to isolate dielectric breakdown quickly and interrupt the parallel energy 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™ 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 should 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, then current-limiting fuses with an adequate energy rating should be considered.

When ungrounded wye capacitor banks are supplied in an enclosure, current-limiting fuses or appropriately designed expulsion fuses having exhaust control devices and intended for use inside enclosures should be used. Arc products from fuses without exhaust control may cause further evolution of the fault inside the confined enclosure. Also note that the fuses may have to interrupt the full system fault current and must be appropriately rated. Even ungrounded capacitor banks could have a fault to ground. For example, on enclosed single-group ungrounded wye banks that are designed with two bushing units, the first bushing is used for the phase connection, the second bushing is used for the neutral connection, and the case is 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. In applications having high short-circuit current, current-limiting fuses may be recommended to reduce the energy during a fault.

NEMA CP1 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. [B10]). 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 should 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 should be coordinated with the voltage withstand capability of the capacitor unit.
- Fuses should handle the transient inrush and outrush current without inappropriately operating.
- Fuses should be designed for the current loadability requirements, including harmonics and adequate allowance factors.
- Fuses should be designed for the inductive and capacitive current interruption capability.
- Fuse characteristics should 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 should 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 should properly isolate the faulted element after fuse operation. Fuses should be designed with a sufficient overvoltage-interrupting capability to assist in ensuring 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 typically considers the following:

- Overvoltage interruption capability
- Transient conditions due to external faults where the fuse should not operate.

— Inrush and outrush currents over the life of the capacitor units

The fastest appropriate element fuse that meets the preceding requirements should be selected. The remaining fuses in a faulted capacitor unit should be capable of safely interrupting subsequent internal element failures.

7.1.4 Capacitor unbalance protection

Unbalance protection normally provides the primary protection for capacitor elements or unit failures, rack faults within a capacitor bank, and other abnormalities that may damage capacitor units and or fuses. Such 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 rack faults.

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 settings 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 therefore should operate quickly because of the possibility of rack fault after 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 affected 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 power system adjacent protection schemes, unless the unbalance relay scheme is a type that does not respond to (or uses compensation for) system unbalance (for example, zero sequence voltage).

The setting of the unbalance trip relay should 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 typically 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 21(b)] should not be relied on 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 on 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 4. 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 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 typically at about 1.35 times normal phase current and using a short time delay (typically 0.1 s). The overcurrent relay should 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 to 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 8.3.2).

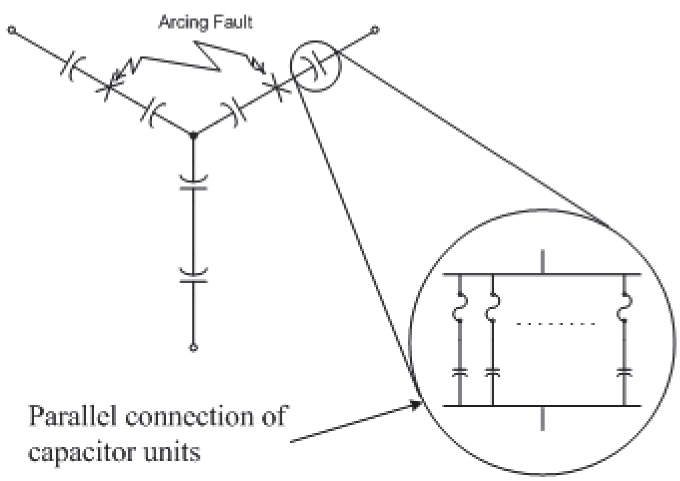


Figure 4—Midrack phase-to-phase arcing fault

7.2 System protection

System protection may help reduce stresses and minimize damage to capacitors on the occurrence of the following events:

- External arcing (rack faults)
- 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 phase 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 Bank overvoltage protection

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, then 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 overvoltage conditions. In this case, a suitable overvoltage relay provided with adequate protection algorithms should be used and set according to the capabilities provided by IEEE Std 1036 or the capacitor manufacturer. If the capacitors are exposed to overvoltages as a result of a combined fundamental and harmonic content, then 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 8 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. Typically, the capacitor bank is locked out when bank protection operates for an internal fault and is not locked out if trip occurred not due to a fault within a bank. This facilitates review of the causes of bank protection operation; in addition, interaction with the automatic voltage regulators (AVRs) or other bank controllers can be reviewed as well.

7.2.3 Overvoltage protection based on current measurements

Bank overvoltage protection relays based on phase currents have been used in the industry instead of conventional overvoltage relays saving the cost of installation of voltage transformers. This application is possible by recognizing that the voltage V across a capacitance C is tied with the current i, flowing through the capacitance, as in Equation (1):

$$V(t) = \frac{1}{C} \times \int i(t)dt \tag{1}$$

The relay estimates the instantaneous value of the voltage based on Equation (1) and therefore incorporates the impact of harmonics and other signal distortions. It then applies the voltage replica to a standard operating overvoltage characteristic as per IEEE Std 1036. The relay designers exercise care to assist in ensuring that the operation of integrating a signal is stable over long periods of time and does not yield to drifts in the voltage replica signal. The current-based overvoltage protection can also be considered a backup function for the loss of potential conditions.

Temperature variations in the actual capacitance would cause some accuracy errors in this protection function as it uses the nominal value of the capacitance per Equation (1). Also, undetected capacitor unit failures alter the value of the actual capacitance and the function either underprotects or overprotects the bank using the nominal value of the capacitance when deriving the voltage replica signal.

7.2.4 Bank overcurrent protection

Each time a large grounded wye capacitor bank is energized, momentary capacitor inrush currents in one phase and in the neutral may approach the ground fault trip level. Where a parallel bank is already energized, the magnitude and frequency of this inrush current is much higher than the inrush to an isolated capacitor bank and 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. Where inrush currents are excessive, certain measures have to be taken, such as usage of current-limiting devices, switching devices with preinsertion resistors, and preinsertion inductors, and proper grounding of parallel bank as described in IEEE Std 1036.

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 the desirable minimum pickup of 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 outrush transients.

Time overcurrent functions in modern relays with fundamental frequency band-pass filters are not that susceptible to inrush or outrush currents. Successful operation may be obtained by setting instantaneous relays at a lower value compared with relays without band-pass filters; typically, three to four times the capacitor rated current (or lower) is sufficient 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 8 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 sensitively 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 8 illustrates one unbalance protection scheme in use on large single-wye grounded EHV capacitor banks. Other schemes are also in use for different bank arrangements (for example, midpoint taps, H-bridges, and wye-wye). Refer to Clause 8 for unbalance protection schemes.

7.2.5 Impedance-based protection

Major bank faults as well as problems with capacitor elements can be detected as changes in the directly measured impedance of the capacitor bank.

With reference to Figure 5, an impedance protection function can be used to monitor the apparent impedance between the bus and the ground (*–jXc*). The CT can be located at the high potential or close to the bank neutral. The CT location does not change sensitivity for detecting internal problems with capacitor units. Response to major bank faults is not affected either by the CT location because of the very small restraint region in the operating impedance characteristic.

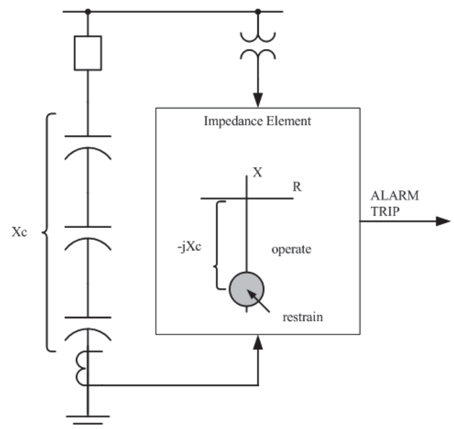


Figure 5—Impedance protection method of shunt capacitor banks

When monitoring each string individually (see Figure 6), the impedance function retains maximum sensitivity because a failure of a capacitor unit generates a larger percentage change in the measured impedance as compared with monitoring the apparent impedance of all parallel strings [Figure 7(a)]. One can consider a solution of monitoring just two or three strings with a single impedance function as a compromise between sensitivity and the number of CTs and amount of relay equipment required [Figure 7(b)].

From this perspective, locating CTs at the bank neutral can be beneficial. When using multiple current measurements to monitor each string individually and placing them closer to the grounded neutral of the bank, the voltage insulation level of the required CTs can be lower.

The apparent impedance is affected by CT, voltage transformer (VT), and relay accuracies. Given the high sensitivity of the method, the complete protection system measurement chain is often calibrated on energizing the bank during initial commissioning or after major bank repair, which is similar to the unbalance protection methods. This process involves selecting the actually measured nominal impedance as the relay setting rather than its value calculated based on the nameplate data.

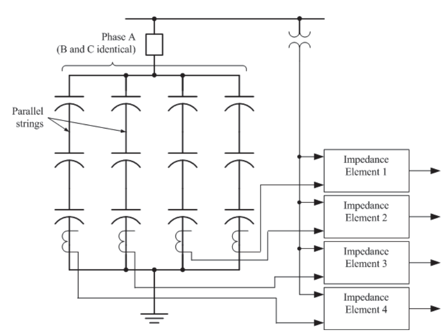


Figure 6—For maximum sensitivity, the impedance method should monitor each capacitor string individually

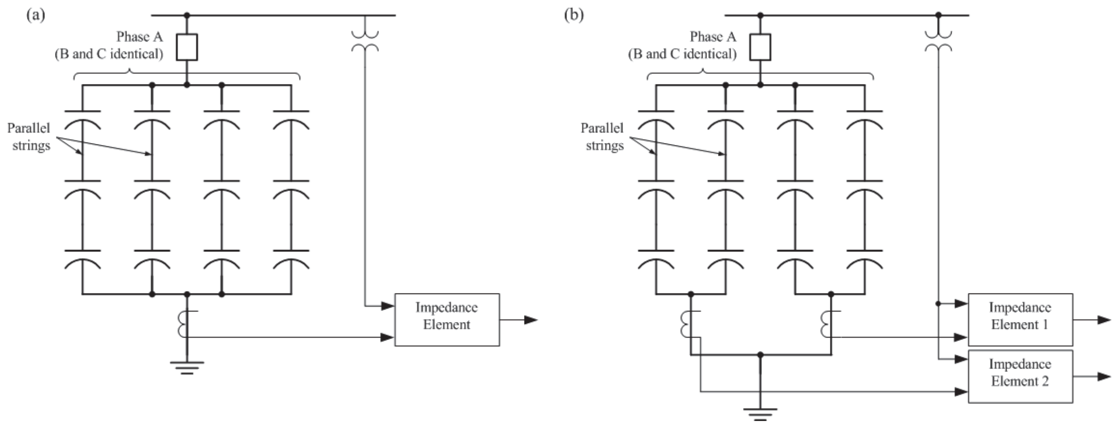


Figure 7—Monitoring all strings with one impedance element (a) reduces sensitivity: a compromise between sensitivity and amount of protection equipment is required (b)

The capacitance of the capacitors is a function of temperature. Thus, the impedance of the capacitor is a function of temperature. Particularly with larger capacitor banks that require very sensitive alarm and trip settings, the relay impedance settings for unbalance might be of the same order of magnitude as the change in impedance caused by temperature variations. For these applications, the relay needs to compensate for the changes in impedance as a function of capacitor temperature. In estimating the capacitor temperature, the effect of sun-loading on the capacitors may need to be considered. Also, there is a small change in capacitance due to the temperature rise in the capacitor following energization.

7.2.6 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 as follows:

- Reenergizing a bank with a trapped charge
- Energizing a capacitor bank without parallel load through a previously deenergized 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 8, will detect loss of system voltage and trip the capacitor bank after a sufficient 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.

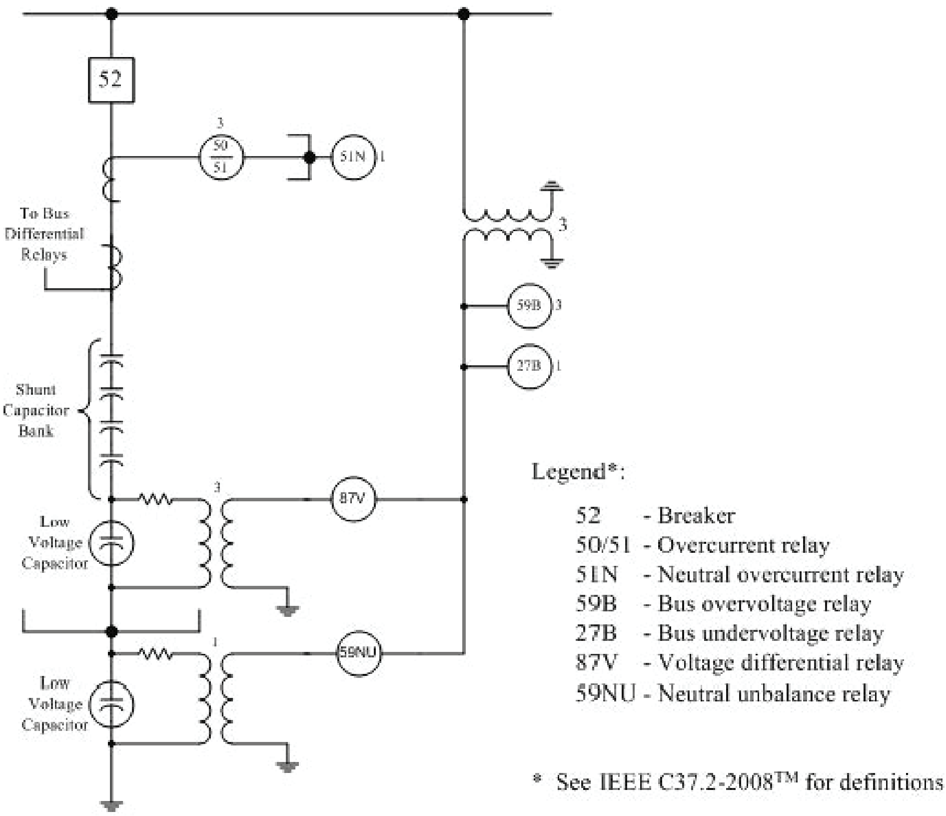


Figure 8—Sample protection scheme for a large EHV capacitor bank

7.2.7 Fusing for capacitor bank relaying

Many protective functions used on large capacitor banks are sensitive to loss of voltage. For this reason, primary fuses may 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 should not cause incorrect operation of protection function, which can be achieved by supervision of the loss-of-potential logic. A voltage transformer with an open primary circuit may have high impedance between the secondary terminals, affecting 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 has typically enough time delay not to operate before the fuses blow, which then can be blocked by loss-of-potential logic.

7.2.8 Capacitor bank breaker failure protection

If the capacitor switching device is a circuit breaker or a circuit switcher, then a breaker failure protection scheme may be incorporated to provide a local backup protection if the switching device fails. If the device does fail, then the capacitor bank is isolated from the system by tripping the adjacent breakers connected to the bank after a breaker failure 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 breaker failure 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.

7.2.9 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 on the length of line between the shunt capacitor bank, the point at which the transient voltage is generated, and the surge duration as well as the rating and location of any surge arresters that may be connected on nearby station buses (IEEE Surge Protective Device Committee [B8]).

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 remove the bank promptly 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.

Unbalance protection for capacitor bank includes the following methods:

- Phase voltage differential
- Neutral voltage unbalance
- Unbalance method for banks grounded through a neutral capacitor
- Unbalance method for banks grounded through a CT with a resistive burden
- Phase current unbalance
- Neutral current unbalance

The fundamentals of these methods are covered later in this subclause. General application considerations are given first.

The unbalance protection is normally applied to the following:

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 or failure of capacitor elements.

c) Trip the bank for unbalances that are large enough to indicate that continuing operation may result in the following:

    1) Damage to remaining healthy capacitor units or elements from overvoltage

    2) Fuse malfunction (blown fuse of healthy units/elements)

    3) Undesirable filter operation (for capacitor banks that are a part of a harmonic filter)

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).

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

- Excessive damage to the capacitor bank such as case rupture and undesirable discharge of dielectric liquid and/or fire
- Spread of damage to adjacent equipment
- Outage of the capacitor bank and loss or limited volt/var control capability

Unbalance protection systems may 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. Conventional overcurrent protection should always compliment unbalance protection systems to provide fast fault clearing for high short-circuit currents. External fusing may also be desirable to avoid major damage of 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.

Unbalance protection normally senses changes associated with capacitor element or unit failure and/or fuse operation. 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 after case rupture.

8.2 Theory of unbalance protection methods

Unbalance protection methods detect problems with capacitor units using the presumed symmetry in the impedances of the protected bank. In other words, to provide increased sensitivity, they are based on the known relationships among the many possible current or voltage measurements taken around the bank. Instead of monitoring the impedance directly, these methods respond to unbalances in the measured signals caused by the changes in the impedances.

This subclause derives and explains the basic unbalance protection methods to demonstrate their applicability to various bank configurations, limitations, and susceptibility to transients. Standing unbalance signals due to capacitor tolerances, temperature drifts, and instrumentation errors are discussed, and the methods of eliminating or reducing the standing unbalance are outlined.

The following unbalance protection methods are described:

- Phase voltage differential
- Neutral voltage unbalance
- Unbalance method for banks grounded through a neutral capacitor
- Unbalance method for banks grounded through a CT with a resistive burden
- Phase current unbalance
- Neutral current unbalance

This subclause is focused on the protection principles rather than on the applications. All voltage and currents are assumed primary values, and all impedances are physical (primary) values. The selection of voltage and current transformers, compensation for various ratios of the instrument transformers, and other practical issues related to instrumentation or relay design are not discussed.

8.2.1 Phase voltage differential method

Consider a capacitor bank in Figure 9. It is assumed that a tap voltage measurement is provided to facilitate a voltage divider principle as the basis for this unbalance protection method.

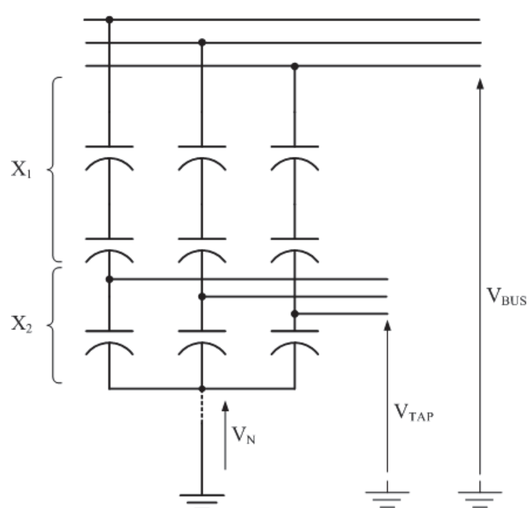


Figure 9—Derivation of the phase voltage differential unbalance protection method

The following relations in Equation (2) hold true for each phase of the bank:

$$\frac{V_{\mathrm{TAP}} - V_N}{V_{\mathrm{BUS}} - V_N} = \frac{X_2}{X_1 + X_2} \tag{2}$$

where

X_1 and X_2	are the capacitive reactance values above and below the tap point in the same phase
V_{TAP} and V_{BUS}	are the voltages corresponding to the same phase
V_{TAP}, V_{BUS}, and V_N	are the fundamental frequency phasors

For solidly grounded banks, $V_N = 0$, and therefore, as in Equation (3):

$$\frac{V_{\mathrm{TAP}}}{V_{\mathrm{BUS}}} = \frac{X_2}{X_1 + X_2} \tag{3}$$

Let us introduce the constant k as follows:

$$k = \frac{X_2}{X_1 + X_2}$$

The balance Equation (2) and Equation (3) can be rewritten as in Equation (4):

$$V_{\mathrm{TAP}} - k \times V_{\mathrm{BUS}} = 0 \tag{4}$$

The above signal stays zero as long as the bank does not change and holds the original value of k.

A protection operating signal can now be defined as in Equation (5):

$$V_{\mathrm{OP}} = \left| V_{\mathrm{TAP}} - k \times V_{\mathrm{BUS}} \right| \tag{5}$$

where | | stands for the magnitude of the signal, typically including some amount of filtering as per design of a given relay that implements the method.

Equation (5) constitutes a voltage differential function because it responds to a vectorial difference of two voltages. The same result is obtained for a grounded bank even if a difference in magnitude of two components V_{TAP} and $k \times V_{\mathrm{BUS}}$ is calculated because the voltage across the capacitor is due to the same current flowing through the bank. Known methods can be applied to balance the sensitivity and the security of this protection function. In addition to a pickup threshold, a definite or inverse-time delay can be used, or a form of restraint as a countermeasure to errors in the two involved voltages.

The k-value is a relay setting selected to zero-out the operating signal under normal capacitor bank conditions. This can be done based on the nameplate data or measurements of the bank impedances while following Equation (3).

Alternatively, the k-value can be set using actual measurements performed by the relay itself, typically during commissioning of the bank protection system. The latter alternative is known as self-setting or k-setting and stems from Equation (5). The k-value set automatically based on the actual measurements is as in Equation (6):

$$k_{\mathrm{SET}} = \left| \frac{V_{\mathrm{TAP}}}{V_{\mathrm{BUS}}} \right| \tag{6}$$

Often, protective relays supporting the concept of self-setting perform a series of measurements based on Equation (6), average the results, check for consistency, and require the commissioning engineer to approve the derived k-value. In the case of the phase voltage differential function, per-phase k-values are used.

When the protected bank experiences a failure or drifts out of tolerance, due to temperature, for example, the actual value of the k factor (k_{ACT}) is different compared with the set value (k_{SET}). From Equation (4), we obtain Equation (7):

$$V_{\mathrm{TAP}} = k_{\mathrm{ACT}} \times V_{\mathrm{BUS}} \tag{7}$$

Inserting Equation (7) into Equation (5) gives the value of the operating signal resulting from bank failures, imprecise setting, or impedance drifts, as in Equation (8):

$$V_{\mathrm{OP}} = \left|k_{\mathrm{ACT}} - k_{\mathrm{SET}}\right| \times \left|V_{\mathrm{BUS}}\right| \tag{8}$$

In other words, the voltage differential function responds to the unbalance that is proportional to the difference between the actual and set values of the k factor, and the voltage applied to the bank. Equation (8) allows analyzing both the sensitivity of the function and its security under measurement errors or impedance drifts.

Equation (8) yields an extra protection function. By analyzing the vectorial position of the operating signal with respect to the bus voltage (in-phase or out-of-phase), the relay can detect whether the k-value increased or decreased as a result of the bank failure and determine whether the failure occurred above or below the tap point. In addition, the voltage differential function is a per-phase function and can pinpoint the affected phase. This rudimentary, yet effective, fault location can speed up troubleshooting and repairs of the bank.

The phase voltage differential method can be applied to ungrounded banks or banks grounded via impedance, using the following operating signal in Equation (9) derived from Equation (2):

$$V_{\mathrm{OP}} = \left|\left(V_{\mathrm{TAP}} - V_N\right) - k \times \left(V_{\mathrm{BUS}} - V_N\right)\right| \tag{9}$$

This can be also written as in Equation (10):

$$V_{\mathrm{OP}} = \left|V_{\mathrm{TAP}} - k \times V_{\mathrm{BUS}} - (1-k) \times V_N\right| \tag{10}$$

In other words, ungrounded banks require the voltage differential method to measure the neutral point voltage and apply it in the operating signal with the factor of $(1 – k)$ to correct for it.

Note that the operating principle of the phase voltage differential is of a differential kind, meaning two voltages are compared with a scaling factor being a real number (imag(k) = 0). This means that the voltage differential unbalance method is not susceptible to transients and high-frequency components—these components appear in both of the compared voltages and cancel mutually as long as the two voltages are measured by instrument transformers having similar frequency characteristics and are filtered by the relay using similar filters.

Also note that this method does not make any assumptions as to the internal connections of the impedances constituting the bank phases. Therefore, it applies to both the wye- and H-connected bank configurations.

This subclause presented the typical scenario with the tap and bus voltages compared through the voltage divider principle. Other variants are possible, such as comparing two tap voltages of two banks connected to the same bus voltage.

8.2.2 Neutral voltage unbalance protection method

Consider an ungrounded capacitor bank as shown in Figure 10.

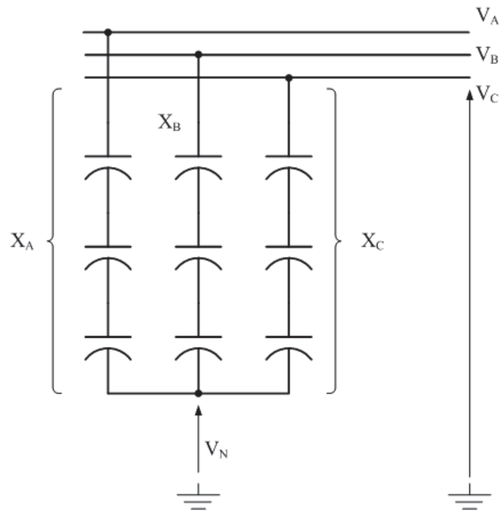


Figure 10—Derivation of the neutral voltage unbalance protection method

The following relation in Equation (11) holds true as long as the bank is ungrounded:

$$I_A + I_B + I_C = 0 \tag{11}$$

The phase currents can be expressed as follows in Equation (12):

$$I_A = \frac{V_A - V_N}{-j \times X_A}\,,\ I_B = \frac{V_B - V_N}{-j \times X_B}\,,\ I_C = \frac{V_C - V_N}{-j \times X_C} \tag{12}$$

Inserting Equation (12) into Equation (11) yields Equation (13):

$$\frac{V_A}{X_A} + \frac{V_B}{X_B} + \frac{V_C}{X_C} - V_N \times \left(\frac{1}{X_A} + \frac{1}{X_B} + \frac{1}{X_C} \right) = 0 \tag{13}$$

When the bank is perfectly balanced, the three phase impedances are equal, and Equation (13) simplifies to Equation (14):

$$3 \times V_0 - 3 \times V_N = 0 \tag{14}$$

Thus, the zero-sequence voltage at the bus equals the neutral-point voltage of the symmetrical bank. This simply reflects two alternative ways of deriving the zero-sequence voltage: by summing the three bus voltages and by measuring the neutral point voltage of a symmetrical wye-connected load.

Equation (14) can now be the base for the neutral voltage unbalance protection method as in Equation (15):

$$V_{\mathrm{OP}} = \left| 3 \times V_0 - 3 \times V_N \right| \tag{15}$$

Strictly speaking, Equation (15) represents a voltage differential principle between two voltages inputs ($3V_N$ from the neutral voltage transformer and $3V_0$ from the broken-delta busbar voltage transformer) or four voltages (V_N, V_A, V_B, and V_C, if the bus zero-sequence is derived internally in the relay by adding the three phase voltages). The neutral voltage unbalance method, being truly a differential principle, is also not susceptible to transients and high-frequency components. These components appear in all the compared voltages and cancel mutually as long as the instrument transformers used have similar frequency characteristics and the relay uses similar filters to treat all the involved voltage signals.

Known methods can be applied to balance the sensitivity and security of the protection function [Equation (15)]. In addition to a pickup threshold, a definite or inverse-time delay can be used, or a form of restraint as a countermeasure to errors in the involved voltages.

Often, the $3V_0$ signal is understood as correction to a simple neutral overvoltage protection responding to V_N. During system faults with ground, both $3V_0$ and $3V_N$ increase in the same proportion, resulting in a low operating signal V_{OP} and therefore allowing for better sensitivity without the need for time coordination.

Equation (15) yields an extra protection function. By analyzing the vector position of the operating signal with respect to the bus voltage, and knowing whether the units fail short (bank without fuses) or open (bank with fuses), the relay can determine in which phase the unit failure occurred. This rudimentary, yet effective, fault location speeds up troubleshooting and repairs of the bank.

Note that the operating principle [Equation (15)] assumes a perfectly balanced bank. An inherent bank unbalance will cause a standing operating signal limiting sensitivity of the neutral voltage unbalance function. A more accurate equation can be derived from [Equation (13)] as follows in Equation (16):

$$\frac{V_A}{X_A}+\frac{V_B}{X_A}-\frac{V_B}{X_A}+\frac{V_B}{X_B}+\frac{V_C}{X_A}-\frac{V_C}{X_A}+\frac{V_C}{X_C}-V_N\times\left(\frac{1}{X_A}+\frac{1}{X_B}+\frac{1}{X_C}\right)=0 \tag{16}$$

Multiplying by X_A and grouping the terms to lead to $3V_0$ and $3V_N$ yields Equation (17):

$$V_A+V_B+V_C+V_B\times\left(\frac{X_A}{X_B}-1\right)+V_C\times\left(\frac{X_A}{X_C}-1\right)-V_N\times\left(3+\frac{X_A}{X_B}-1+\frac{X_A}{X_C}-1\right)=0 \tag{17}$$

Equation (17) allows for following the expected equation with the extra terms signifying the standing unbalance signal, as in Equation (18):

$$3\times V_0-3\times V_N+V_B\times\left(\frac{X_A}{X_B}-1\right)+V_C\times\left(\frac{X_A}{X_C}-1\right)-V_N\times\left(\frac{X_A}{X_B}-1+\frac{X_A}{X_C}-1\right)=0 \tag{18}$$

Now, the operating signal of the neutral voltage unbalance method compensated for inherent bank unbalance can be written as in Equation (19):

$$V_{\mathrm{OP}}=\left|3\times V_0-3\times V_N+V_{\mathrm{UNB}}\right| \tag{19}$$

Where the standing unbalance component is, as in Equation (20):

$$V_{\mathrm{UNB}}=V_B\times\left(\frac{X_A}{X_B}-1\right)+V_C\times\left(\frac{X_A}{X_C}-1\right)-V_N\times\left(\frac{X_A}{X_B}-1+\frac{X_A}{X_C}-1\right) \tag{20}$$

Introducing two k factors to describe the inherent bank unbalance, we obtain Equation (21) and Equation (22):

$$k_{AB}=\frac{X_A}{X_B}-1 \text{ and } k_{AC}=\frac{X_A}{X_C}-1 \tag{21}$$

$$V_{\mathrm{UNB}}=k_{AB}\times\left(V_B-V_N\right)+k_{AC}\times\left(V_C-V_{\mathrm{N}}\right) \tag{22}$$

For balanced banks, the k-values [Equation (21)] are zeros, and the standing unbalance signal is zero as well. In such circumstances, the more general Equation (19) simplifies to Equation (15).

Equation (21) and Equation (2) allow analyzing both the sensitivity of the function and its security under measurement errors or temperature drifts.

Note that the concept of self-setting of the k-values still applies. The k-values are selected to null out the standing unbalance. The phasor equation for the standing unbalance is as follows in Equation (23):

$$V_{\mathrm{UNB}} = k_{AB} \times (V_B - V_N) + k_{AC} \times (V_C - V_N) = 0 \tag{23}$$

is a set of two equations (real and imaginary parts) that can be solved for the two unknowns k_{AB} and k_{AC}.

Compensation for the inherent bank unbalance can be performed using Equation (23) or using the memorized (M) value of the standing unbalance as follows in Equation (24):

$$V_{\mathrm{UNB}} = V_{\mathrm{UNB}(M)} \times \frac{V_1}{V_{1(M)}} \tag{24}$$

where V_1 stands for positive-sequence bus voltage.

In other words, when capturing the unbalance signal as a standing value of the operating quantity V_{OP}, the positive-sequence voltage is captured as well. When using it for compensation, the relay applies the positive-sequence voltage at the time to account for changes in the bus voltages between the moment of compensation and the historical moment of capturing the inherent unbalance value.

Note that the neutral voltage unbalance method does not make any assumptions as to the internal connections of the impedances constituting the bank. Therefore, it applies to both the wye- and H-connected configurations as long as the bank is ungrounded.

8.2.3 Unbalance protection for banks grounded through a capacitor

Consider a bank as in Figure 11.

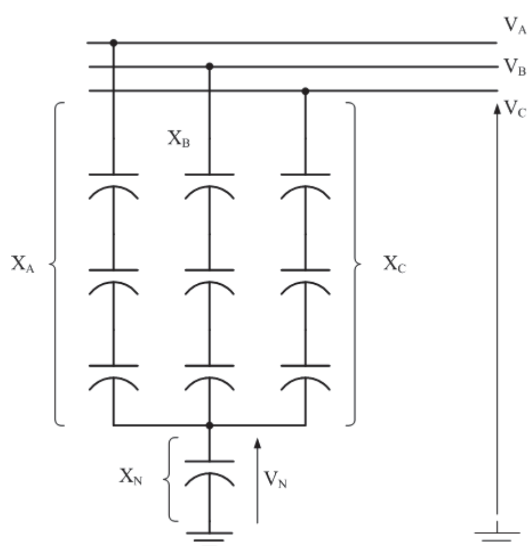


Figure 11—Unbalance protection of a bank grounded via capacitor

If the grounding impedance is relatively low, then this configuration can be protected with the phase voltage differential method. In this approach, either the neutral-point voltage is measured by the relay, and used as shown in Equation (25), or the voltage is neglected resulting in the reduced sensitivity to maintain security of the function.

If the grounding impedance is relatively high, then this configuration can be protected using a modified neutral voltage unbalance method. Equation (25) holds true for the bank of Figure 11:

$$\left(\frac{V_A - V_N}{-j \cdot X_A} + \frac{V_B - V_N}{-j \cdot X_B} + \frac{V_C - V_N}{-j \cdot X_C}\right) \times \left(-j \times X_B\right) = V_N \tag{25}$$

By performing similar mathematical manipulations as for the neutral voltage unbalance method, we obtain the following balance equation in Equation (26):

$$3 \times V_0 - \left(3 + \frac{X_A}{X_N}\right) \times V_N + k_{AB} \times \left(V_B - V_N\right) + k_{AC} \times \left(V_C - V_N\right) = 0 \tag{26}$$

which allows for creating the following protection function in Equation (27):

$$V_{\mathrm{OP}} = \left| 3 \times V_0 - \left(3 + \frac{X_A}{X_N}\right) \times V_N + k_{AB} \times \left(V_B - V_N\right) + k_{AC} \times \left(V_C - V_N\right) \right| \tag{27}$$

The operating signal in Equation (27) is similar to the neutral voltage unbalance method for ungrounded banks. The last two terms compensate for the inherent bank unbalance. The second term includes the ratio of the phase and neutral impedances in addition to the multiplier of 3 of the traditional neutral voltage unbalance method. Neglecting the inherent unbalance, one may apply the following protection principle in Equation (28):

$$V_{\mathrm{OP}} = \left| 3 \times V_0 - \left(3 + \frac{X_A}{X_N}\right) \times V_N \right| \tag{28}$$

which can be implemented using a neutral voltage unbalance relay capable of ratio compensation, so that the X_A/X_N value is taken into account.

Note that if the bank of Figure 11 is ungrounded ($X_N \to \infty$), Equation (27) reduces to Equation (14) and this approach can therefore be considered a more general version of the neutral voltage unbalance method.

8.2.4 Unbalance protection method for bank grounded through a CT with resistive burden

Consider a capacitor bank as in Figure 12.

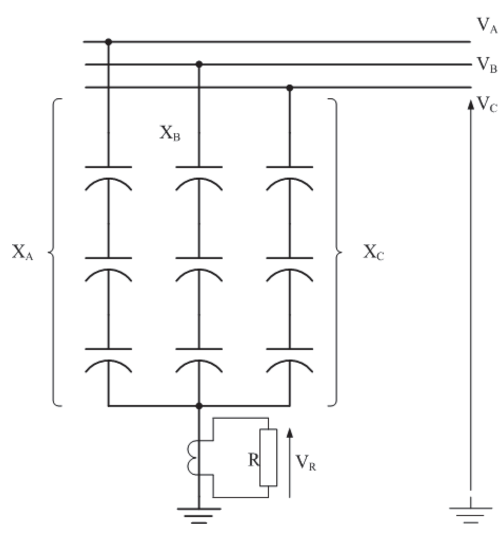


Figure 12—Unbalance protection of a bank grounded via CT with a resistive burden

Assuming for simplicity the CT ratio to be 1:1, the following balance equation in Equation (29) holds true (in actual installations, one needs to factor the CT ratio):

$$\left(\frac{V_A}{-j \cdot X_A} + \frac{V_B}{-j \cdot X_B} + \frac{V_C}{-j \cdot X_C}\right) \times R = V_R \tag{29}$$

Assuming the bank to be perfectly balanced, we can simplify Equation (29) as follows in Equation (30):

$$V_A + V_B + V_C + j \times \frac{X}{R} \times V_R = 0 \tag{30}$$

Or further in Equation (31):

$$3 \times V_0 + j \times \frac{X}{R} \times V_R = 0 \tag{31}$$

As Equation (31) balances the neutral voltage at the bus with a voltage associated with the bank neutral, this method is sometimes referred to as the neutral voltage unbalance method. Indeed, the method can be implemented using a neutral voltage unbalance relay capable of ratio compensation, so that the *X*/*R* value is taken into account. However, the relay requires also shifting one of the two compared voltages by 90° [the "*j*" value in Equation (31)].

The operating signal of this unbalance protection method is based on Equation (32):

$$V_{\mathrm{OP}} = \left|3 \times V_0 + j \times \frac{X}{R} \times V_R\right| \tag{32}$$

Known methods can be applied to balance the sensitivity and security of the protection function. In addition to a pickup threshold, a definite or inverse-time delay can be used, or a form of restraint as a countermeasure to errors in the involved voltages.

It is to be noted that unlike the previously derived methods, this method is not truly a differential method. One of the two voltages compared needs to be shifted by 90°, which means the balance holds true for fundamental frequency phasors only. Transients in the measured signals will not necessarily mutually cancel, calling for very strict filtering of the two voltages before using them in the operating equation in Equation (32).

The protection method defined by Equation (31) is related more to monitoring the apparent zero-sequence impedance of the bank than to the true neutral voltage differential principle (the actual neutral point voltage is zero in this case, and as such, it cannot be balanced against any other signal to detect bank failures). To understand better, assume a simple pickup is used to actuate the protection function, as in Equation (33):

$$\left|3 \times V_0 + j \times \frac{X}{R} \times V_R\right| > V_{\mathrm{PKP}} \tag{33}$$

Equation (33) can be rewritten as follows in Equation (34):

$$\left|3 \times V_0 + j \times X \times \frac{V_R}{R}\right| > V_{\mathrm{PKP}} \tag{34}$$

And further in Equation (35):

$$\left|3 \times V_0 + j \times X \times 3 \times I_0\right| > V_{\mathrm{PKP}} \tag{35}$$

Or in Equation (36):

$$\left|\frac{V_0}{I_0} + j \times X\right| > \frac{V_{\mathrm{PKP}}}{3 \times |I_0|} \tag{36}$$

And further in Equation (37):

$$\left|Z_0 - (-j \times X)\right| > \frac{V_{\mathrm{PKP}}}{3 \times |I_0|} \tag{37}$$

Z_0 is the apparent zero-sequence impedance of the bank; $-jX$ is the expected value of the zero-sequence impedance of the bank; the left-hand side of Equation (37) defines a circle around the expected value of the bank impedance; and the right-hand side of Equation (37) defines the radius of the circular pickup characteristic (Figure 13). This radius is current dependent—smaller if a large zero-sequence current is present, and larger if a small zero-sequence current is present. That dependence on the level of the zero-sequence current has a positive impact on the security and sensitivity of this unbalance protection function.

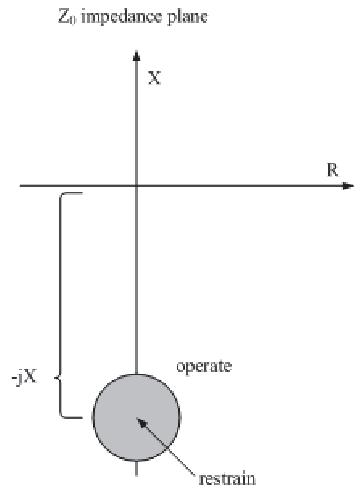


Figure 13 —Effective operating region of the unbalance protection method using voltage across the resistor in the grounding CT

As shown by Equation (37), however, the method effectively responds to the apparent zero-sequence impedance of the bank using a circular (mho) characteristic with the center at $-jX$, and a current-dependent radius.

Referring to the original Equation (32) and examining the impact of the inherent bank unbalance, the operating voltage can be obtained by rearranging the terms as was done for the neutral voltage unbalance method in Equation (38):

$$V_{\mathrm{OP}} = \left|3 \times V_0 + j \times \frac{X_A}{R} \times V_R + V_{\mathrm{UNB}}\right| \tag{38}$$

where in Equation (39):

$$V_{\mathrm{UNB}} = k_{AB} \times V_B + k_{AC} \times V_C \tag{39}$$

Compensation for the inherent bank unbalance can be performed using Equation (39), or using the memorized value of the standing unbalance as follows in Equation (40):

$$V_{\mathrm{UNB}} = V_{\mathrm{UNB}(M)} \times \frac{V_1}{V_{1(M)}} \tag{40}$$

Note that this method does not make any assumptions as to the internal connections of the impedances constituting the bank phases. Therefore, it applies to both the wye- and H-connected configurations as long as the neutral point is solidly grounded.

8.2.5 Phase current unbalance protection method

Consider a capacitor bank as shown in Figure 14 with each phase comprising two parallel impedances. The double bank can be grounded or ungrounded. This applies to a single bank with two strings per phase or to a double bank with a single string per phase in each bank.

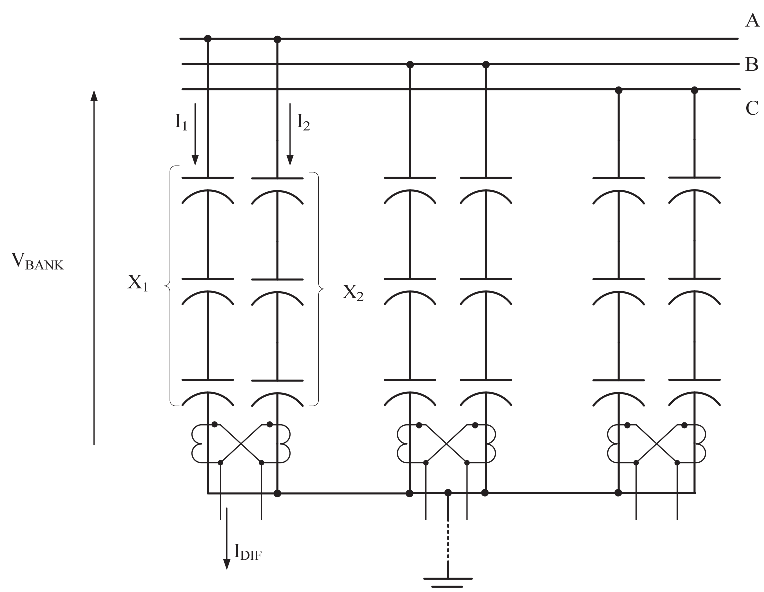


Figure 14—Derivation of the phase current unbalance protection method

A common voltage is applied across the two impedances, and therefore, the following holds true for each phase of the bank in Equation (41):

$$I_1 = \frac{V_{\mathrm{BANK}}}{-j \times X_1} \quad \text{and} \quad I_2 = \frac{V_{\mathrm{BANK}}}{-j \times X_2} \tag{41}$$

The phase current unbalance method responds to the vectorial difference between the two currents, as follows in Equation (42):

$$I_{\mathrm{DIF}} = \frac{V_{\mathrm{BANK}}}{-j \times X_1} - \frac{V_{\mathrm{BANK}}}{-j \times X_2} \tag{42}$$

Note that the total phase current drawn by the bank in the considered phase is as follows in Equation (43):

$$I_{\mathrm{BANK}} = \frac{V_{\mathrm{BANK}}}{-j \times X_1} - \frac{V_{\mathrm{BANK}}}{-j \times X_2} \tag{43}$$

Using Equation (43) to calculate the bank voltage and substituting the bank voltage in Equation (42) yields Equation (44):

$$I_{\mathrm{DIF}} = I_{\mathrm{BANK}} \times \left(\frac{X_2 - X_1}{X_2 + X_1}\right) \tag{44}$$

When the two banks are perfectly matched ($X_1 = X_2$), the differential current is zero. When there is an inherent unbalance between the banks or when the failure occurs, the differential current reflects the amount of unbalance.

The *k*-value is defined as in Equation (45):

$$k_1 = \frac{X_2 - X_1}{X_2 + X_1} \tag{45}$$

The operating signal of the phase unbalance method compensated for the inherent unbalance is as in Equation (46):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIF}} - k_1 \times I_{\mathrm{BANK}} \right| \tag{46}$$

If the method is not compensated for the inherent unbalance (the *k*-value assumed to be zero), then the relay simply responds to the following measured differential current in Equation (47):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIF}} \right| \tag{47}$$

Note that the operating principle as defined in Equation (46) is of a differential kind, meaning two currents are compared with a scaling factor being a real number (imag(k_1) = 0). This means that the phase current unbalance method is not susceptible to transients and high-frequency components—these components appear in both of the compared currents and cancel mutually. In contrast, the uncompensated principle of Equation (46) responding to the differential current is susceptible to elevated current reading during transients.

The concept of self-setting can be applied to this protection method using Equation (48):

$$k_{1\mathrm{SET}} = \frac{\left| I_{\mathrm{DIF}} \right|}{\left| I_{\mathrm{BANK}} \right|} \tag{48}$$

Implementation of Equation (48) requires measuring the total bank current. More often, the bus voltage is available to the relay. For grounded banks, a fixed relationship exists between the phase voltage and the phase current. Therefore, the following implementation is feasible for the phase current unbalance method, compensated for the inherent unbalance, as in Equation (49):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIF}} - j \times k_V \times V_{\mathrm{BUS}} \right| \tag{49}$$

Equation (49) can be followed directly, or the alternative method can be used as explained earlier, in Equation (50) and Equation (51):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIF}} - I_{\mathrm{UNB}} \right| \tag{50}$$

$$I_{\mathrm{UNB}} = I_{\mathrm{UNB}(M)} \times \frac{V_1}{V_{1(M)}} \tag{51}$$

The angle between the operating current and the phase voltage or current can be used to locate the failed unit, assuming the relay knows whether the elements fail short or open (“left” bank vs. “right” bank). In addition, the phase current unbalance method is phase segregated and naturally points to the affected phase.

8.2.6 Neutral current unbalance protection method

Consider a capacitor bank of Figure 15 with each phase comprising two parallel impedances. The bank can be grounded or ungrounded. The differential current measurement is not performed on a per-phase basis as in the phase current unbalance method but between the neutrals of the two banks.

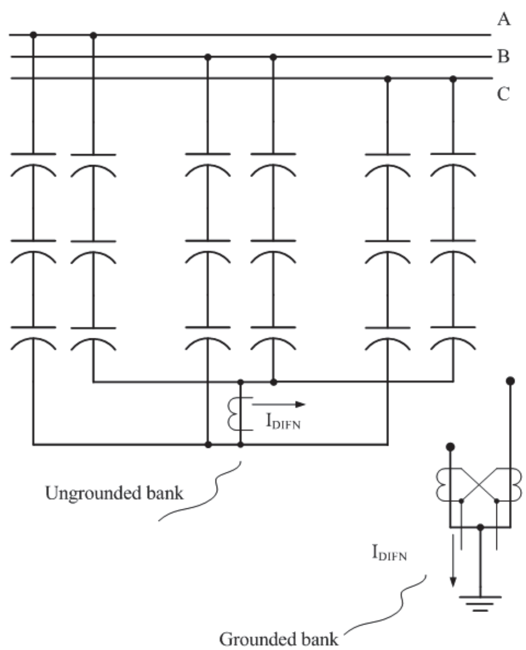


Figure 15—Derivation of the neutral current unbalance protection method

From the derivation for the phase current unbalance method, we obtain Equation (52):

$$I_{\mathrm{DIFA}} = k_A \times I_A \, , I_{\mathrm{DIFB}} = k_B \times I_B \, , I_{\mathrm{DIFC}} = k_C \times I_C \tag{52}$$

The neutral differential measurement is the sum of the phase differential signals; therefore, as in Equation (53):

$$I_{\mathrm{DIF}N} = I_{\mathrm{DIFA}} + I_{\mathrm{DIFB}} + I_{\mathrm{DIFC}} = k_A \times I_A + k_B \times I_B + k_C \times I_C \tag{53}$$

Equation (53) allows for writing the following neutral current unbalance method compensated for the inherent bank unbalance in Equation (54):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIFN}} - \left(k_A \times I_A + k_B \times I_B + k_C \times I_C \right) \right| \tag{54}$$

The uncompensated version uses just the measured neutral differential current, as in Equation (55):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIFN}} \right| \tag{55}$$

Note that the operating principle as defined by Equation (54) is of a differential kind, meaning that the involved currents are compared with scaling factors being real numbers. This means that the compensated neutral current unbalance method is not susceptible to transients and high-frequency components—these components appear in all the compared currents and cancel mutually. In contrast, the uncompensated principle as defined by Equation (55) responding to the neutral differential current is susceptible to elevated current reading during transients.

The *k*-values in Equation (54) cannot be, however, self-set by the relay. The three unknowns (k_A, k_B, and k_C) cannot be calculated from the two equations available (null out the real and imaginary parts of the standing operating signal). Some implementations work on symmetrical components rather than on phase currents and null out the standing unbalance signal caused by the positive- and negative-sequence components only, as in Equation (56):

$$I_{\mathrm{OP}} = \left| I_{\mathrm{DIFN}} - \left(k \times I_1 + k^* \times I_2 \right) \right| \tag{56}$$

where * is the complex conjugate.

Implementation of Equation (56) allows for self-setting the compensation for the positive- and negative-sequence components of the inherent unbalance, leaving the zero-sequence uncompensated. The latter may be acceptable, particularly for ungrounded banks where zero-sequence currents are not present.

The method can be compensated for the inherent unbalance using voltages instead of currents in the way explained for the phase current unbalance method.

The angle between the operating current and the phase voltage or current can be used to locate the fault assuming the relay knows whether the capacitor units fail short or open (“left” bank vs. “right” bank and the affected phase).

8.3 General unbalance relay considerations

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

8.3.1 Inherent bank unbalance, system unbalance, and other sources of error

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 errors described in the following list.

a) The primary unbalance, which exists on all capacitor bank installations (with or without fuses), is due to basically two factors: 1) system voltage unbalance and 2) bank inherent unbalance due to 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 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 the equations in 8.4 through 8.7 and Annex C. A worst-case estimate can be made by assuming the unbalance errors to be additive.

   If the unbalance error approaches 50% of the alarm setting, then compensation may be beneficial to correctly alarm for the failure of one unit or element as specified. Subclause 8.2 explains the principles of compensation. Compensation can reduce errors due to both system unbalance and bank inherent unbalance. In some cases, a different bank connection can improve the sensitivity without adding compensation.

For example, a wye bank can be split into a wye-wye bank, thereby doubling the sensitivity of the protection and greatly reducing the effect of system voltage unbalance.

b) Where unbalance due to system variations or capacitor manufacturing tolerances is not negligible, a compensating means should be provided to negate the effect of this unbalance. Careful consideration of bank design may also remedy the problem. Before attempting any compensation adjustments to reduce unbalance, the load current of each phase and the capacitance (or load current) of each capacitor should be checked for indication of failure of a single capacitor element within the capacitor unit. The unbalance relay should be set taking the total unbalance into account.

c) The influence of harmonic voltages and currents on the operation of the unbalance relay depends on the unbalance scheme used. Few schemes such as voltage differential schemes are unaffected by harmonics and transients as explained in 8.2.1. Power frequency band-pass or other appropriate filtering is needed on unbalance relaying schemes affected by harmonics.

d) Subclause 8.2.2 describes in detail compensating system voltage unbalance on single ungrounded banks. The voltage appearing at the capacitor bank neutral due to system unbalance is the zero sequence component. Bus zero-sequence voltage can be derived by the neutral voltage unbalance relay from three phase voltages or measured from three voltage-sensing devices with their high-side wye-connected from line to ground, and the secondaries connected in a broken delta. Often, the voltage transformers are already available for station relaying, with the exception of low-voltage isolation transformers to derive the broken delta. The difference voltage between the neutral unbalance signal due to system unbalance and the broken delta output of the voltage transformers is then adjusted to zero. Once this adjustment is made, the effect of system voltage unbalance will be compensated for all conditions of system unbalance. A compensating algorithm will eliminate the remaining error appearing at the neutral due to the manufacturer’s capacitor tolerance.

e) Instrument transformer errors also contribute to the unbalance signal seen by the relay. Relays providing compensation for the bank inherent unbalance will greatly reduce the unbalance signal under healthy bank conditions. Means to block unbalance relays under instrument transformer failures should be provided. Also, relays utilizing differential methods have to be blocked when one source of differential signal is not energized. For example, a voltage differential scheme using capacitor bank bus VTs and tap VTs has to be blocked when the bank is deenergized.

f) The effects of inherent bank unbalance can be greatly reduced with unbalance methods that use compensating factors as described in 8.2. These can be calculated automatically or applied manually during normal system and healthy bank conditions. Also, if the relay is provided with biasing, then it will minimize measurement errors and reduce the risk of nuisance operations, while providing sensitive unbalance protection for the capacitor bank.

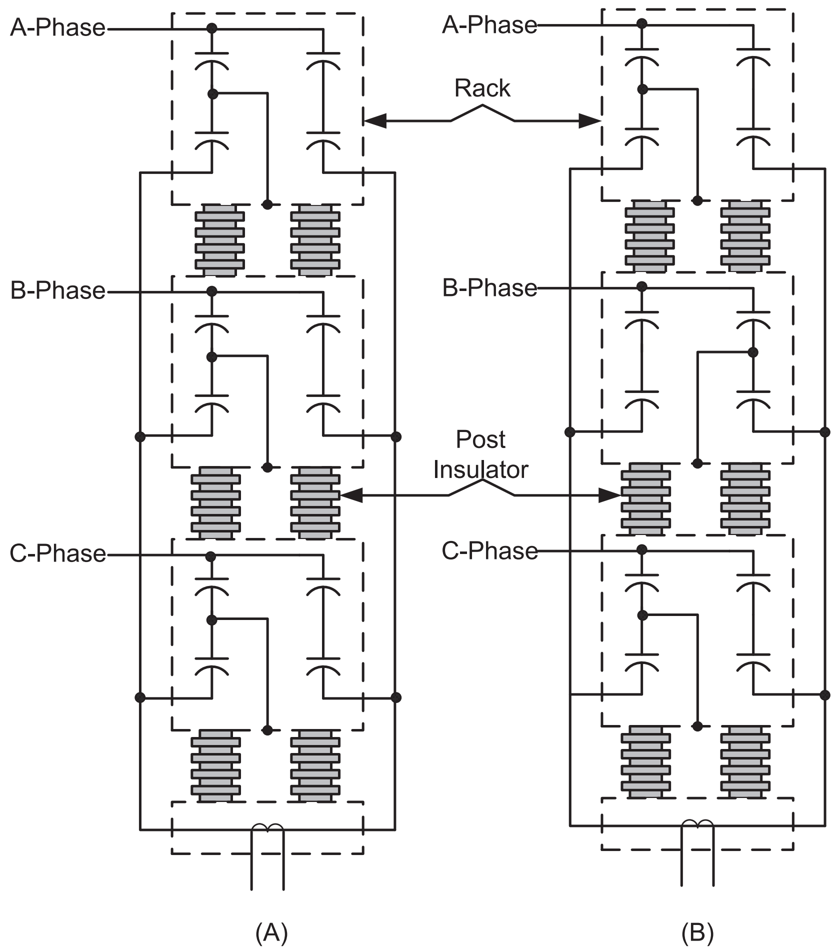
8.3.2 Undetectable failure modes

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

- Rack-to-rack faults for banks with two series groups connected phase-over-phase and using neutral voltage or current for unbalance protection methods
- 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 so that the unbalance protection will be responsive to rack-to-rack flashover. See Figure 16 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 though 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.[8]

Figure 16—Bonding of the frames of an ungrounded wye-wye bank

8.3.3 Capacitor bank failures with ambiguous indication

Ambiguous indications may come from two or more different conditions of the bank but provide the same indication. Initial failure may indicate a failure, but subsequent failures may cancel the first failure to indicate a normal state. For instance, under normal conditions with a balanced bank, negligible current may

[8] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

flow through the current transformer between the neutrals of an ungrounded wye-wye capacitor bank. 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 of such a condition 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.

The common failures with ambiguous indication are as follows:

- In wye-wye banks (Figure 17), the operation of fuses or short-circuiting of elements in one wye may cancel the unbalance signal generated in the other wye.
- In H-bridge banks (Figure 18), 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.
- In midpoint-tapped banks (Figure 19), the operation of fuses or short-circuiting of elements above the tap point may cancel the unbalance signal generated below the tap point.

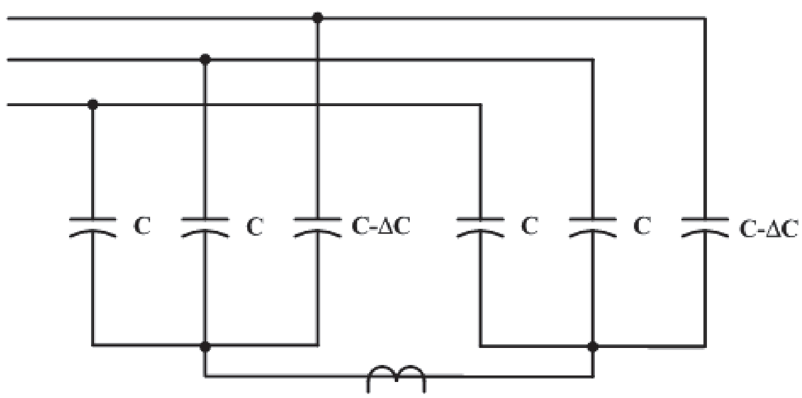


Figure 17—Wye-wye compensating failures result in no unbalance signal, even though the bank is unbalanced

When designing a capacitor bank protection scheme, it is always desirable to select alternative schemes to reduce the possibility of maloperations during canceling failures. For example, for the scheme shown in Figure 17, failure of the neutral current unbalance scheme may be backed up by application of the neutral voltage unbalance scheme as well.

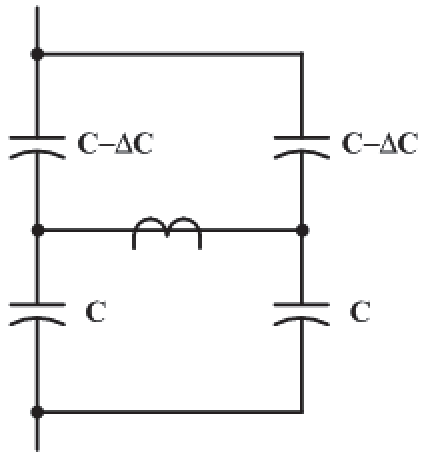


Figure 18—H bridge: Compensating failures result in no unbalance signal even though the bank may be unbalanced

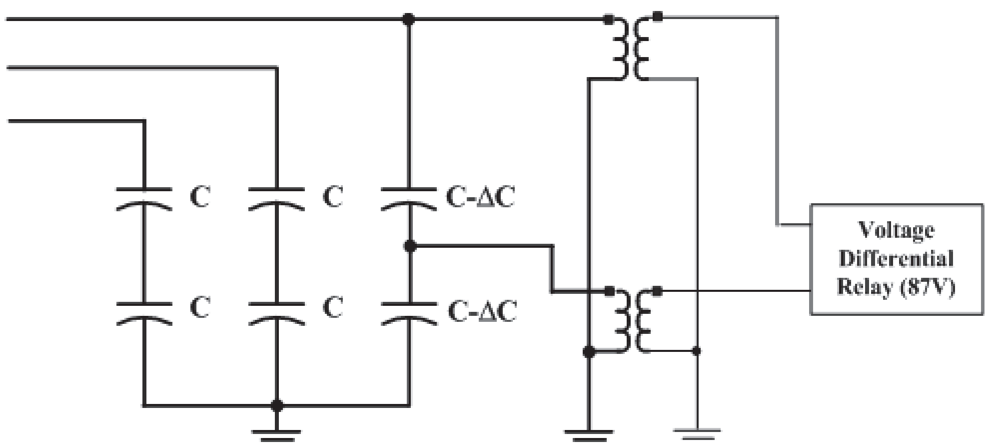


Figure 19—Midpoint taps: Compensating failures result in no unbalance signal even though the bank may be unbalanced

8.3.4 Unbalance trip relay considerations

Unbalance relay trip delay times are set based on the following considerations:

a) The unbalance trip relay time delay should be minimized to reduce damage from an arcing fault within the bank structure and prevent exposure of the remaining capacitor units to overvoltage conditions beyond their permissible limits. For a single-phase or an open-phase condition, the time delay should also be short enough to avoid damage to the current transformer or voltage transformer and to the relay system.

b) The unbalance trip relay should have enough time delay to avoid false operations due to inrush, system ground faults, switching of nearby equipment, and nonsimultaneous pole operation of the energizing switch if these affect the applied unbalance protection principle. For most applications, 0.1 s should be adequate. For unbalance relaying systems that do not compensate for system unbalance and may therefore operate on a system voltage unbalance (ground fault), time coordination with upstream protection is required to avoid tripping due to a system fault. However, longer delays increase the probability of catastrophic bank failure.

c) With grounded capacitor banks, the failure of one pole of the switching device or the single phasing from a blown bank fuse will allow zero-sequence currents to flow in system ground relays. Capacitor bank relaying, including the operating time of the switching device, should be coordinated with the operation of the system ground relays to avoid false tripping.

d) The unbalance trip relay may need to be delayed to account for the settling time of the protection system on initial energization and for the transient response of certain capacitor voltage transformers, and so on, which may be a part of the unbalance protection system.

e) The unbalance trip relay scheme can have a lockout feature to prevent inadvertent closing of the capacitor bank switching device if an unbalance trip has occurred.

f) To allow for the effects of inherent unbalance, the unbalance relay trip should be set to operate at a signal level halfway between the critical step and the next lower step. The critical step is the number of fuse operations or shorted elements that will cause an overvoltage on healthy capacitor units in excess of 110% of the capacitor unit rated voltage or the capacitor unit manufacturer's recommended maximum continuous operating voltage. In addition, for internally fused capacitor units, the critical step may be the number of internal fuse operations at which tripping should occur as recommended by the capacitor manufacturer.

g) If switch failure or single phasing due to a blown main fuse could result in continuous voltage exceeding the relay rating, operation of the lockout relay should deenergize the voltage relay. If chattering of the seal-in unit is a problem when used on ac, a lockout relay contact can bypass the voltage relay contact.

It is desirable to apply an unbalance relay with two or more sensing stages, each with individual pickup and time delay settings. This allows flexibility to set the stages with different operate times to provide better coordination for unbalances of different severity.

8.3.5 Unbalance alarm relay considerations

Ideally the alarm level should be set to detect failure of a single capacitor unit, but not to assert a nuisance alarm due to system unbalance. The unbalance signal during normal bank operation may be significant due to errors as described earlier in 8.3.1. It is a good practice to monitor the unbalance signal over a period of time and then set the alarm level accordingly. The alarm signal should have sufficient time delay to override external disturbances if they affect the applied unbalance protection principle.

8.3.6 Comments on various protection schemes

8.3.6.1 Neutral voltage unbalance protection method

Subclause 8.2 explains the fundamentals of the neutral voltage unbalance method. The neutral voltage unbalance protection method is mostly used for ungrounded banks where the voltage-sensing device is connected between the bank neutral and the ground. This method compares the zero-sequence voltage at the bus with the zero-sequence voltage at the bank neutral point. Figure 20 and Figure 21 show protection connections for a single-wye ungrounded bank.

8.3.6.1.1 Neutral voltage unbalance protection method for ungrounded wye banks

A neutral unbalance protection method with compensation for inherent unbalance is normally required for very large banks. The neutral unbalance signal due to the loss of one or two individual capacitor units may be less than the normal inherent unbalance. Unbalance compensation should be used if the inherent unbalance exceeds one half of the desired setting for detecting failure in a capacitor unit.

The voltage-sensing device may be a voltage transformer, capacitive potential device, or resistive potential device. The voltage-sensing device should be selected for the lowest voltage ratio attainable, while still being able to withstand transient and continuous overvoltage conditions to obtain the maximum unbalance detection sensitivity. However, a voltage transformer used in this application should be rated for full system voltage because the neutral voltage can under some conditions rise to as high as 2.5 per-unit during switching. Under these conditions, an underrated voltage transformer will be driven into deep saturation (Harner and Owen [B6]).

The use of an underrated resistance potential device, with secondary voltage limiter, can permit relay operation with an open phase to the capacitor bank. The resistive potential device should be capable of withstanding this overvoltage condition.

De-energized ungrounded wye capacitor banks may have voltage induced on the capacitor bank from an overhead transmission line, adjacent energized capacitor bank, or other energized object. On occasion, this has caused the unbalance relay to alarm or trip, even though the capacitor bank is not energized. To avoid this situation, it is suggested that an auxiliary contact of the capacitor switch be used to short circuit the output of the neutral to ground transformer (or in some other way disable the unbalance protection) when the switch is in the open position.

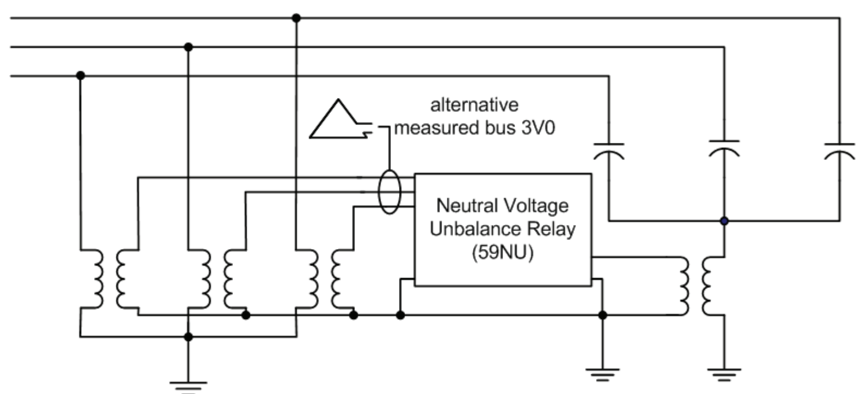


Figure 20 —Neutral voltage unbalance protection basic method for single-wye ungrounded bank

Figure 21(a) shows a variation of the neutral unbalance relay protection scheme for an ungrounded wye capacitor bank using three line-to-neutral voltage transformers with their secondaries connected in broken delta and then connected to an overvoltage relay. Compared to the scheme in Figure 21(b), this scheme has the advantage of not being sensitive to system voltage unbalance. Also, the unbalance voltage to the overvoltage relay is three times the neutral shift voltage as obtained from Figure 21(b). For the same voltage transformer ratio, there is a gain of three in sensitivity over the single neutral-to-ground voltage transformer scheme. The voltage transformers should be rated for line-to-line voltage.

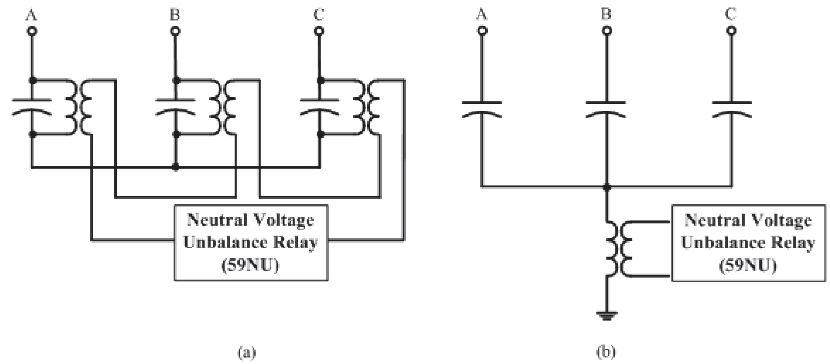


Figure 21—Voltage unbalance measurements variants

However, both schemes shown in Figure 21 do not take into account bank inherent unbalance, and the additional scheme shown in Figure 21(a) does not compensate for system unbalance. Both of these disadvantages are accounted for in the scheme shown in Figure 20.

8.3.6.1.2 Neutral voltage unbalance protection method for grounded wye banks

The protection is based on a voltage measurement derived from a current transformer connected between the capacitor bank neutral and the ground. The current transformer output can be put through a burden resistor. A sensitive voltage relay with a fundamental band-pass filter should be used for the unbalance protection.

The current transformer with a wound primary used in this application has unusual overvoltage and current requirements (Harder [B5]) (10.5 and 10.6). Single-turn CTs of 600 V ratings have been used in the industry. The ratio is selected to give both adequate overcurrent capability and appropriate signal for protection.

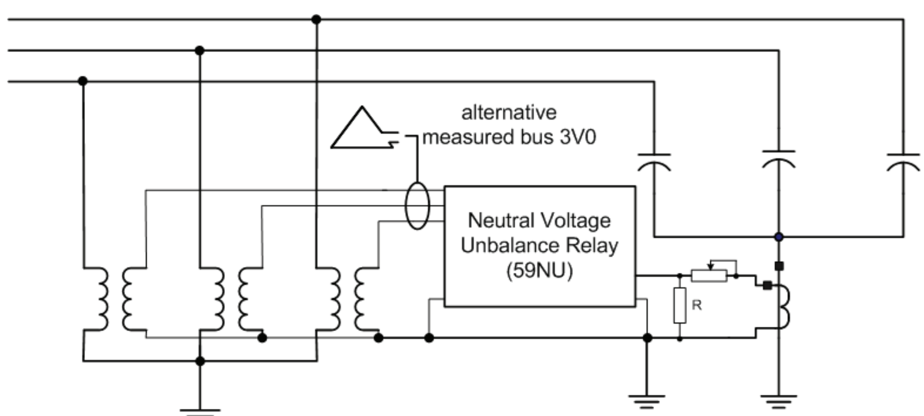


Figure 22—Neutral voltage unbalance protection method for grounded single-wye bank

The neutral voltage unbalance relay shown in Figure 22 could be a voltage relay connected across the neutral CT with the resistor as is the case in small, grounded wye capacitor banks.

Because of the presence of harmonic currents (particularly the third, a zero-sequence harmonic that flows in the neutral-to-ground connection), the relay should be tuned to reduce its sensitivity to frequencies other than the power frequency.

The voltage across the burden resistor is in phase with the neutral-to-ground current. This neutral-to-ground current is the vector sum of the three phase currents, which are 90° out of phase with the system phase-to ground voltages. This scheme may be compensated for power system voltage unbalances, by accounting for the 90° phase shift, and is not usually appropriate for very large capacitor banks requiring very sensitive settings. This 90° phase shift may be accounted for internally using relays supporting this application or compensated externally using appropriate phase-shifting components and techniques. The value of the resistor R should be chosen such as the voltage measured at the bank neutral point input of the relay matches bus 3V0 during system unbalance.

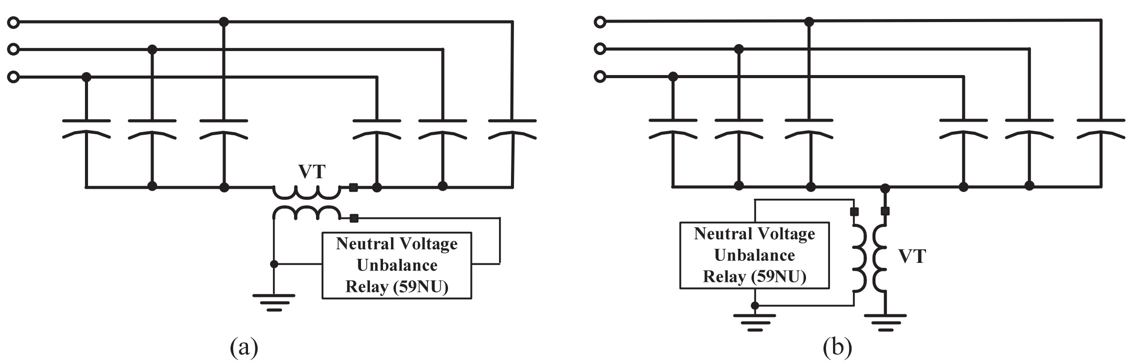
In some designs, the voltage relay operates a latching or lockout relay to initiate the opening of the capacitor switch and to block its closing. Contacts of the lockout relay should also short out the neutral current transformer secondary.

8.3.6.1.3 Neutral voltage unbalance protection method for ungrounded double-wye banks

Ungrounded double-wye banks, as shown in Figure 23, can be protected using the neutral voltage unbalance method. This method is not sensitive to system voltage unbalance or third harmonic components. Protective relays designed to compensate for inherent unbalance of the bank will achieve greater sensitivity.

The neutral voltage value can be determined in the same manner used for a single-wye bank as one section of the double-wye bank. Protection scheme connection is as shown in Figure 23(a). Although a low-ratio voltage transformer would be desirable, a voltage transformer rated for system voltage is required for the ungrounded neutral. The resulting unbalance signal voltage may be very small.

Both schemes in Figure 23 do not compensate for bank inherent unbalance and may not provide sufficient sensitivity to protect individual capacitor units.



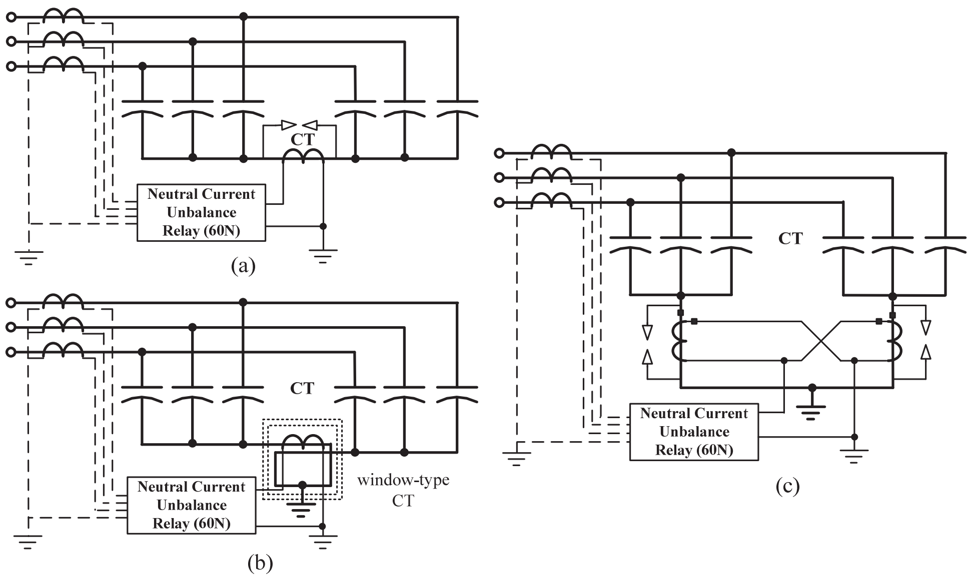
(a) - neutral voltage unbalance protection method, ungrounded double wye-connected capacitor bank (neutrals isolated)
(b) - neutral voltage unbalance protection method, ungrounded double wye-connected capacitor bank (neutrals tied together)

Figure 23—Neutral voltage unbalance protection methods for double-wye banks

In scheme (b) in Figure 23, the neutrals of the two capacitor sections are connected to a voltage transformer. The voltage transformer, or potential device, is used to measure the voltage (shift) between the capacitor bank neutral and the ground. The relay should preferably have a harmonic filter and respond only to the fundamental.

8.3.6.2 Neutral current unbalance protection method for double-wye banks

The neutral current unbalance method responds to the current circulating between the connected neutrals of two parallel banks. It is used for both grounded and ungrounded banks. If the banks are not perfectly balanced, then the circulating current is not zero, which degrades the sensitivity of protection. Therefore, relays providing compensation for bank inherent unbalance facilitate more sensitive and reliable protection. In Figure 24, basic schemes for both grounded and ungrounded banks are shown. All schemes respond to a differential current. This is the vector difference of the neutral currents flowing in the paralleled banks. The scheme in Figure 24(a) is for an ungrounded wye bank, while the schemes in Figure 24(b) and Figure 24(c) are for grounded banks. To compensate for unwanted circulating zero sequence current caused by capacitor unit differences, the total bank zero sequence current can be measured. The dashed lines in Figure 24 show this input. This additional compensation allows for more sensitive relay settings.



(a) - neutral current unbalance protection method for ungrounded double wye-connected capacitor bank

(b) - neutral current unbalance protection method for grounded double wye-connected capacitor bank using window-type CT

(c) - neutral current unbalance protection method for grounded double wye-connected capacitor bank using differential connection of CTs

Figure 24—Neutral current unbalance protection methods on double-wye banks

The neutral current is one half that of a single grounded bank of the same size. However, the current transformer ratio and relay rating may be selected for the desired sensitivity because they are not subjected to switching surge currents or single-phase load currents as they are with the grounded neutral scheme.

In scheme (c) in Figure 24 (for grounded-wye banks), the neutrals of the two sections are grounded through separate current transformers to a common ground. The current transformer secondaries are cross connected to a neutral current unbalance relay so that the relay is insensitive to any outside condition that affects both sections of the capacitor bank in the same manner. The current transformers can be subjected to switching transient currents and, therefore, require surge protection. They should be sized for single-phase load currents if possible. Alternatively, the connections from neutral to ground from the two wyes may be in opposite directions through a single-window current transformer as shown in scheme (b) in Figure 24.

8.3.6.3 Voltage differential protection method for grounded-wye banks

Voltage differential protection methods for grounded-wye capacitor banks are illustrated in Figure 25(a) for a single wye-connected bank and in Figure 25(b) for a double wye-connected bank. This approach is, in essence, three separate single-phase voltage differential relays monitoring each phase of the capacitor bank.

A signal responsive to the loss of individual capacitor elements or units is derived by comparing the capacitor bank tap voltage with the bus voltage. The capacitor bank tap voltage is obtained by connecting a voltage-sensing device across the ground end parallel group (or groups) of capacitors as in the case of fused capacitor banks. This may be a midpoint tap, where the voltage is measured between the midpoint of the phase and ground. Alternatively, the tap voltage may be measured across low-voltage capacitors (that is, a capacitive shunt) at the neutral end of the phase as in the case of a fuseless capacitor bank. The bus voltage is usually available. Tapping across the bottom series groups or a midpoint tap is not possible for fuseless banks with multiple strings because the strings are not connected to each other at the tap point. Tapping across the low-voltage capacitors is suitable for fuseless capacitor banks.

After checking that all capacitors are good and no fuses have operated in the externally fused bank, the voltage levels are initially adjusted to be equal. The initial difference signal between the capacitor bank tap voltage and the bus voltage signals is zero, and the capacitor tolerance and initial system voltage unbalance is compensated. If the system voltage unbalance should vary, then the relay system is still compensated because a given percentage change in bus voltage results in the same percentage change on the capacitor bank tap. Any subsequent voltage difference between capacitor tap voltage and bus voltage will be due to unbalances caused by loss of capacitor units within that particular phase. Secondary errors may be introduced by sensing device variation and temperature differences between capacitor units within the bank. Loss of capacitor units in each phase is detected independently (Alexander [B2] and Tom [B13]).

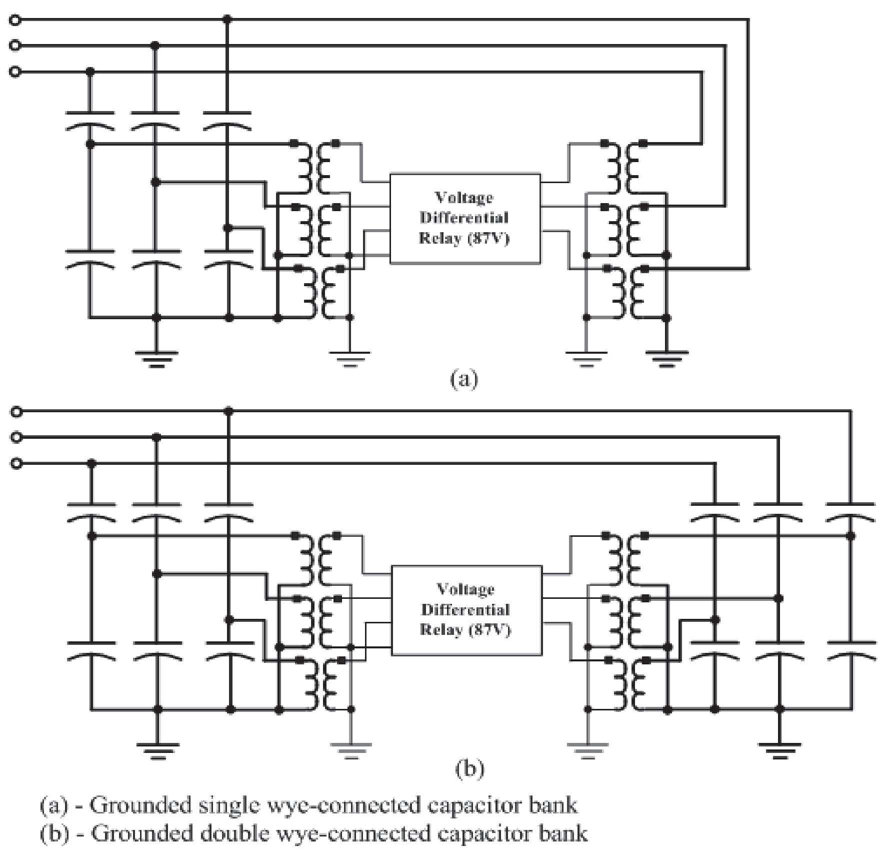


Figure 25—Voltage differential protection methods

The sensitivity of this method is high, and it is particularly well suited for high-voltage banks or banks that consist of a large number of capacitor units.

If the fused bank is tapped at the midpoint, then the sensitivity is the same for failures within and outside the tapped portion. If the bank is tapped below (above) the midpoint, then the sensitivity for failures within the tapped portion will be greater (less) than for failures outside the tap portion. This difference may cause difficulty in achieving an appropriate relay setting. The sensitivity for a midpoint tap and a tap across low-voltage capacitors at the neutral end of the phase is the same.

For grounded double wye-connected capacitor banks having both tap and bus voltages available, it is possible to connect the voltage differential protection between both tap voltages of the parallel bank strings and between bus voltage and each tap voltage. This approach will still function if there is a unit failure both above and below the VT connection point.

The voltage differential relay has to be blocked from operation if a VT fuse fails. The voltage differential must also be disabled when the bank is taken out of service. The single bus voltage input may cause an unwanted operation.

8.3.6.4 Voltage differential protection in split wye grounded fuseless bank

In fuseless single-wye banks with a large number of series elements, the capacitance changes due to unequal solar heating on the capacitor units could be sufficient to cause nuisance alarms or trips with conventional relays. The use of modern relays with dynamic unbalance compensation will mitigate this problem. Differentially connected voltage or current unbalance configurations of double-wye banks have inherent compensation to reduce the unequal solar heating effect.

Figure 26 shows a special (split-wye) configuration of fuseless banks similar to the double-wye configuration to mitigate the effect of unequal solar heating on strings. The tap voltage transformer is connected across the phase side of low-voltage capacitors connected on the neutral side of two groups of capacitor strings. The differential voltage will be zero if the number of strings on either side of the transformer is equal or there will be a standing voltage across the transformer with an unequal number of strings on either side. Unbalance calculations are the same as those for single wye bank.

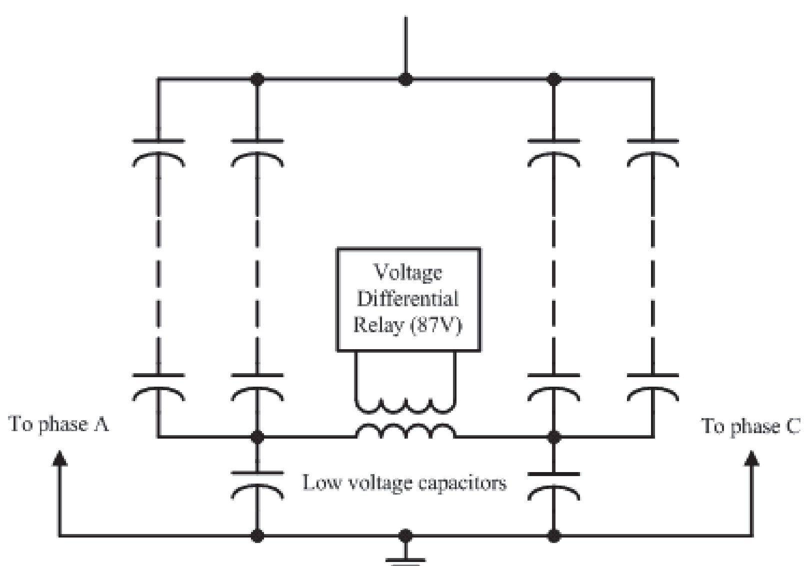
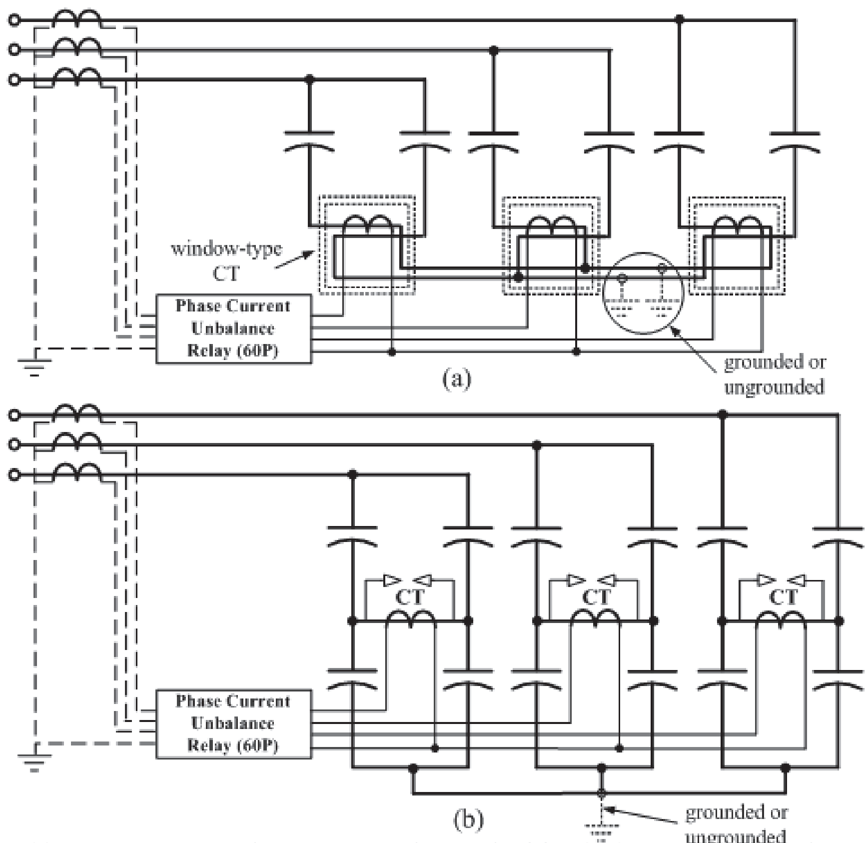


Figure 26—Split wye configuration, voltage differential measurement (only phase B shown)

8.3.6.5 Phase current unbalance method

Figure 27 shows two basic schemes using phase current unbalance protection. The scheme in Figure 27(a) is using a window-type CT with parallel banks connected at the neutral point, while the scheme in Figure 27(b) is for an H-bridge bank.

The CT is used to measure the vector sum of the two currents. The relays that can compensate for capacitor unit differences will provide more sensitive protection. If the two banks are slightly different in size, then the resulting circulating current can be compensated for by monitoring total phase current (dashed lines). This will also allow for a more sensitive relay setting.



(a) - phase current unbalance protection method for double wye-connected capacitor bank using window type CTs at the neutral point connection

(b) - phase current unbalance protection method for double wye-connected H-bridge configuration capacitor bank

Figure 27 —Phase current unbalance protection methods

The scheme shown in Figure 27(a) can be applied to banks with the same string reactances only, while the scheme shown in Figure 27(b) can be applied to H-bridge configurations where string reactance is different. For H-bridge configurations, the crossbar should be connected at the bank midpoint. If a regular CT is used in the H-bridge configuration, then surge protection is required. Alternatively, the connection can be made with a window-type CT without surge protection.

8.3.7 Very large capacitor banks

Very large grounded wye-connected capacitor banks (i.e., at voltages of 345 kV and above) require a protective device sensitive enough to detect the loss of a single-capacitor unit in externally fused banks or the loss of a few elements in internally fused or fuseless banks. Because the failure of a single unit in the large bank generates an operate signal that is so low, the signal may be below the sensitivity (cutoff) level of many traditional protective devices. Depending on the unbalance method, the system and bank inherent unbalance can make the situation worse: During normal operating conditions, the operate signal may be too high. Therefore, when the protective method and particular protective device are being selected for a large capacitor bank, it is preferable to use those that compensate for system and inherent bank unbalance, and that allow for achieving the required sensitivity. Typically, few protective functions are used to protect large capacitor banks, including two to three unbalance functions and three to five conventional functions. For example, the voltage differential relay in Figure 8 compares voltages on secondaries of voltage transformers connected to the capacitor bank's tap point and the bus. A capacitor bank's tap point connection depends on the type and configuration of the bank, as shown in Figure 8. In the case of many capacitor banks (for example, externally fused, internally fused, and fuseless banks), low-voltage protection capacitors are used, as shown in Figure 8. Resistors may be used in series with voltage transformers to avoid ferroresonance problems. In many externally fused banks, the voltage transformer in each phase is connected across one or more series groups depending on the sensitivity requirement.

For very large EHV capacitor banks, a backup (redundant) capacitor bank neutral voltage unbalance protection scheme is generally provided. The unbalance protection relay in Figure 8 is connected to a voltage transformer that measures the voltage across a low-voltage capacitor unit in the capacitor bank neutral. The unbalance relay is set to detect the loss of a specified number of capacitor units or elements depending on the type of the capacitor bank. The relay is set to trip after a time delay if the overvoltage greater than the allowable level occurs on the remaining units or elements. The relay criterion is described in detail in 8.2 through 8.6. Relay setting philosophies may differ from one application to another. However, a short time delay should be provided to prevent nuisance tripping (of a capacitor bank in an alarm state) on a system overvoltage transient. However, both voltage differential and neutral voltage unbalance relays rely on the same bus VT for correct operation: In case of failure of the latter, both functions become nonfunctional. Therefore, provision should be made to back up VT or use a current-based method as well.

The overvoltage relay mentioned previously should either use fundamental frequency quantities or be equipped with a fundamental frequency band-pass filter to avoid false operations due to harmonic currents. A third harmonic blocking filter may not prevent all false operations of this relay.

Some relays provide compensation schemes to overcome the effects of system and bank inherent unbalance on sensitivity. In this regard, the neutral voltage is compared either with the open delta voltage on the bus voltage transformer in grounded wye-connected banks or with voltage across another low-voltage capacitor (not shown in Figure 8) in case of double wye-connected banks.

8.3.8 Protection of unbalance relays

The unbalance relay should be protected against the following:

a) Damaging transient voltages appearing on control wiring (see IEEE Std C37.90.1™).

b) Excessive current flowing for longer times due to the failure of the switching device. The latching or lockout relay operated by the unbalance relay should have contacts wired to short out the neutral current transformer secondary.

A current transformer loading resistor, if used, should be able to withstand rapid heating in the event of single phasing until the unbalance protection voltage relay and lockout relay operate.

8.3.9 Current transformers of unbalance relaying

Wound primary current transformers used to measure neutral current may be subject to damaging high-voltage transients associated with capacitor switching or capacitor discharge into nearby faults and may require special protection. Current transformers installed neutral to ground for unbalance protection are particularly vulnerable because of the sensitivity requirements. If metal oxide varistors (MOVs) are used to protect the current transformers or relays, then care should be taken to ascertain that the MOVs have adequate energy-absorbing capability. A capacitor switching or fault transient may have very high energy. A shorted MOV may disable the unbalance protection (Harder [B5]). See 10.5 for additional comments.

8.4 Externally fused capacitor banks

8.4.1 General considerations

The unbalance relay should coordinate with the individual capacitor unit fuses so that the fuses operate to isolate a defective capacitor unit before the protection switches the bank out of service. [A reliable fuse operation provides a convenient, visual means for locating the defective capacitor unit(s).]

Where possible, the unbalance relay should be sensitive enough to alarm for the loss of one unit within a group. It should also trip and lock out on the loss of additional capacitor units that cause a group overvoltage in excess of 110% of capacitor unit rated voltage (or the capacitor unit manufacturer's recommendation).

8.4.2 Using the calculated values

The trip level is based on protecting the capacitor units and fuses from excessive voltages. The alarm level is based on providing an early indication of failures within the bank.

The number of blown fuses for trip can be determined by knowing the voltage on the capacitor units in parallel with the blown fuses (Vcu) indicated in 8.4.3 to 8.4.6 and the capability of the units based either on industry standards or on the documentation provided by the manufacturer. In the example calculated in Table 2 and Table 3, for standard units applied at rated voltage with a continuous contingency overvoltage capability of 110%, tripping should occur after the operation of the first fuse. At this point, the voltage on the capacitor units in parallel with the blown fuses is greater than 111% (above the 110% overvoltage capability).

The number of capacitor units in parallel per series group is governed by both a minimum and a maximum limitation and can be either single wye or double wye (see IEEE Std 1036). This arrangement may result in less than 110% voltage on parallel units after the operation of the first fuse. Alternatively, the bank might be made of slightly higher voltage units so that the resulting overvoltage would not be above 110% of the unit rating after the operation of the first fuse.

The trip level would normally be set to operate reliably after the operation of the fuse that results in more than 110% of capacitor unit rated voltage on parallel units. The relay may be set midway between the unbalance signal with that fuse having operated and the unbalance signal with one less fuse having operated. (Alternatively, the trip relay could be set at an unbalance that would result in 110% of capacitor unit rated voltage on the remaining elements, regardless of whether this condition could be anticipated in service.)

The alarm would normally be set to operate reliably on the operation of the first fuse. This alarm set point would typically be 50% to 75% of the signal associated with one fuse having operated.

The actual unbalance signal will depend on the protection scheme employed for the bank. A wide variety of protection schemes is in use on externally fused shunt capacitor banks. Sample calculations of unbalance signals for some protection schemes for wye, delta, or single phase are given in 8.4.4. Other calculated values are given in 8.4.5 and 8.4.6 under separate discussions of tap voltage and H-bridge protection schemes.

8.4.3 Introduction to capacitor bank unbalance calculations

The sample calculations in 8.4.4 through 8.4.6 are in three groups, as follows:

a) Wye, delta, and single-phase (see 8.4.4 for discussion, Figure 28 through Figure 30 for the bank diagram, and Table 2 through Table 4 for tabulated calculations). These calculations provide the information required for setting the unbalance protection based on the following:
   1) Neutral-to-ground voltage for ungrounded wye banks
   2) Neutral current for ungrounded wye-wye banks
   3) Neutral voltage difference for ungrounded wye-wye banks
   4) Neutral-to-ground current for grounded wye banks
   5) Voltage across low-voltage capacitors at the neutral end of each phase or in the neutral-to-ground connection of grounded wye banks
   6) Difference in neutral-to-ground currents for grounded wye-wye banks
   7) Delta and single-phase bank protection based on schemes similar to item a1) through item a6)
b) Tap voltage protection schemes (see 8.4.5 for discussion, Figure 31 for the bank diagram, and Table 5 for tabulated calculations). These calculations provide the information required for setting the unbalance protection based on the following:
   1) Midpoint-to-ground tap voltages for grounded wye banks.
   2) Differential protection for comparing the voltage across one or more series groups with the system line-to-ground voltage for grounded wye banks
   3) Delta and single-phase bank protection based on schemes similar to item b1) and item b2)
c) H-bridge protection schemes (see 8.4.6 for discussion, Figure 32 for the bank diagram, and Table 6 for tabulated calculations). These calculations provide the information required for setting the unbalance protection based on the current between midpoints of two similar legs connected phase to neutral or ground, phase to phase, or in the phase (series capacitors).

The system of units used for most of these calculations assumes every normal nonzero voltage, capacitance, and current is 1 per-unit under normal conditions, with no fuses having operated.

Some examples are not realistic. For instance, for high-voltage banks with several series groups, it is desirable to have at least 10 parallel capacitor units in each series group so that voltage is not excessive on the remaining capacitor units in a group after the operation of one fuse. Also, having many parallel units gives substantial overcurrent for fast fuse operation on a faulted unit. Fewer parallel units have been used in some examples in this subclause to keep the diagrams simple enough to read.

In addition to providing the necessary information for protective relay settings, this type of tabulation gives a good feel for the performance of the bank with varying numbers of fuses having operated.

For specific bank configurations, it is possible to combine the calculations of the various columns and to calculate only the following:

- The current through the fuse on a shorted capacitor unit
- The voltage on the capacitor units in parallel with blown fuses
- The unbalance signals for the type of protection to be utilized

For some cases, because of the complexity of the configuration, the resulting equations become onerous. The layout of the tabulated calculations in 8.3.4 through 8.3.6 is general and allows for the analysis of a wide variety of capacitor bank configurations.

Tabulations like those illustrated in 8.4.4 through 8.4.6 have been helpful in understanding the performance of a proposed bank before purchase. In addition, a copy of the tabulation at the capacitor bank location can be helpful for those concerned with the future maintenance of the bank. Some manufacturers of capacitor banks may provide this type of tabulation for the banks they propose or supply.

8.4.4 Unbalance calculations—wye, delta, single, and double banks

Step-by-step calculations and principal equation for each column for banks configured as per Figure 28 through Figure 30 are given in Table 2 through Table 4. [Some equations for the conditions where a capacitor unit was short-circuited (SC) but the fuse has not yet blown (SU) are different from the equations in the tables. Also, different equations are used for cases where the equations shown in the tables result in a division by zero. Some of these equations for unusual conditions are not given in the tables.]

These tabulations illustrate the unbalance that occurs in the affected parts of this bank as a result of individual fuse operations.

The column headings in the tabulations are based on wye-connected, three-phase capacitor banks. For delta-connected banks, the same formulas and tabulation(s) can be used by treating a leg of the delta as one phase of a grounded wye bank; all formulas are identical. For a delta bank, the currents shown as per-unit of-phase current become per-unit-of-leg current (phase current divided by √3). The difference current (equal wyes) becomes the difference in current between two equal delta-connected legs.

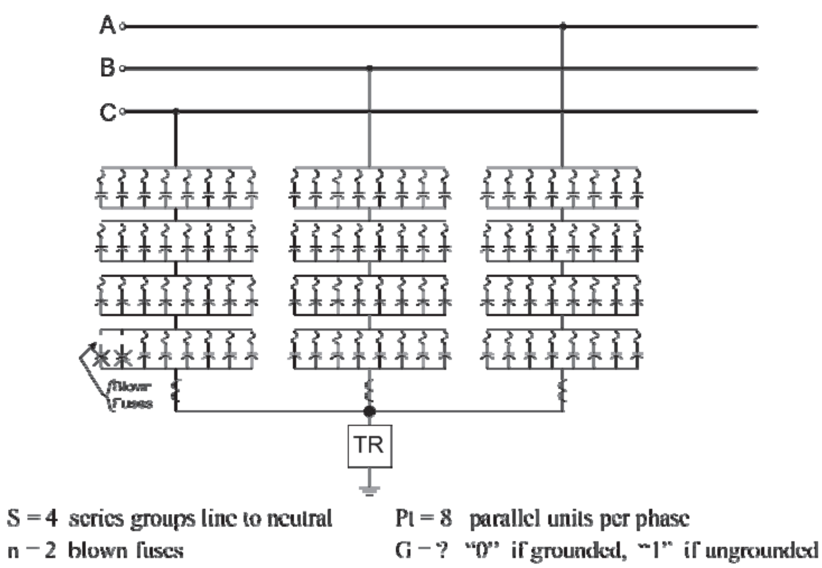


Figure 28 —Illustration of a single wye-connected capacitor bank

TR in Figure 28 represents a resistor potential device or a voltage transformer on an ungrounded bank; a current transformer or a low-voltage capacitor; or a direct ground on a grounded bank.

Table 2 illustrates the unbalance calculations for the single wye-connected bank and gives tabulated results for the sample bank shown in Figure 28.

Table 2—Unbalance calculations for the single wye-connected capacitor bank in Figure 28

Column title	Formula and comment	G	Number of blown capacitor fuses *n* (The number of fuses that have blown in one parallel group of capacitor units. *n* = 0 is the system normal condition.)					
			0	**SU**	**1**	**2**	**3**	**4**
Parallel group per-unit capacitance *Cg*	$Cg = \frac{Pt-n}{Pt}$ The capacitance of the parallel group of capacitors that includes the blown fuse(s).	0	1.0000	SC	0.8750	0.7500	0.6250	0.5000
		1	1.0000	SC	0.8750	0.7500	0.6250	0.5000
Affected wye capacitance *Cp*	$Cp = \frac{S \times Cg}{Cg \times (S-1)+1}$ The per-unit phase-to-neutral capacitance of the series/parallel group of capacitor units that includes the blown fuse(s). For the group including the affected unit, the per-unit capacitance is *Cg*. For all other groups, the per-unit capacitance is 1.	0	1.0000	1.3333	0.9655	0.9231	0.8696	0.8000
		1	1.0000	1.3333	0.9655	0.9231	0.8696	0.8000
Neutral-to-ground voltage (per-unit of *Vlg*) *Vng*	$Vng = G \times \left(\frac{3}{2+Cp} - 1\right)$ For grounded banks (*G* = 0), this voltage is always 0. For ungrounded wye banks, the calculation is made assuming the affected phase has a capacitance *Cp*, and the other two phases each have a per-unit capacitance of 1.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	-0.1000	0.0116	0.0263	0.0455	0.0714
Voltage on affected phase *Vln*	$Vln = 1 + Vng$ The voltage line to neutral across the phase that includes the blown fuse(s). The operation of the fuse(s) reduces the capacitance of that phase and increases the voltage across the affected phase; therefore, the numbers are always greater than one except before the operation of the fuse on a faulted capacitor unit.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9000	1.0116	1.0263	1.0455	1.0714
Voltage on affected series group *Vcu*	$Vcu = \frac{Vln \times Cp}{Cg}$ (If *Cg* = 0, *Vcu* = *Vln* × *S*) The per-unit voltage on the capacitor units in the group with the blown fuse(s), based on the capacitance division of the actual voltage on the affected phase (*Vln*).	0	1.0000	4.0000	1.1034	1.2308	1.3913	1.6000
		1	1.0000	3.6000	1.1163	1.2632	1.4545	1.7143
Current through affected capacitor(s) *Iu*	$Iu = Vcu \times Cu$ The current through the individual capacitor units in the group with the blown fuse(s), per-unit of the value with no fuses blown. Note that for healthy capacitor units *Cu* = 1. The value for SU indicates the short circuit current available to blow the fuse on a faulted capacitor unit. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel capacitors into the faulted one). $Iu(SU) = \frac{S \times Pt}{(S-1)}$	0	1.0000	10.667	1.1034	1.2308	1.3913	1.6000
		1	1.0000	10.667	1.1163	1.2632	1.4545	1.7143
Phase current change *Iph*	$Iph = Cp \times Vln$ The current in the phase with the blown fuses. This may be useful for setting protection based on phase current.	0	1.0000	1.3333	0.9655	0.9231	0.8696	0.8000
		1	1.0000	1.2000	0.9767	0.9474	0.9091	0.8571
Ground current change	$Ig = (1-G) \times (1-Iph)$ The change in current to ground, which is used with	0	0.0000	-0.3333	0.0345	0.0743	0.1207	0.1759

Column title	Formula and comment	G	Number of blown capacitor fuses *n* (The number of fuses that have blown in one parallel group of capacitor units. $n = 0$ is the system normal condition.)					
			0	**SU**	**1**	**2**	**3**	**4**
Ig	protective relay schemes utilizing either neutral-to-ground current, or the voltage across a low-voltage capacitor(s) in the neutral or in each phase.	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

NOTE 1—*Vng* voltage equation is convenient to develop based on an instant in time when the affected phase has one per-unit voltage and the other two phases have −0.5 per-unit voltage. For this condition, the two unaffected phases can be paralleled, and the voltage divider between −0.5 per-unit and +1 per-unit can be calculated for the midpoint voltage, which is recorded as *Vng*.

NOTE 2—*Ig* the per-unit change in current to ground is the per-unit change in voltage across a low-voltage capacitor in the affected phase. It is also the per-unit change in voltage across a low-voltage capacitor in the neutral-to-ground connection because the other two phase currents do not change in a grounded wye bank.

NOTE—A limited number of unbalance protection methods is available for the single wye-connected bank. However, when the bank is connected in a double wye, the number of protection methods available is increased, thus, allowing more flexibility and security for protective purposes.

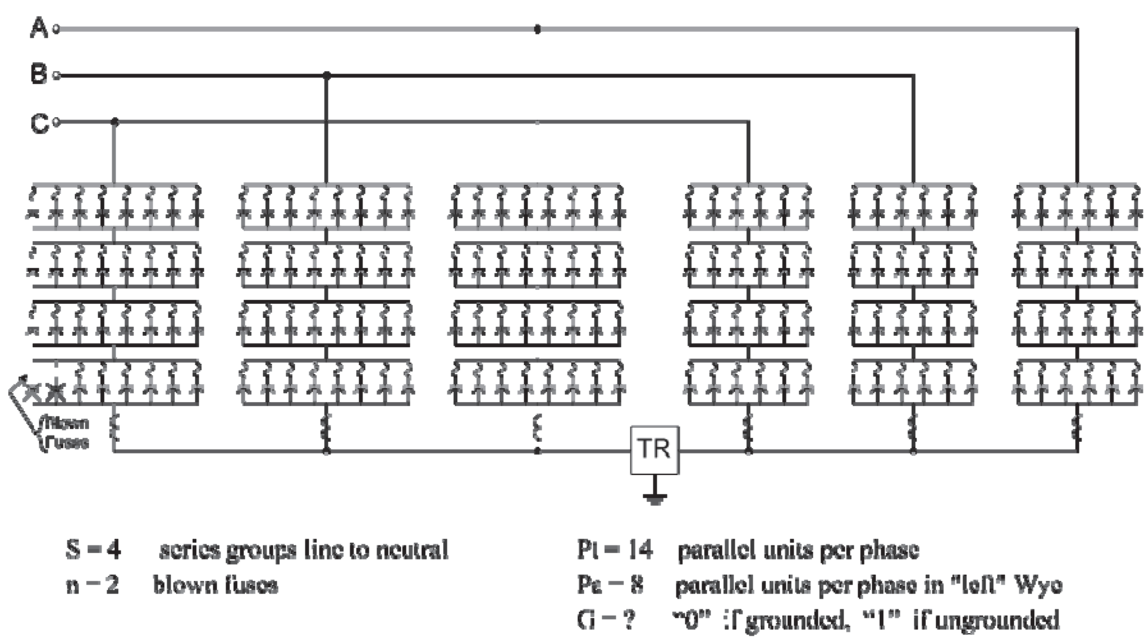


Figure 29—Illustration of a double wye-connected capacitor bank

TR in Figure 29 represents a current transformer or a resistor potential device or a voltage transformer on an ungrounded bank; a current transformer or a low-voltage capacitor; or a direct ground on a grounded bank.

Table 3—Unbalance calculations for the double wye-connected capacitor bank in Figure 29

Column title	Formula and comment	G	Number of blown capacitor fuses *n* (The number of fuses that have blown in one parallel group of capacitor units. *n* = 0 is the system normal condition.n)					
			0	**SU**	**1**	**2**	**3**	**4**
Parallel group per-unit capacitance *Cg*	$Cg = \frac{Pa - n}{Pa}$ The capacitance of the parallel group of capacitors that includes the blown fuse(s).	0	1.0000	SC	0.8750	0.7500	0.6250	0.5000
		1	1.0000	SC	0.8750	0.7500	0.6250	0.5000
Affected wye capacitance *Cs*	$Cs = \frac{S \times Cg}{Cg \times (S-1)+1}$ The per-unit phase-to-neutral capacitance of the series/parallel group of capacitor units that includes the blown fuse(s). For the group including the affected unit, the per-unit capacitance is *Cg*. For all other groups, the per-unit capacitance is 1.	0	1.0000	1.3333	0.9655	0.9231	0.8696	0.8000
		1	1.0000	1.3333	0.9655	0.9231	0.8696	0.8000
Per-unit capacitance, phase with blown fuses *Cp*	$Cp = \frac{(Cs \times Pa) + Pt - Pa}{Pt}$ The per-unit capacitance of the phase (both wyes) that includes the blown fuse(s). For single wye banks, *Pa* = *Pt* and *Cp* = *Cs*.	0	1.0000	1.1905	0.9803	0.9560	0.9255	0.8857
		1	1.0000	1.1905	0.9803	0.9560	0.9255	0.8857
Neutral-to-ground voltage (per-unit of *Vlg*) *Vng*	$Vng = G \times \left(\frac{3}{2+Cp} - 1\right)$ For grounded banks (*G* = 0), this voltage is always 0. For ungrounded wye banks, the calculation is made assuming the affected phase has a capacitance *Cp* and the other two phases each have a per-unit capacitance of 1.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	–0.0597	0.0066	0.0149	0.0255	0.0396
Voltage on affected phase *Vln*	$Vln = Vng + 1$ The voltage line to neutral across the phase that includes the blown fuse(s). The operation of the fuse(s) reduces the capacitance of that phase and increases the voltage across the affected phase; therefore, the numbers are always greater than one except before the operation of the fuse on a faulted capacitor unit.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9403	1.0066	1.0149	1.0255	1.0396
Voltage on affected series group *Vcu*	$Vcu = \frac{Vln \times Cs}{Cg}$ (If *Cg* = 0, *Vcu* = *Vln* × *S*) The per-unit voltage on the capacitor units in the group with the blown fuse(s), based on the capacitance division of the actual voltage on the affected phase (*Vln*).	0	1.0000	SC	1.1034	1.2308	1.3913	1.6000
		1	1.0000	SC	1.1107	1.2491	1.4268	1.6634
Current through affected capacitor(s) *Iu*	$Iu = Vcu \times Cu$ The current through the individual capacitor units in the group with the blown fuse(s), per-unit of the value with no fuses blown. Note that for healthy capacitor units *Cu* = 1. The value for SU indicates the power frequency current available to blow the fuse on a faulted capacitor unit. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel capacitor units into the faulted one).	0	1.0000	10.667	1.1034	1.2308	1.3913	1.6000
		1	1.0000	10.667	1.1107	1.2491	1.4268	1.6634
Current in affected wye *Iy*	$Iy = Cs \times Vln$ The per-unit current in the series/parallel group with the blown fuse(s). This value may be useful for differential schemes comparing the current in different series/parallel groups.	0	1.0000	1.3333	0.9655	0.9231	0.8696	0.8000
		1	1.0000	1.2537	0.9719	0.9368	0.8917	0.8317
Current in affected phase *Iph*	$Iph = Cp \times Vln$ The current in the phase with the blown fuses. This may be useful for setting protection based on phase current.	0	1.0000	1.1905	0.9803	0.9560	0.9255	0.8857
		1	1.0000	1.1194	0.9868	0.9703	0.9490	0.9208

Column title	Formula and comment	G	Number of blown capacitor fuses *n* (The number of fuses that have blown in one parallel group of capacitor units. *n* = 0 is the system normal condition.n)					
			0	SU	1	2	3	4
Ground current change *Ig*	$Ig=(1-G)\times(1-Iph)$ The change in current to ground, which is used with protective relay schemes utilizing either neutral-to-ground current, or the voltage across a low-voltage capacitor(s) in the neutral or in each phase.	0	0.0000	–0.1905	0.0197	0.0440	0.0745	0.1143
		1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Neutral current between wyes *In*	$In=\frac{3\times Vng\times G\times(P_t-P_a)}{P_t}$ Unbalance current for ungrounded wye-wye banks. [The current is calculated assuming the neutral-to-ground (zero sequence) voltage is applied at the neutral of the wye with no blown fuses.]	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	–0.0896	0.0099	0.0223	0.0382	0.0594

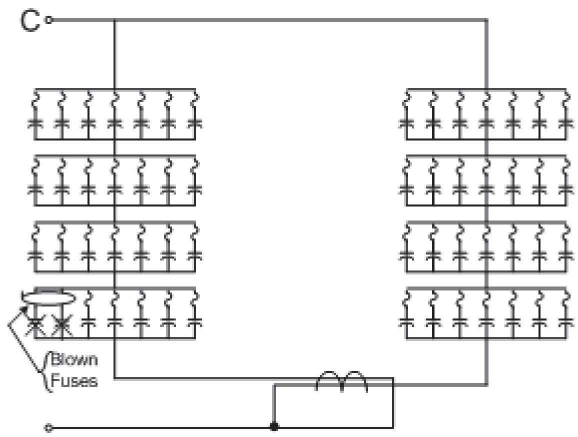


Figure 30—Capacitor bank arranged to measure difference current between two equal legs of each phase (only one phase shown)

Calculations are similar to a double wye-connected bank with uneven legs shown in Figure 30 with all formulas applicable. Additionally, differential current between two equal legs is calculated, which makes it suitable for the phase current unbalance method.

Table 4—Unbalance calculations for the double wye-connected capacitor bank in Figure 30

Column title	Formula and comment	G	Number of blown capacitor fuses *n* (The number of fuses that have blown in one parallel group of capacitor units. *n* = 0 is the system normal condition.)					
			0	SU	1	2	3	4
Parallel group per-unit capacitance *Cg*	$Cg=\frac{Pa-n}{Pa}$ The capacitance of the parallel group of capacitors that includes the blown fuse(s).	0	1.0000	SC	0.8571	0.7143	0.5714	0.4286
		1	1.0000	SC	0.8571	0.7143	0.5714	0.4286
Affected wye capacitance *Cs*	$Cs=\frac{S\times Cg}{Cg\times(S-1)+1}$ The per-unit phase-to-neutral capacitance of the series/parallel group of capacitor units that includes the blown fuse(s). For the group including the affected unit, the per-unit capacitance is *Cg*. For all other groups, the per-unit capacitance is 1.	0	1.0000	1.3333	0.9600	0.9091	0.8421	0.7500
		1	1.0000	1.3333	0.9600	0.9091	0.8421	0.7500
Per-unit capacitance,	$Cp=\frac{(Cs\times Pa)+Pt-Pa}{Pt}$	0	1.0000	1.3333	0.9600	0.9091	0.8421	0.7500

Column title	Formula and comment	G	Number of blown capacitor fuses *n* (The number of fuses that have blown in one parallel group of capacitor units. *n* = 0 is the system normal condition.)					
			0	**SU**	**1**	**2**	**3**	**4**
phase with blown fuses *Cp*	The per-unit capacitance of the phase (both wyes) that includes the blown fuse(s).	1	1.0000	1.3333	0.9600	0.9091	0.8421	0.7500
Neutral-to-ground voltage (per-unit of *Vlg*) *Vng*	$Vng = G\times\left(\frac{3}{2+Cp}-1\right)$ For grounded banks (*G* = 0), this voltage is always 0. For ungrounded wye banks, the calculation is made assuming the affected phase has a capacitance *Cp*, and the other two phases each have a per-unit capacitance of 1.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	–0.1000	0.0135	0.0313	0.0556	0.0909
Voltage on affected phase *Vln*	$Vln = Vng + 1$ The voltage line to neutral across the phase that includes the blown fuse(s). The operation of the fuse(s) reduces the capacitance of that phase and increases the voltage across the affected phase; therefore, the numbers are always greater than one except before the operation of the fuse on a faulted capacitor unit.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9000	1.0135	1.0313	1.0556	1.0909
Voltage on affected series group *Vcu*	$Vcu = \frac{Vln\times Cs}{Cg}$ (If *Cg* = 0, *Vcu* = *Vln* × *S*) The per-unit voltage on the capacitor units in the group with the blown fuse(s), based on the capacitance division of the actual voltage on the affected phase (*Vln*).	0	1.0000	4.0000	1.1200	1.2727	1.4737	1.7500
		1	1.0000	3.6000	1.1351	1.3125	1.5556	1.9091
Current through affected capacitor(s) *Iu*	$Iu = Vcu\times Cu$ The current through the individual capacitor units in the group with the blown fuse(s), per-unit of the value with no fuses blown. The value for SU indicates the power frequency current available to blow the fuse on a faulted capacitor unit. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel capacitor units into the faulted one).	0	1.0000	9.3333	1.1200	1.2727	1.4737	1.7500
		1	1.0000	9.3333	1.1351	1.3125	1.5556	1.9091
Current in affected wye *Iy*	$Iy = Cs\times Vln$ The per-unit current in the series/parallel group with the blown fuse(s). This value may be useful for differential schemes comparing the current in different series/parallel groups.	0	1.0000	1.3333	0.9600	0.9091	0.8421	0.7500
		1	1.0000	1.2000	0.9730	0.9375	0.8889	0.8182
Current in affected phase *Iph*	$Iph = Cp\times Vln$ The current in the phase with the blown fuses. This may be useful for setting protection based on phase current.	0	1.0000	1.3333	0.9600	0.9091	0.8421	0.7500
		1	1.0000	1.2000	0.9730	0.9375	0.8889	0.8182
Ground current change *Ig*	$Ig = (1-G)\times(1-Iph)$ The change in current to ground, which is used with protective relay schemes utilizing either neutral-to-ground current, or the voltage across a low-voltage capacitor(s) in the neutral or in each phase.	0	0.0000	–0.3333	0.0400	0.0909	0.1579	0.2500
		1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Neutral current between wyes *In*	$In = \frac{3\times Vng\times G}{2}$ Unbalance current for ungrounded wye-wye banks. [The current is calculated assuming the neutral-to-ground (zero sequence) voltage is applied at the neutral of the wye with no blown fuses.]	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	–0.1500	0.0203	0.0469	0.0833	0.1364
Difference current, equal wyes *Id*	$Id = (1-Cp)\times Vln$ For grounded wye-wye banks, where the difference in the neutral current between the two equal wyes is used as a basis for protection (Figure 30). Values are per-unit of total phase current for seven parallel units in each group.	0	0.0000	–0.3333	0.0400	0.0909	0.1579	0.2500
		1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

8.4.5 Unbalance calculations—tap voltage

A variety of protection schemes, primarily for grounded wye banks, is based on the measurement of a voltage across some number of series groups of the bank. Two common schemes are to

— Measure a voltage near the middle of a phase (midpoint tap; see Figure 31)
— Measure the voltage across the bottom series group(s)

In either case, the measured voltage may be compared with the phase voltages (differential protection) or combined with each other to determine unbalance.

Regardless of the relay type used, the schemes are based on the change in tap voltage caused by a change in the effective capacitance of one series group, resulting from a failure and/or capacitor fuse operations. This change may depend on whether the affected capacitor units are located outside or inside the tap portion of the bank. The calculations assume all of the blown fuses are in one series group in one phase (either inside or outside the tap portion, but not both places at the same time).

Figure 31 illustrates a midpoint-tapped capacitor bank. Table 5 gives the unbalance calculations for grounded wye, delta, or single-phase banks.

For delta or single-phase banks, tap is from the tap point to the reference end of the leg or bank (instead of the neutral). The calculations are made in the same way as shown for three-phase grounded wye banks.

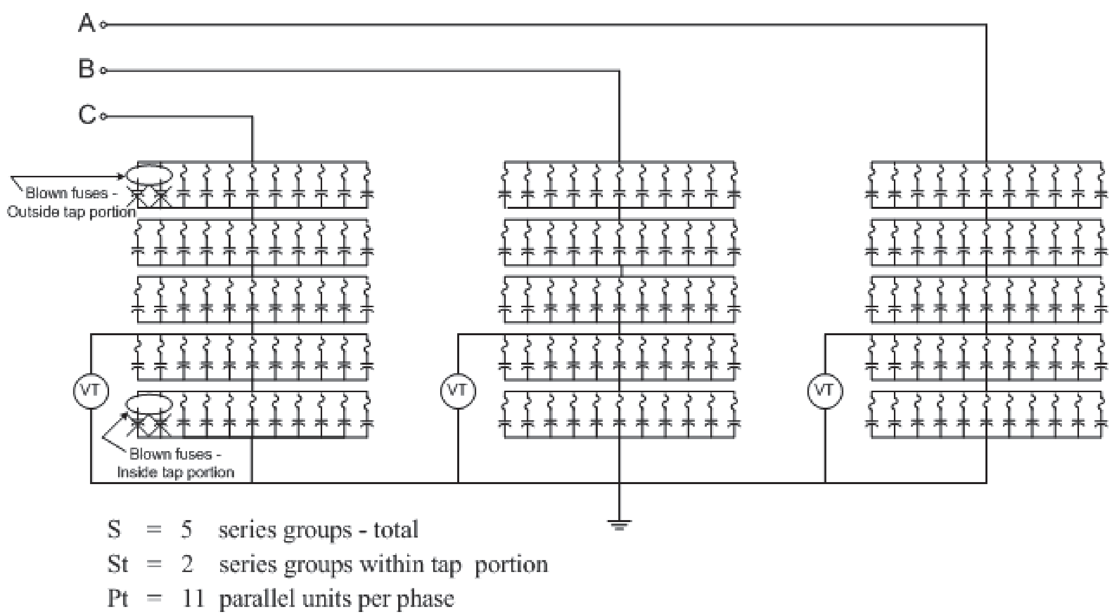


Figure 31 —Illustration of a tapped wye-connected capacitor bank

Table 5—Unbalance calculations for the tapped wye-connected capacitor bank in Figure 31

Column title	Formula and comment	**Number of blown capacitor fuses *n*** (The number of fuses that have blown in one parallel group of capacitor units. $n = 0$ is the system normal condition.)					
		0	**SU**	**1**	**2**	**3**	**4**
Affected phase capacitance Cp	$Cp = \frac{Pt \times (Pt-n)}{Pt + (Pt-n) \times (S-1)}$ The capacitance of the phase from end to end, assuming the capacitance of one healthy capacitor unit is 1 per-unit	2.2000	2.7500	2.1569	2.1064	2.0465	1.9744
Voltage on affected capacitor group Vcu	$Vcu = \frac{Cp \times S}{Pt-n}$ Voltage across the group of capacitors that includes the affected capacitor unit, per-unit of the normal voltage across that group	1.0000	0.0000	1.0784	1.1702	1.2791	1.4103
Current through affected capacitor Iu	$Iu = Vcu \times Cu$ The current through the affected capacitor unit(s), per-unit of the value with no fuses blown. The value for SU indicates the power frequency current available to blow the fuse on a faulted capacitor. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel capacitor units into the faulted one). For healthy capacitor units $Cu = 1$, and the equation can be simplified to $Iu = Vcu$.	1.0000	13.750	1.0784	1.1702	1.2791	1.4103
For blown fuses outside tap portion							
Capacitance tap to neutral Ctn	$Ctn = \frac{Pt}{St}$ The capacitance of the tap portion of the phase, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	5.5000	5.5000	5.5000	5.5000	5.5000	5.5000
Tap voltage, per-unit of Vlg Vtg	$Vtg = \frac{Cp}{Ctn}$ The voltage across the tap, assuming 1 per-unit voltage is the actual voltage on the phase.	0.4000	0.5000	0.3922	0.3830	0.3721	0.3590
Tap voltage change, per-unit of normal $dVtg$	$dVtg = \frac{Vtg_n - Vtg_{n=0}}{Vtg_{n=0}}$ The per-unit change in the tap voltage, assuming 1 per-unit is the normal tap voltage.	0.0000	0.2500	–0.0196	–0.0426	–0.0698	-0.1026
For blown fuses inside tap portion							
Capacitance tap to neutral Ctn	$Ctn = \frac{Pt \times (Pt-n)}{Pt + (Pt-n) \times (St-1)}$ The capacitance of the tap portion of the phase, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	5.5000	11.000	5.2381	4.9500	4.6316	4.2778
Tap voltage, per-unit of Vlg Vtg	$Vtg = \frac{Cp}{Ctn}$ The voltage across the tap, assuming 1 per-unit voltage is the actual voltage on the phase.	0.4000	0.2500	0.4118	0.4255	0.4419	0.4615
Tap voltage change, per-unit of normal $dVtg$	$dVtg = \frac{Vtg_n - Vtg_{n=0}}{Vtg_{n=0}}$ The per-unit change in the tap voltage, assuming 1 per-unit is the normal tap voltage.	0.0000	–0.3750	0.0294	0.0638	0.1047	0.1538

8.4.6 Unbalance calculation—H-bridge

An H-bridge may be used for unbalance protection in a variety of capacitor bank connections: grounded wye, ungrounded wye, delta, and single phase (series capacitors). The H-bridge is based on a current measurement in a leg connecting two strings of capacitors together near the midpoints of the strings. The current transformer for unbalance detection appears on the crossbar of the capital letter H (Figure 32), thus, the designation H-bridge. Any change in the capacitance of any capacitor in the bridge will cause a change in the H current.

Calculations (Table 6) are based on fuse operations in one parallel group of capacitor units. The ambiguity resulting from the operation of fuses in another part of the bank that may cancel the unbalance signal needs a sensitive alarm level (preferably one fuse) so that the defective unit can be replaced before there are many scattered fuse operations. In addition, assuming that one or two “canceling” fuse operations occur at the time of unacceptably high voltages on the affected capacitor units, it may be desirable to set the trip level somewhat lower than suggested by the overvoltages of Table 6.

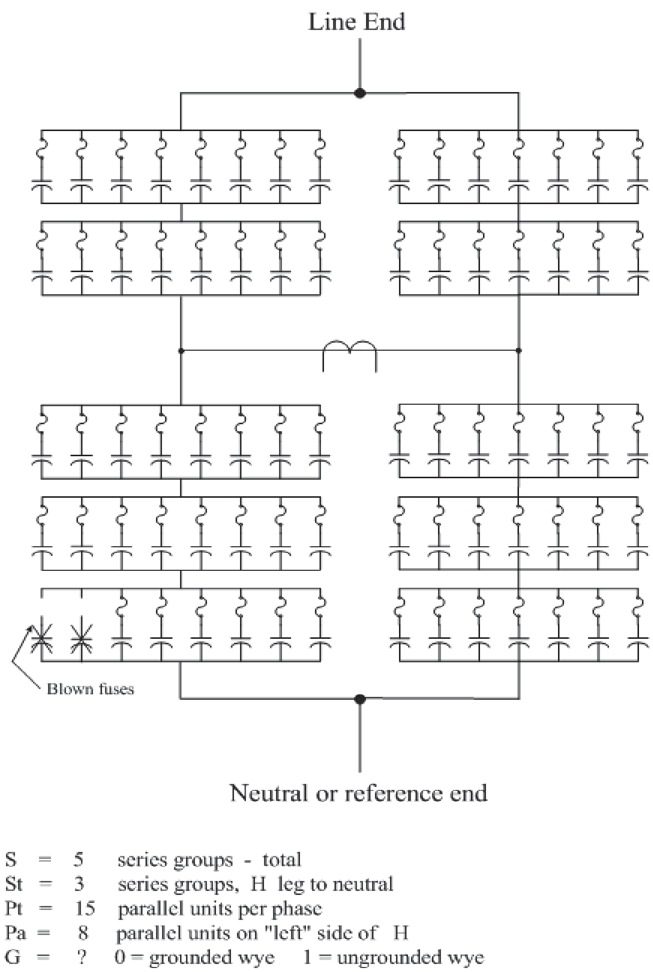


Figure 32—Illustration of one phase or leg of an H-bridge capacitor bank

For an unsymmetrical arrangement such as shown in Figure 32, the effects of blowing fuses in units in other parts of the bank on the overvoltages H current, and so on, may easily be investigated by changing the values of *St* and *Pa* so that the affected unit appears to be in the lower left quadrant of Figure 32. All of these calculations assume that all blown fuses are in one parallel group of capacitor units on one side of the H only.

Table 6—Unbalance calculations for the H-bridge capacitor bank in Figure 32

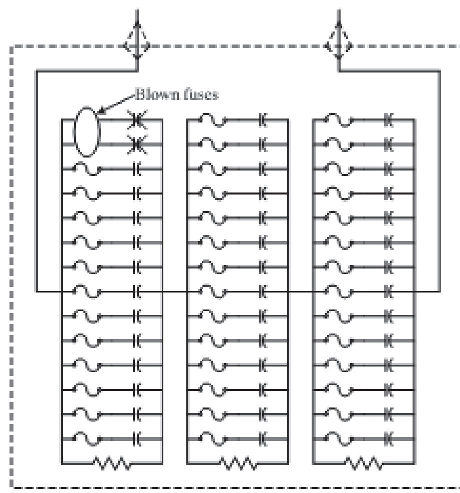
Column title	**Formula and comment**	**G**	**Number of blown capacitor fuses *n*** (The number of fuses that have blown in one parallel group of capacitor units. $n = 0$ is the system normal condition.)					
			0	**SU**	**1**	**2**	**3**	**4**
Capacitance H-bridge to neutral *Chn*	$Chn = \frac{(Pa-n)\times Pa}{(Pa-n)\times(St-1)+Pa} + \frac{Pt-Pa}{St}$ The capacitance from the H leg to the neutral or reference end of the phase, assuming the capacitance of one capacitor unit is 1 per-unit.	0	5.0000	6.3333	4.8788	4.7333	4.5556	4.3333
		1	5.0000	6.3333	4.8788	4.7333	4.5556	4.3333
Affected wye capacitance *Cp*	$Cp = \frac{Chn\times Pt}{Chn\times(S-St)+Pt}$ The capacitance of the phase from end to end, assuming the capacitance of one capacitor unit is 1 per-unit.	0	3.0000	3.4337	2.9559	2.9019	2.8341	2.7465
		1	3.0000	3.4337	2.9559	2.9019	2.8341	2.7465
Affected phase voltage *Vln*	$Vln = 1+G\times\left(\frac{3}{2+Cp/Cp(0)}-1\right)$ The voltage across the affected phase will be 1 for grounded wye or delta, where $G = 0$. For ungrounded wye, this voltage is the per-unit voltage across the affected phase including the effect of the neutral shift from capacitance unbalance.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9540	1.0049	1.0110	1.0188	1.0290
H leg voltage, per-unit of *Vln* *Vhn*	$Vhn = \frac{Cp}{Chn}$ The voltage of the H leg, per-unit of the actual voltage on the affected phase.	0	0.6000	1.0000	0.6059	0.6131	0.6221	0.6338
		1	0.6000	0.5422	0.6059	0.6131	0.6221	0.6338
"H" current, per unit of total phase current *Ih*	$Ih = -Vln\times\left(\frac{St}{S}-Vhn\right)\times\left(\frac{1}{S-St}+\frac{1}{St}\right)\times\left(\frac{S\times(Pt-Pa)}{Pt}\right)$ The current in the H leg, per-unit of the normal total phase current for a wye-connected or single phase bank or per-unit of total leg current for a delta bank.	0	0.0000	0.7778	0.0114	0.0254	0.0430	0.0657
		1	0.0000	–0.1073	0.0115	0.0257	0.0438	0.0676
Voltage on affected capacitor units *Vcu*	$Vcu = \frac{Vln\times Vhn\times Pa\times S}{Pa+(St-1)\times(Pa-n)}$ The voltage across the capacitor units in parallel with the blown fuses, per-unit of the value with no fuses blown.	0	1.0000	SC	1.1016	1.2262	1.3825	1.5845
		1	1.0000	SC	1.1070	1.2397	1.4085	1.6304
Current through affected capacitor(s) *Iu*	$Iu = Vcu\times Cu$ The current through the capacitor units in the group with the blown fuse(s), per-unit of the value with no fuses blown. The value for SU indicates the power frequency current available to blow the fuse on a faulted capacitor unit. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel capacitor units into the faulted one). $Iu(SU) = \frac{St\times Pa}{(St-1)}\times\frac{Cp_{n=0}}{Cp_{SU}}$	0	1.0000	10.4842	1.1016	1.2262	1.3825	1.5845
		1	1.0000	10.4842	1.1070	1.2397	1.4085	1.6304

The example illustrated in Figure 32 and Table 6 is not a recommended H-bridge design, as the overvoltage on remaining units may be excessive after the first fuse operation. Better practice would normally be to have more parallel units or fewer series groups, so that there could be an alarm before trip.

8.5 Internally fused capacitor banks

8.5.1 General considerations

Internally fused capacitor units (Figure 33) are subject to overvoltage across elements and fuses within the unit as internal fuses blow and remove elements from a parallel group. The overvoltage on these remaining elements and fuses should be considered in addition to the overvoltage on units without blown fuses. The bank design will dictate unbalance signals available to the relay, which in its turn affects the protection sensitivity.



N = 14 parallel elements in a group
Su = 3 series groups in the capacitor unit
f = 2 blown fuses in one group

Figure 33—Schematic of an internally fused capacitor unit

The setting of the unbalance protection of an internally fused capacitor bank should take into consideration the capability of the internal fuses, the transient overvoltage capability of the elements, and the consequences of a failure to the case or the failure of an internal fuse. These considerations are in addition to the usual considerations of external arcing within the bank and avoiding exposure of healthy capacitor units to voltages in excess of 110% of their rated voltage.

In an internally fused capacitor bank, the unbalance detection gives an indication of the total number of failed capacitor elements within a capacitor unit. In practice, the actual number of failed elements can be determined only by a complete measurement of all units in a bank. This measurement may be recommended only when a relay alarm or trip occurs, and it may or may not be a part of the regular maintenance schedule.

8.5.2 Using the calculated values

The trip level should be set as follows:

— The number of operated fuses in the affected capacitor unit does not exceed the maximum number recommended by the manufacturer.

— The voltage on the healthy capacitors does not exceed the contingency overvoltage capability of the capacitor units (usually 110% of rated voltage). Note that the element voltage in the unit with blown fuses may exceed 110% of normal.

For instance, for the example shown in Figure 34 and Figure 35, the number of blown fuses is shown in the top row of Table 7. If the capacitor manufacturer recommends that the bank should be tripped after the operation of the seventh fuse, then to assure reliable operation, the trip relay set point would be midway between the unbalance signal with six fuses having operated and the unbalance signal with seven fuses having operated. For this example, the voltage on the healthy capacitor units with seven fuses blown in one capacitor is about 1.069 per-unit, which is less than 10% overvoltage. For banks where the voltage on the healthy units becomes excessive before the maximum number of blown fuses recommended by the manufacturer, the trip relay set level would be set halfway between the signal associated with the maximum number of blown fuses with acceptable voltage on healthy capacitor units and the signal associated with the number of fuses that results in excessive voltage on healthy capacitor units.

The alarm would be set above natural errors so that it would operate reliably on the loss of the first or second fuse. This alarm set point would typically be halfway between the signal associated with the selected number of fuses having operated and the signal associated with one fewer fuse having operated.

The actual unbalance signal will depend on the protection scheme employed for the bank. A wide variety of protection schemes are in use on internally fused shunt capacitor banks. The unbalance signals for some of the more common connections are given in Figure 34 and Table 7. Other calculated values are given in 8.4.5 and 8.4.6 under separate discussions of tap voltage and H-bridge protection schemes.

In addition to providing the necessary information for protective relay settings, this type of tabulation gives a good feel for the performance of the bank with varying numbers of internal fuses having operated. Some manufacturers of internally fused capacitor banks will provide this type of tabulation for the banks they propose or supply.

Of course, it is possible to combine the calculations of the various columns and calculate only the following:

— The voltage on the affected elements

— The voltage on the affected unit (which is also the voltage on the parallel units)

— The unbalance signal for the type of protection to be utilized

Because of the complexity of the configuration (for example, parallel elements and series groups in a capacitor unit, parallel capacitor units in a group, series groups in a string, and parallel capacitor units in a phase), the resulting equations become complex.

The time delay for tripping should be minimized to reduce the probability of case rupture in the event of a fault to the case or fuse failure within a capacitor unit. In addition to the considerations of 8.2.4, it may be desirable to coordinate with the melting of an individual fuse element where there is no parallel energy to speed up the fuse operation. [The manufacturer of the capacitor units should be able to supply the maximum clearing time (curve) for the internal fuses.] There is no need to wait to coordinate for fuse operation with unbalance signals that are larger than would occur for a shorted element before fuse operation.

Normally, a time delay of 0.01 s to 0.05 s is adequate for this coordination. With this intentional time delay in the trip relay, the additional time required for the lockout relay and breaker operation may result in total clearing times of the order of 0.1 s for a capacitor unit with an internal fault or a capacitor bank with an arcing fault. A time of 0.1 s is reasonably achievable to clear a capacitor bank with a problem, but it still may result in substantial damage. Once parts of a capacitor bank start to become damaged, then further damage will escalate rapidly. Such escalation will increase the risk of major damage and fire and may result in increased damage to the capacitor bank. Keeping the clearing time short is important to minimizing damage in the event of a fault within a bank.

With internally fused capacitors, it is not appropriate to use protection schemes with enough delay to override the effect of system faults (which may persist for cycles).

Generally, the most appropriate alarm level is the lowest level that can be set without resulting in false alarms from thermal variations in capacitance within the bank, practical initial bank balance, and so on. (The earliest reliable alarm gives maximum opportunity to repair the capacitor bank during a scheduled outage.) Responding reasonably to early alarms and maintaining the bank in the best possible condition tend to minimize the probability of further element failures and forced or unscheduled outages and to maximize the availability of the bank. False or unreliable alarms can be costly, and they decrease the credibility of the capacitor protection.

In unbalance protection schemes with ambiguous indication, it is desirable to use an alarm setting sensitive to the loss of the first element to avoid the ambiguity. This alarm should seal in so that it should be manually reset after the removal of the failed capacitor units from the bank. It would be undesirable to have the alarm shut off after the operation of a subsequent fuse that cancels the unbalance signal.

The timing of the alarm should be long enough to avoid operation during system faults or temporary overvoltages but short enough in the case of ambiguous schemes to minimize the probability of two compensating fuse operations before the initiation of the alarm. Usually about a 10 s delay is appropriate for the alarm.

In managing the protection of an internally fused capacitor bank, the unbalance protection should not be reset or "rebalanced" without first making sure that all capacitor units with failed elements have been removed from the bank.

If the installation is to be rebalanced with units having one (or two) failed elements remaining in service, then the trip level should be adjusted downward so that the fuses and elements in these units do not exceed their capability before operation of the trip relay.

8.5.3 Introduction to capacitor bank unbalance calculations

The sample calculations in 8.5.4 through 8.5.6 are in the following three groups:

a) Wye, delta, and single phase (see 8.5.4 for discussion, Figure 34 for the bank diagram, and Table 7 for tabulated calculations). These calculations provide the information required for setting the unbalance protection based on the following:
    1) Neutral-to-ground voltage for ungrounded wye banks
    2) Neutral current for ungrounded wye-wye banks
    3) Neutral voltage difference for ungrounded wye-wye banks
    4) Neutral-to-ground current for grounded wye banks
    5) Voltage across low-voltage capacitors at the neutral end of each phase or in neutral-to-ground connection of grounded wye banks
    6) Difference in neutral-to-ground currents for grounded wye-wye banks
    7) Delta and single-phase bank protection based on schemes similar to item a1) through item a6)

b) H-bridge protection schemes (see 8.4.5 for discussion, Figure 36 for the bank diagram, and Table 8 for tabulated calculations). These calculations provide the information required for setting the unbalance protection based on the current between midpoints of two similar legs connected phase to neutral or ground, phase to phase, or in the phase (series capacitors).

c) Tap voltage protection schemes (see 8.4.6 for discussion, Figure 37 for the bank diagram, and Table 9 for tabulated calculations). These calculations provide the information required for setting the unbalance protection based on the following:

    1) Midpoint to ground tap voltages for grounded wye banks

    2) Differential protection, comparing the voltage across one or more series groups with the system line to ground voltage for grounded wye banks

    3) Delta and single-phase bank protection based on schemes similar to item c1) and item c2)

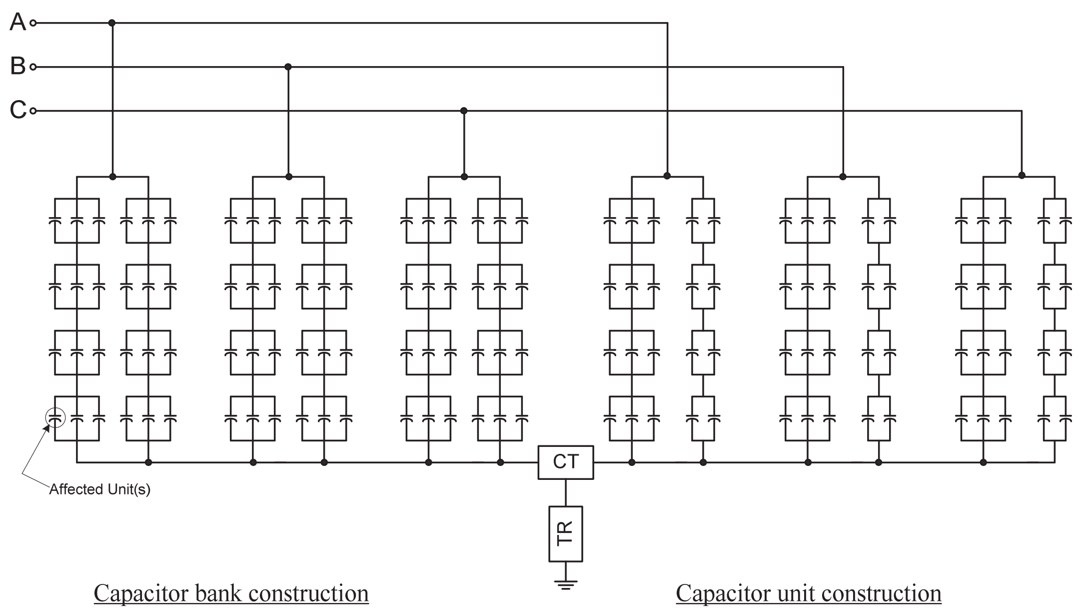
The system of units used for most of these calculations assumes every normal nonzero voltage, capacitance, and current is 1 per-unit under normal conditions, with no fuses having operated (exceptions are indicated).

8.5.4 Unbalance calculations—wye, delta, and single-phase banks

The principal equation for each row of tabulated values is given in the first column of Table 7. [Some equations for the conditions where an element has faulted, but the fuse has not yet blown (SE), are different. Different equations are also used for cases where the equations in Table 7 result in dividing by zero.]

These tabulations illustrate the unbalance that occurs in the affected phase of the bank as a result of individual fuse operations.

Tabulations of the sample bank are provided for both grounded and ungrounded banks. For delta-connected banks, the same formulas and tabulation(s) can be used by treating a leg of the delta as one phase of a grounded wye bank; all formulas are identical. For a delta bank, the currents shown as per-unit-of-phase current become per-unit-of-leg current (phase current divided by $\sqrt{3}$). The difference current (equal wyes) becomes the difference in current between two equal delta-connected legs.



Capacitor bank construction

S = 4 series groups line to neutral
Pt = 11 parallel units per phase
Pa = 6 parallel units per phase in "left" wye
P = 3 parallel units in affected string
G = ? (0 = grounded, 1 = ungrounded)

Capacitor unit construction

N = 14 parallel elements in a group
Su = 3 number of series groups in capacitor unit

Figure 34—Illustration of an uneven double wye-connected bank

NOTE—CT is a current transformer on ungrounded wye-wye banks.

TR in Figure 34 represents a resistor potential device or a voltage transformer on an ungrounded bank; a current transformer or low-voltage capacitor; or a direct ground on a grounded bank.

Table 7—Unbalance calculations for the double wye-connected capacitor bank in Figure 34

Column title	Formula and comment	G	**Number of blown capacitor fuses *f*** [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a faulted element (SE) before the operation of the element fuse.]					
			0	**SE**	**1**	**2**	**3**	**4**
Internal group per-unit capacitance *Ci*	$Ci = \frac{N-f}{N}$ The per-unit capacitance of the group, based on the number of blown fuses.	0	1.0000	SC	0.9286	0.8571	0.7857	0.7143
		1	1.0000	SC	0.9286	0.8571	0.7857	0.7143
Internal group voltage (for capacitor unit at 1 per-unit voltage) *Vg*	$Vg = \frac{Su \times N}{(Su-1)\times(N-f)+N}$ The voltage that would occur across the affected group of elements where the fuses are blowing if there was 1 per-unit voltage on the capacitor unit. For the calculation, the capacitance of all groups except the affected group is 1 per-unit. The capacitance of the affected group is *Ci*.	0	1.0000	0.0000	1.0500	1.1053	1.1667	1.2353
			1.0000	0.0000	1.0500	1.1053	1.1667	1.2353
Capacitor unit per-unit capacitance	$Cu = \frac{Su \times Ci}{Ci \times (Su-1)+1}$ The capacitance of the affected capacitor unit, assuming all		1.0000	1.5000	0.9750	0.9474	0.9167	0.8824

Column title	Formula and comment	G	Number of blown capacitor fuses *f* [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a faulted element (SE) before the operation of the element fuse.]					
			0	**SE**	**1**	**2**	**3**	**4**
Cu	groups except the affected group have 1 per-unit capacitance and the affected group has the capacitance *Ci*.		1.0000	1.5000	0.9750	0.9474	0.9167	0.8824
Parallel group per-unit capacitance *Cg*	$Cg = \frac{P-1+Cu}{P}$ The capacitance of the group of capacitors that includes the affected unit. For all of the units in that group except the affected unit, the per-unit capacitance is 1. For the affected unit, the per-unit capacitance is *Cu*.	0	1.0000	1.1667	0.9917	0.9825	0.9722	0.9608
		1	1.0000	1.1667	0.9917	0.9825	0.9722	0.9608
Affected string capacitance *Cs*	$Cs = \frac{S\times Cg}{Cg\cdot\times(S-1)+1}$ The per-unit capacitance of the string of (parallel groups of) capacitor units from phase to neutral that includes the affected capacitor unit. For the group including the affected unit, the per-unit capacitance is *Cg*. For all other groups, the per-unit capacitance is 1.	0	1.0000	1.0370	0.9979	0.9956	0.9929	0.9899
		1	1.0000	1.0370	0.9979	0.9956	0.9929	0.9899
Per-unit capacitance, phase with affected unit *Cp*	$Cp = \frac{(Cs\times P)+Pt-P}{Pt}$ The per-unit capacitance of the phase (all parallel strings) that includes the affected unit. For this calculation the capacitance of the affected string is *Cs*. The capacitance of all the other strings is 1 per-unit.	0	1.0000	1.0101	0.9994	0.9988	0.9981	0.9972
		1	1.0000	1.0101	0.9994	0.9988	0.9981	0.9972
Neutral-to-ground voltage (per-unit of *Vlg*) *Vng*	$Vng = G\times\left(\frac{3}{2+Cp}-1\right)$ The neutral-to-ground voltage. For grounded banks (*G* = 0), this voltage is always 0. For ungrounded wye banks, the calculation assumes the affected phase has a capacitance *Cp*, and the other two phases each have a per-unit capacitance of 1.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	–0.0034	0.0002	0.0004	0.0006	0.0009
Voltage on affected phase *Vln*	$Vln = Vng + 1$ The voltage line to neutral across the phase that includes the affected unit. With fused units, the operation of the fuse reduces the capacitance of that phase and increases the voltage across the affected phase; therefore, the numbers are always greater than one except before the operation of the fuse on a faulted element.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9966	1.0002	1.0004	1.0006	1.0009
Voltage on affected unit *Vcu*	$Vcu = \frac{Vln\times Cs}{Cg}$ (If *Cg* = 0, *Vcu* = *Vln* × *S*) The actual per-unit voltage on the affected capacitor unit, based on the capacitance division of the actual voltage on the affected phase (*Vln*).	0	1.0000	0.8889	1.0063	1.0133	1.0213	1.0303
		1	1.0000	0.8859	1.0065	1.0137	1.0219	1.0313
Voltage on affected elements *Ve*	$Ve = Vcu\times Vg$ The actual per-unit voltage on the affected elements, based on the actual voltage on the affected unit.	0	1.0000	0.0000	1.0566	1.1200	1.1915	1.2727
		1	1.0000	0.0000	1.0568	1.1205	1.1923	1.2739
Current through affected capacitor(s) *Iu*	$Iu = Vcu\times Cu$ The current through the affected capacitor unit, per-unit of the value with no fuses blown. The value for SE indicates the power frequency current available to blow the fuse on a faulted element. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel elements into the faulted one).	0	1.0000	1.3333	0.9811	0.9600	0.9362	0.9091
		1	1.0000	1.3289	0.9813	0.9604	0.9368	0.9099

Column title	Formula and comment	G	**Number of blown capacitor fuses *f*** [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a faulted element (SE) before the operation of the element fuse.]					
			0	**SE**	**1**	**2**	**3**	**4**
Current in affected string *Ist*	$Ist = Cs \times Vln$ The per-unit current in the affected string. This value may be useful for differential schemes comparing the current in parallel strings.	0	1.0000	1.0370	0.9979	0.9956	0.9929	0.9899
		1	1.0000	1.0336	0.9981	0.9960	0.9935	0.9908
Current in affected phase *Iph*	$Iph = Cp \times Vln$ The current in the affected phase. This equation may be useful for setting protection based on phase current.	0	1.0000	1.0101	0.9994	0.9988	0.9981	0.9972
		1	1.0000	1.0067	0.9996	0.9992	0.9987	0.9982
Ground current change *Ig*	$Ig = (1 - G) \times (1 - Iph)$ For use with protective relay schemes utilizing neutral-to-ground current, or the voltage across a low-voltage capacitor in the neutral or in each phase. The per-unit change in current to ground is the per-unit change in voltage across a low-voltage capacitor in the affected phase. It is also the per-unit change in voltage across a low-voltage capacitor in the neutral-to-ground connection because the other two phase currents do not change in a grounded bank.	0	0.0000	–0.0101	0.0006	0.0012	0.0019	0.0028
		1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Neutral current between wyes *In*	$In = \frac{3 \times Vng \times G \times (Pt - Pa)}{Pt}$ Unbalance current for ungrounded wye-wye banks. [The current is calculated assuming the neutral-to-ground (zero sequence) voltage is applied at the neutral of the unaffected wye, which is half the of the bank].	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	–0.0252	0.0014	0.0030	0.0048	0.0069
Difference current, equal wyes *Id*	$Id = Vln \times (1 - Cp)$ For grounded wye-wye banks where the difference in the neutral current between the two equal wyes is used as a basis for protection. Values are per-unit of total phase current (Figure 35).	0	Applicable to equal wyes only ($Pt = 2 \times Pa$)					
		1	Applicable to equal wyes only ($Pt = 2 \times Pa$)					

NOTE 1—For *Vng* calculations, it is convenient to develop this equation based on an instant in time when the affected phase has 1 per-unit voltage and the other two phases have −0.5 per-unit voltage. For this condition, the two unaffected phases can be paralleled, and the voltage divider between −0.5 per-unit and +1 per-unit can be calculated for the midpoint voltage, which is recorded as *Vng*.

NOTE 2—Calculations above apply to both single and double wye-connected banks; double wye-connected banks calculations are applicable starting from the *Ist* value calculation onward.

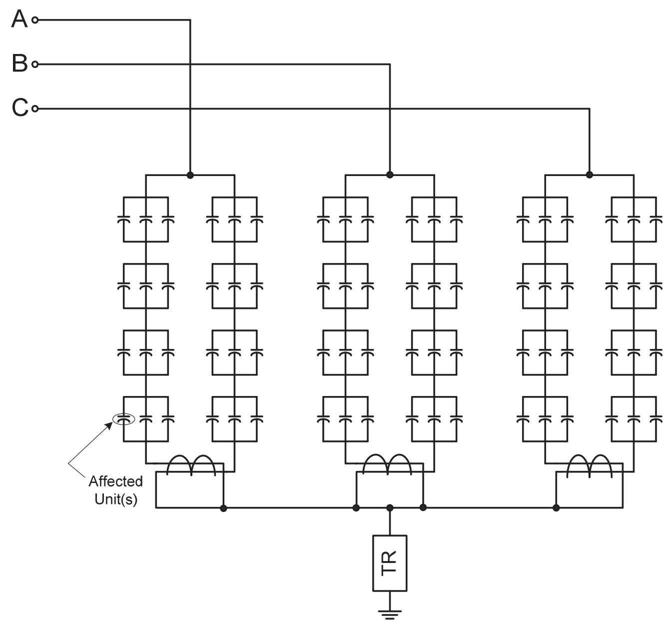


Figure 35—Capacitor bank arranged to measure difference current between two equal legs in each phase (phase current unbalance)

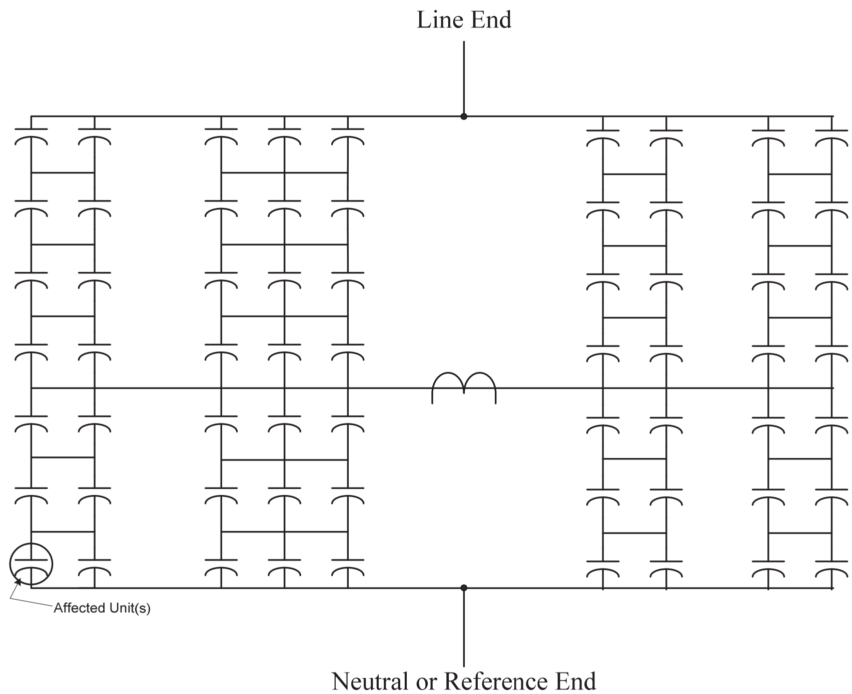
TR in Figure 35 represents a resistor potential device or a voltage transformer on an ungrounded bank or a direct ground on a grounded bank.

8.5.5 Unbalance calculations—H-bridge

An H-bridge may be used for unbalance protection in a variety of capacitor bank connections: grounded wye, ungrounded wye, delta, and single phase (series capacitors). The H-bridge is based on a current measurement in a leg connecting two strings of capacitors together near the midpoints of the strings. The current transformer appears to be on the crossbar of the capital letter H (see Figure 36), thus, the designation H-bridge. Any change in the capacitance of any capacitor in the bridge will cause a change in the current in the H.

Calculations (see Table 8) are based on internal fuse operations in one group of elements in one capacitor unit. The ambiguity resulting from the operation of fuses in another part of the bank that may cancel the unbalance signal needs to be addressed (see 8.3.3).

For an unsymmetrical arrangement such as shown in Figure 36, the effects of blowing fuses in units in other parts of the bank on the overvoltages and H current, and so on, may easily be investigated by appropriately changing the values of *St*, *Pa*, and *P* so that the affected unit appears to be in the lower left part of Table 8. All of these calculations assume that all blown fuses are in one group of the affected unit only.



Capacitor bank construction

S = 7 series groups - total
St = 3 series groups, H leg to neutral
Pt = 9 parallel units per phase
Pa = 5 parallel units on "left" side of H
P = 2 parallel units in affected string
G = ? (0 = grounded, 1 = ungrounded)

Capacitor unit construction

N = 16 parallel elements in a group
Su = 3 number of series groups in capacitor unit

Figure 36—Illustration of one leg of an H-bridge capacitor bank

Table 8—Unbalance calculations for the H-bridge capacitor bank in Figure 36

Column title	Formula and comment	G	Number of blown capacitor fuses *f* [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a shorted element (SE) before the operation of the element fuse.]					
			0	**SE**	**1**	**2**	**3**	**4**
Affected capacitor per-unit capacitance *Cu*	$Cu = Su \times \frac{N-f}{(N-f)\times(Su-1)+N}$ The per-unit capacitance of the affected capacitor unit, based on the number of blown fuses.	0	1.0000	1.5000	0.97826	0.95455	0.92857	0.9000
		1	1.0000	1.5000	0.97826	0.95455	0.92857	0.9000
Capacitance H-bridge to neutral *Chn*	$Chn = \frac{(Cu+P-1)\times P}{(Cu+P-1)\times(St-1)+P} + \frac{Pt-P}{St}$ The capacitance from the H leg to the neutral or reference end on the phase, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	0	3.0000	3.0476	2.9976	2.9949	2.9919	2.9885
		1	3.0000	3.0476	2.9976	2.9949	2.9919	2.9885
Affected phase capacitance *Cp*	$Cp = \frac{Chn\times Pt}{Chn\times(S-St)+Pt}$ The capacitance of the phase from end to end, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	0	1.2857	1.2944	1.2853	1.2848	1.2842	1.2836
		1	1.2857	1.2944	1.2853	1.2848	1.2842	1.2836

Column title	Formula and comment	G	**Number of blown capacitor fuses *f*** [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a shorted element (SE) before the operation of the element fuse.]					
			0	**SE**	**1**	**2**	**3**	**4**
Affected phase voltage *Vln*	$Vln = 1 + G \times \left(\frac{3}{2 + Cp / Cp(0)} - 1 \right)$ The voltage across the affected phase, that is, 1 for grounded wye or delta, where $G = 0$. For ungrounded wye, this voltage is the per-unit voltage across the affected phase including the effect of the neutral shift from capacitance unbalance.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9978	1.0001	1.0002	1.0004	1.0005
H leg voltage, (per-unit of *Vln*) *Vh*	$Vh = \frac{Cp}{Chn}$ The voltage of the H leg, per-unit of the actual voltage on the affected phase.	0	0.4286	0.4247	0.4288	0.4290	0.4292	0.4295
		1	0.4286	0.4247	0.4288	0.4290	0.4292	0.4295
H current, per unit of total phase current *Ih*	$Ih = -Vln \times \left(\frac{St}{S} - Vh \right) \times \left(\frac{1}{S - St} + \frac{1}{St} \right) \times \left(\frac{S \times (Pt - Pa)}{Pt} \right)$ The current in the H leg, per-unit of the normal total phase current for a wye-connected or single-phase bank or per-unit of total leg current for a delta bank.	0	0.0000	–0.0070	0.0004	0.0008	0.0012	0.0017
		1	0.0000	–0.0070	0.0004	0.0008	0.0012	0.0017
Voltage on affected capacitor unit *Vcu*	$Vcu = \frac{V\ln \times Vh \times P \times S}{P + (St - 1) \times (Cu + P - 1)}$ The voltage across the affected capacitor unit, per-unit of the value with no fuses blown.	0	1.0000	0.8494	1.0078	1.0164	1.0260	1.0368
		1	1.0000	0.8475	1.0079	1.0166	1.0264	1.0373
Voltage on affected elements *Ve*	$Ve = \frac{Vcu \times Su \times N}{Su \times (N - f) + f}$ The voltage across the remaining elements in the affected element group (also the voltage across the blown fuses in that group), per-unit of the value with no fuses blown.	0	1.0000	0.0000	1.0516	1.1088	1.1725	1.2441
		1	1.0000	0.0000	1.0517	1.1090	1.1730	1.2448
Current through affected capacitor unit *Iu*	$Iu = Vcu \times Cu$ The current through the affected capacitor unit, per-unit of the value with no fuses blown. The value for SE indicates the power frequency current available to blow the fuse on a faulted element. This value may be used to estimate the maximum clearing time of the fuse (assuming no discharge from parallel elements into the faulted one).	0	1.0000	1.2742	0.9859	0.9702	0.9527	0.9331
		1	1.0000	1.2713	0.9860	0.9704	0.9531	0.9336

8.5.6 Unbalance calculations—(midpoint) tap

A variety of protection schemes, primarily for grounded wye banks, are based on the measurement of a voltage across some number of series groups of the bank. Two common schemes are to perform the following:

— Measure a voltage near the middle of a phase (midpoint tap).

— Measure the voltage across the bottom series group(s).

In either case, the measured voltage may be compared with the phase voltages (differential protection) or combined with each other to determine unbalance.

Regardless of the relay type used, the schemes are based on the change in tap voltage as a result of a change in the capacitance of an affected capacitor unit. This change may depend on whether the affected capacitor unit is located outside or inside the tap portion of the bank. Figure 37 illustrates a midpoint-tapped capacitor bank. Table 9 gives the unbalance calculations for grounded wye or single-phase banks.

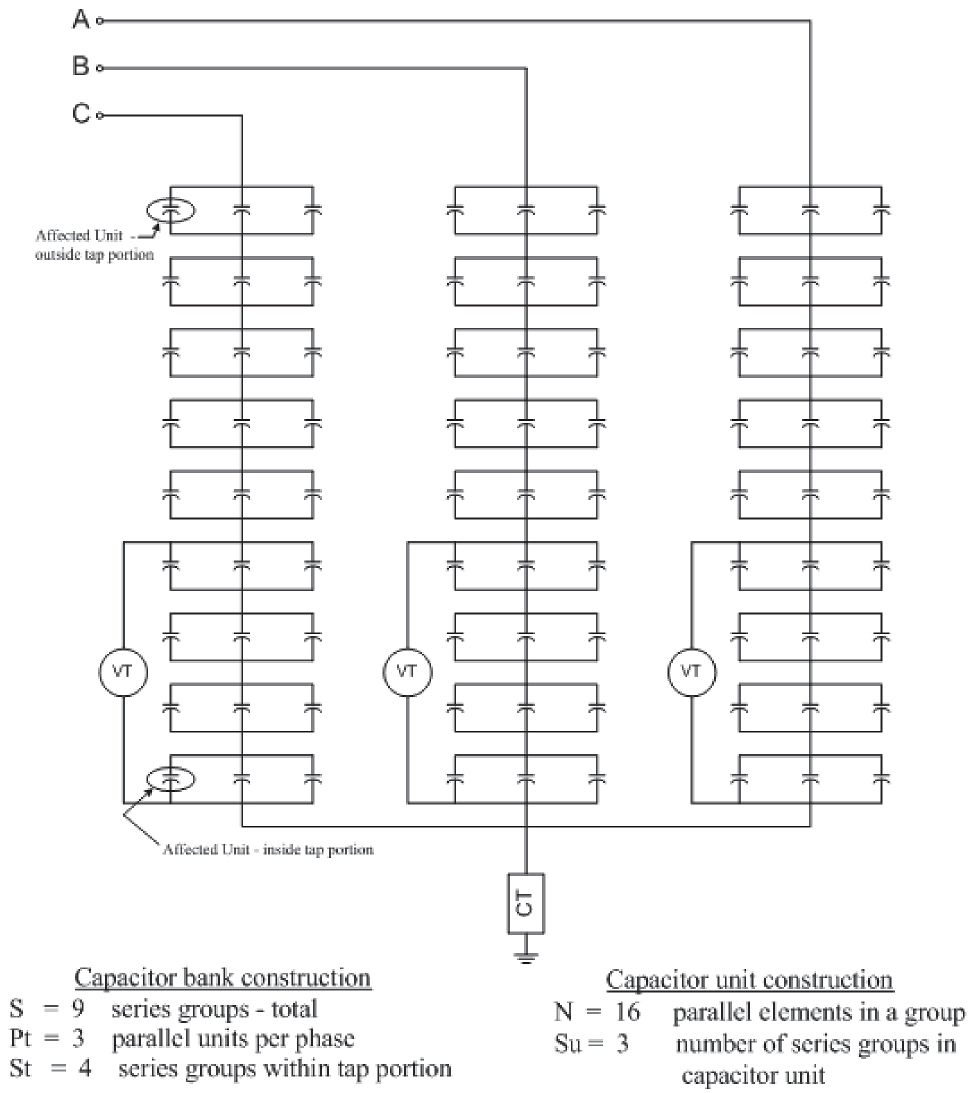


Figure 37 —Illustration of a midpoint-tapped internally fused capacitor bank

Table 9—Unbalance calculations for voltage differential protection for the tapped wye-connected capacitor bank in Figure 37

Column title	Formula and comment	Number of blown capacitor fuses *f* [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a shorted element (SE) before the operation of the element fuse.]					
		0	**SE**	**1**	**2**	**3**	**4**
Affected capacitor per-unit capacitance *Cu*	$Cu = Su \times \frac{N-f}{(N-f)\times(Su-1)+N}$ The per-unit capacitance of the affected capacitor unit, based on the number of blown fuses in one group (in the affected capacitor).	1.0000	1.5000	0.97826	0.95455	0.92857	0.9000
Affected phase capacitance *Cp*	$Cp = \frac{Pt\times(Pt-1+Cu)}{Pt+(Pt-1+Cu)\times(S-1)}$ The capacitance of the phase from end to end, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	0.3333	0.3387	0.3331	0.3328	0.3324	0.3321

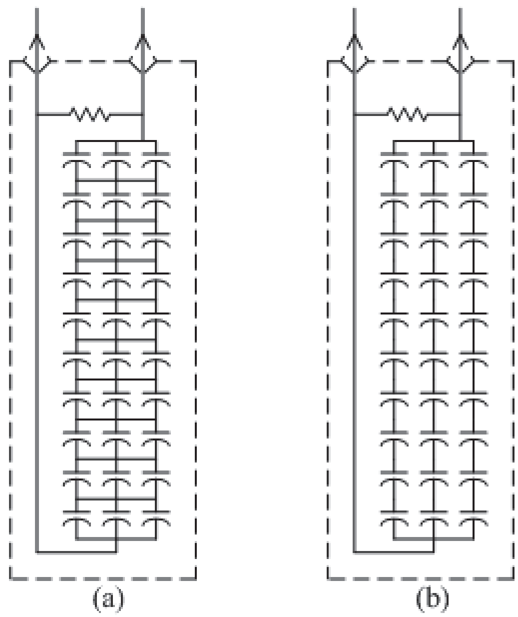
Column title	Formula and comment	Number of blown capacitor fuses *f* [The number of fuses that have blown in one parallel group of elements inside one capacitor unit. *f* = 0 is the system normal condition. *f* = SE is the condition with a shorted element (SE) before the operation of the element fuse.]					
		0	**SE**	**1**	**2**	**3**	**4**
Voltage on affected capacitor group *Vcu*	$Vcu = \frac{Cp \times S}{Pt - 1 + Cu}$ Voltage across the group of capacitors that includes the affected capacitor unit, per-unit of the normal voltage across that group.	1.0000	0.8710	1.0065	1.0137	1.0216	1.0305
Voltage on affected element group *Ve*	$Ve = \frac{Vcu \times Su \times N}{Su \times (N - f) + f}$ The voltage across the remaining elements in the affected element group (also the voltage across the blown fuses in that group), per-unit of the value with no fuses blown.	1.0000	0.0000	1.0502	1.1058	1.1676	1.2366
Current through affected capacitor *Iu*	$Iu = Vcu \times Cu$ The current through the affected capacitor unit, per-unit of the value with no fuses blown. The value for SE indicates the power frequency current available to blow the fuse on a faulted element. This value may be used to estimate the maximum clearing time of the fuse, assuming no discharge from parallel elements into the faulted one).	1.0000	1.3065	0.9846	0.9676	0.9486	0.9275
For affected unit outside tap portion							
Capacitance tap to neutral *Chn*	$Chn = \frac{Pt}{St}$ The capacitance of the tap portion of the phase, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	0.7500	0.7500	0.7500	0.7500	0.7500	0.7500
Tap voltage, per-unit of *Vlg* *Vtg*	$Vtg = \frac{Cp}{Chn}$ The voltage across the tap, assuming 1 per-unit voltage is the actual voltage on the phase.	0.4444	0.4516	0.4441	0.4437	0.4432	0.4427
Tap voltage change, per-unit of normal *dVtg*	$dVtg = \frac{Vtg - Vtg_{(f=0)}}{Vtg_{(f=0)}}$ The per-unit change in the tap voltage, assuming 1 per-unit is the normal tap voltage.	0.0000	0.0161	–0.0008	–0.0017	–0.0027	–0.0038
For affected unit inside tap portion							
Capacitance tap to neutral *Chn*	$Chn = \frac{Pt \times (Pt - 1 + Cu)}{Pt + (Pt - 1 + Cu) \times (St - 1)}$ The capacitance of the tap portion of the phase, assuming the capacitance of one healthy capacitor unit is 1 per-unit.	0.7500	0.7778	0.7486	0.7471	0.7455	0.7436
Tap voltage, per-unit of *Vlg* *Vtg*	$Vtg = \frac{Cp}{Chn}$ The voltage across the tap, assuming 1 per-unit voltage is the actual voltage on the phase.	0.4444	0.4355	0.4449	0.4454	0.4459	0.4466
Tap voltage change, per-unit of normal *dVtg*	$dVtg = \frac{Vtg - Vtg_{(f=0)}}{Vtg_{(f=0)}}$ The per-unit change in the tap voltage, assuming 1 per-unit is the normal tap voltage.	0.0000	–0.0202	0.0010	0.0021	0.0034	0.0048

8.6 Fuseless capacitor banks

8.6.1 General considerations

The internal construction of the capacitor units used in fuseless capacitor banks is similar to that used for externally fused banks. The parallel-connected capacitor unit of Figure 38(a) illustrates a unit with 10 series groups of three elements each. In this construction, if one element fails, then it short-circuits itself and the two elements in parallel with it.

In the capacitor bank, individual capacitor units are connected in series with each other from the phase connection to the neutral connection. Each such series connection is a “string.” Within the string, all of the elements (groups) are in series with each other. For instance, if the string consists of six capacitor units, each having eight series (groups of) elements, the string would have 6 × 8 = 48 elements in series (see Figure 39). If one of the elements fails, the applied voltage is then divided among the remaining (groups of) healthy elements in series with the faulted element. The voltage across the remaining elements will thus be 48/47 of what it had been before the failure.



a) Parallel-connected capacitor unit
b) Series-connected capacitor unit

Figure 38—Schematic of a fuseless capacitor unit

The calculation of unbalance performance of fuseless capacitor banks is based on the number of failed elements (element groups) and on the total number of (groups of) elements in series.

On occasion, series connected capacitor units [see Figure 38(b)] have been offered for fuseless capacitor banks. Series connected capacitor units have the individual elements connected in series strings between the terminals, with a number of such series strings in each unit. Banks built with series connected capacitor units need more sensitive unbalance protection requiring an advanced protection compensating system to correct for inherent unbalances and utilizing biasing for security.

As indicated, the number of elements in series in a string is the number of capacitor units in series times the number of elements in series in each capacitor unit. Sometimes the manufacturer will provide the number of elements in series. See the capacitor unit nameplate or data sheet. If the number of series elements per capacitor unit is not available from the manufacturer, then the number may be estimated. Each element usually has a nominal voltage rating of 1800 V to 2400 V. Dividing the capacitor unit voltage by 2400 and rounding up to the next integer will usually give a useable estimate for the unbalance calculations and settings. For instance, a 7960 V capacitor unit will probably have about 7960 / 2400 = 3.3, which rounds up to four series elements. (It may have five series elements per capacitor unit, which will make a small difference in the overvoltages and unbalance signals. However, the settings based on four series elements will still provide adequate protection for the five series element design.)

In a fuseless capacitor bank, the unbalance detection gives an indication of the total number of failed elements within a string of capacitor units. The location of these failures is determined by capacitance measurements on the strings indicated by the unbalance protection.

8.6.2 Using the calculated values

The trip level should be set so that the voltage on the remaining elements in the affected string does not exceed the maximum recommended by industry standards or the manufacturer.

The number of shorted elements for trip and alarm can be determined by knowing the voltage on the affected elements (for instance, the *Ve* value calculated in Table 10) and the capability of the elements (either 110% of rating based on industry standards or the information provided by the capacitor manufacturer). Based on the example calculated in Table 10, for standard capacitor units applied at rated voltage and element capability of 110%, tripping should occur after the shorting of the fifth element. At this point, the voltage on the remaining elements is 110.2%.

Calculations may also be made without knowing the number of series elements by using the total string capacitance and tripping on the capacitance change that will result in a 110% voltage on the remaining capacitors in the string. Also, to avoid case rupture in the event of a terminal-to-case fault, the bank should trip on the loss of elements equivalent to the shorting of one capacitor unit. For capacitor banks with more than 10 capacitor units per string, the tripping for the loss of one capacitor unit will be lower than 110% voltage on the remaining units.

To verify that elements are not subjected to voltages in excess of their intended application, the trip would normally be set halfway between the signal associated with four shorted elements and the signal associated with five shorted elements (for the example calculated in Table 10). Alternatively, the trip relay may be set at an unbalance that would result in 110% voltage on the remaining elements.

In managing the protection of a fuseless capacitor bank, the unbalance protection should not be reset or "rebalanced" without first verifying that all capacitor units with failed elements have been removed from the bank and replaced with healthy capacitor units. If the installation is to be rebalanced with units having one (or two) shorted elements remaining in service, then the trip level should be adjusted downward so that the elements in these units do not exceed their capability before operation of the trip relay.

The time delay for tripping should be minimized to minimize the probability of major damage in the event of a major problem in the bank. Practical limitations on the minimum time include the following:

a) Preventing a bank that is operating in the alarm state from tripping on a system transient overvoltage.
b) Accounting for the settling time of the protection system on initial energization and for the transient response of certain capacitor voltage transformers, and so on, which may be a part of the unbalance protection system.
c) Preventing smaller banks that do not incorporate system unbalance compensation in the protection scheme from tripping during a system fault.

Normally a time delay of 0.01 s to 0.05 s is adequate for this coordination. With this intentional time delay in the trip relay, the additional time required for the lockout relay and breaker operation may result in total clearing times of the order of 0.1 s. A time of 0.1 s is reasonably achievable to clear a capacitor bank with a problem, but it still may result in substantial damage. Once parts of a capacitor bank start to become damaged, further damage will escalate rapidly. Such escalation will increase the risk of other damage in the substation. Keeping the clearing time short is important to minimizing damage in the event of a fault within a bank.

Longer time delays are sometimes used for uncompensated protection (to avoid tripping during a system fault that may persist for a longer period of time), and the risk of major damage in the bank is accepted. Other users may allow the bank to trip for these conditions in order to minimize the possibility of bank damage.

The alarm would be set above natural errors so that it would operate reliably on the shorting of the first or second element. This alarm set point would typically be halfway between the signal associated with the selected number of shorted elements and the signal associated with one fewer shorted elements.

Generally, the most appropriate alarm level is the lowest level that can be set without resulting in false alarms from thermal variations in capacitance within the bank, practical initial bank balance, and so on. (The earliest reliable alarm gives maximum opportunity to repair the capacitor bank during a scheduled outage.) Responding reasonably to early alarms and maintaining the bank in the best possible condition tend to minimize the probability of further element failures and forced or unscheduled outages and to maximize the availability of the bank. False or unreliable alarms can be costly, and they reduce the credibility of the capacitor protection.

In unbalance protection schemes with ambiguous indication, it is desirable to use an alarm setting sensitive to the loss of the first element to avoid any ambiguity. This alarm should seal in so that it should be manually reset after the removal of the failed capacitor unit(s) from the bank. It would be undesirable to have the alarm go away after the shorting of a subsequent element that cancels the unbalance signal.

The timing of the alarm should be long enough to avoid operation during system faults or temporary overvoltages but short enough in the case of ambiguous schemes to minimize the probability of two compensating fuse operations before the initiation of the alarm. Usually about a 10 s delay is appropriate for the alarm.

8.6.3 Introduction to capacitor bank unbalance calculations

The sample calculations in 8.6.4 provide the information required for setting the unbalance protection based on the following:

a) Neutral-to-ground voltage for ungrounded wye banks
b) Neutral current for ungrounded wye-wye banks
c) Neutral voltage difference for ungrounded wye-wye banks
d) Neutral-to-ground current for grounded wye banks
e) Voltage across low-voltage capacitors at the neutral end of each phase or in the neutral-to-ground connection of grounded wye banks
f) Difference in neutral-to-ground currents for grounded wye-wye banks
g) Delta and single-phase bank protection based on schemes similar to item a) through item f).

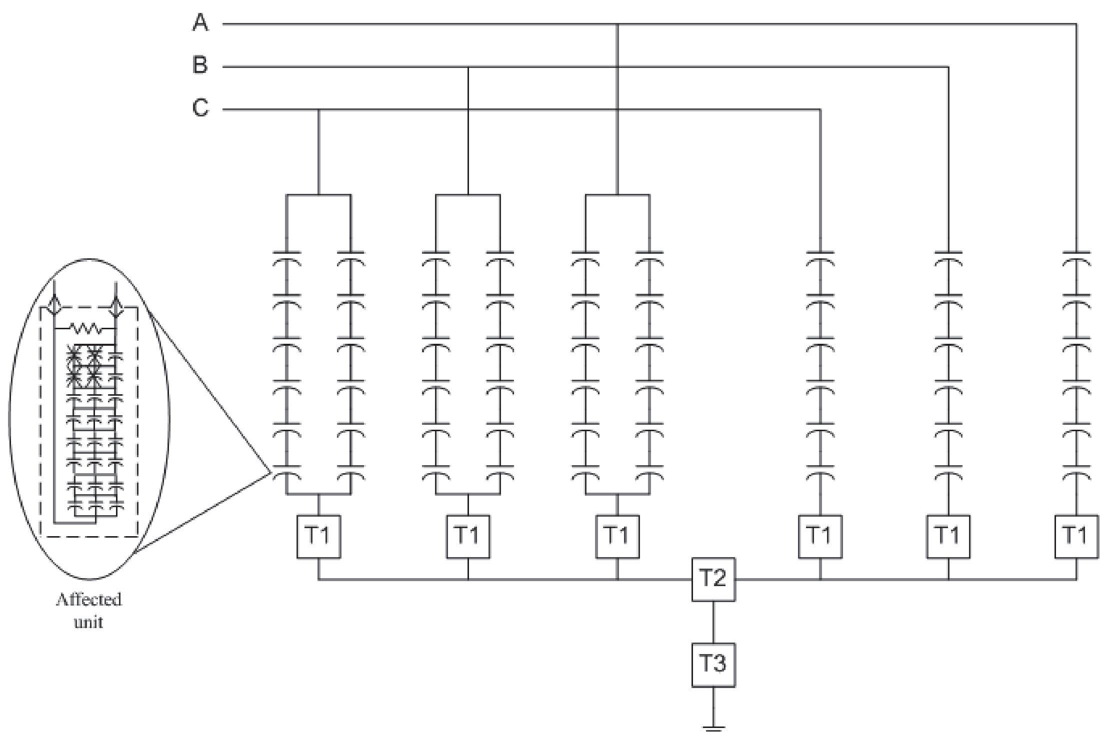
The system of units used for most of these calculations assumes every normal nonzero voltage, capacitance, and current is 1 per-unit under normal conditions, with no shorted elements.

In addition to providing the necessary information for protective relay settings, this type of tabulation gives a good feel for the performance of the bank with varying numbers of shorted elements. Some manufacturers of fuseless capacitor banks will provide this type of tabulation for the banks they propose or supply.

It is, of course, possible to combine the calculations of the various columns and to calculate only the voltage on the affected elements, the voltage on the affected unit (which is also the voltage on the parallel units), and the unbalance signal for the type of protection to be utilized. Because of the complexity of the configuration (for example, parallel elements and series groups in a capacitor unit, parallel capacitor units in a group, series groups in a string, and parallel strings in a phase), the resulting equations become complex.

8.6.4 Unbalance calculations

Figure 39 illustrates a generalized wye-connected fuseless capacitor bank. The figure shows two strings in the left wye and one string in the right wye. In the calculations of Table 10, the total number of strings (*Sp*) and the number of strings in the left wye (*Sl*) can be specified. For a single-wye bank, *Sl* = *Sp*. For the calculations, all failures are assumed to be in the leftmost string. This string is defined as one string. If other strings have more or less capacitance than the leftmost string, then they may be specified as fractional strings. For instance, if the leftmost string is made up of 400 kvar units and one of the other strings is made up of the same number and voltage rating of 600 kvar units, the string with the 600 kvar units would be considered 1.5 strings for calculation purposes. For the example of Figure 39, the bank is considered to have two strings in each phase of the left wye (*Sl*) and three strings in each phase of the bank (*Sp*). With such an unbalanced arrangement, the calculations would normally be done both with *Sl* = 2 and *Sl* = 1 to investigate the effects of failures in both wyes.



Note: T1, T2, And T3 are the appropriate low voltage capacitors, current transformers, voltage transformers, etc. for the protection being used.

Capacitor bank construction

E = 48 series elements, phase to neutral
Sp = 3 parallel units per phase
Sl = 6 parallel units per phase in "left" wye
G = ? (0 = grounded, 1 = ungrounded)

Figure 39—Unsymmetrical fuseless double wye-connected capacitor bank

The principal equation for each calculated value is given in the second column of Table 10. These tabulations illustrate the unbalance that occurs in the affected phase of the bank as a result of the shorting of elements in one string.

The actual unbalance signal will depend on the protection scheme employed for the bank. A wide variety of protection schemes are in use on fuseless shunt capacitor banks. The unbalance signals for usual connections are given in Table 10.

The column headings in the tabulations are based on wye-connected, three-phase capacitor banks. For delta-connected banks, the same formulas and tabulation(s) can be used by treating a leg of the delta as one phase of a grounded wye bank; all formulas are identical. For a delta bank, the currents shown as per-unit-of-phase current become per-unit-of-leg current (phase current divided by). The difference current (equal wyes) becomes the difference in current between two equal delta-connected legs.

Table 10 —Unbalance calculations for the fuseless double wye-connected capacitor bank in Figure 39

Column title	Formula and comment	G	Number of shorted capacitor elements *e* (The number of elements that have shorted in one string of elements between phase and neutral.) 0	1	2	3	4	5
String per-unit capacitance *Cst*	$Cst = \frac{E}{E-e}$ The capacitance of the affected string of capacitor units.	0	1.0000	1.0213	1.0435	1.0667	1.0909	1.1163
		1	1.0000	1.0213	1.0435	1.0667	1.0909	1.1163
Affected wye capacitance *Cy*	$Cy = \frac{Sl-1+Cst}{Sl}$ The capacitance of all strings of capacitors in phase of the wye that includes the affected string. For all of the strings in that wye except the affected string, the per-unit capacitance is Sl – 1. For the affected string, the per-unit capacitance is *Cst*.	0	1.0000	1.0106	1.0217	1.0333	1.0455	1.0581
		1	1.0000	1.0106	1.0217	1.0333	1.0455	1.0581
Affected per-unit phase capacitance *Cp*	$Cp = \frac{(Cy \times Sl) + Sp - Sl}{Sp}$ The per-unit capacitance of the phase (all parallel strings) that includes the affected string. For this calculation the capacitance of the affected wye is Cy. The capacitance of the other wye is 1 per-unit.	0	1.0000	1.0071	1.0145	1.0222	1.0303	1.0388
		1	1.0000	1.0071	1.0145	1.0222	1.0303	1.0388
Neutral-to-ground voltage (per-unit of *Vlg*) *Vng*	$Vng = G \times \left(1 - \frac{3}{2+Cp}\right)$ For grounded banks ($G = 0$), this voltage is always 0. For ungrounded wye banks, the calculation assumes the affected phase has a capacitance *Cp* and the other two phases each have a per-unit capacitance of 1.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	0.0024	0.0048	0.0074	0.0100	0.0128
Voltage on affected phase *Vln*	$Vln = 1 - Vng$ The voltage line to neutral across the phase that includes the affected string. With fuseless capacitor banks, the shorting of elements increases the capacitance of that phase and decreases the voltage across the affected phase; therefore, the voltage is always less than 1 per-unit with shorted elements, except with grounded wye banks.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9976	0.9952	0.9926	0.9900	0.9872
Voltage on affected elements *Ve*	$Ve = Vln \times \frac{E}{E-e}$ The per-unit voltage on the remaining elements in the affected string, based on the actual voltage on the affected string.	0	1.0000	1.0213	1.0435	1.0667	1.0909	1.1163
		1	1.0000	1.0189	1.0385	1.0588	1.0800	1.1020
Current in affected wye *Iy*	$Iy = Cy \times Vln$ The per-unit current in the affected phase of the affected	0	1.0000	1.0106	1.0217	1.0333	1.0455	1.0581

Column title	Formula and comment	G	Number of shorted capacitor elements ***e*** (The number of elements that have shorted in one string of elements between phase and neutral.)					
			0	**1**	**2**	**3**	**4**	**5**
	wye. This equation may be useful for estimating the increase in voltage across a low-voltage capacitor at the neutral end of the affected phase of the affected wye.	1	1.0000	1.0083	1.0168	1.0257	1.0350	1.0446
Current in affected phase *Iph*	$Iph = Cp \times Vln$ The current in the affected phase. This equation may be useful for setting protection based on phase current or the voltage across a low capacitor at the neutral end of the affected phase.	0	1.0000	1.0071	1.0145	1.0222	1.0303	1.0388
		1	1.0000	1.0047	1.0096	1.0147	1.0200	1.0255
Ground current change *Ig*	$Ig = (1 - G) \times (1 - Iph)$ For use with protective relay schemes utilizing neutral-to-ground current, or the voltage across a low-voltage capacitor in the neutral-to-ground connection.	0	0.0000	–0.0071	–0.0145	–0.0222	–0.0303	–0.0388
	The per-unit change in current to ground is the per-unit change in voltage across a low-voltage capacitor in the affected phase. It is also the per-unit change in voltage across a low-voltage capacitor in the neutral-to-ground connection because the other two phase currents do not change in a grounded bank.	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Neutral current between wyes *In*	$In = \frac{3 \times Vng \times G \times (Sp - Sl)}{Sp}$ The unbalance current for ungrounded wye-wye banks.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	[The current is calculated assuming the neutral-to-ground (zero sequence) voltage is applied at the neutral of the unaffected wye.]	1	0.0000	0.0024	0.0048	0.0074	0.0100	0.0128
Difference current, equal wyes *Id*	$Id = Vln \times (1 - Cp)$ For grounded wye-wye banks where the difference in the neutral current between the two equal wyes is used as a basis for protection. Values are per-unit of total phase current	0	Applicable to equal wyes only (Sp = 2 × Sl)					
		1	Not applicable					

NOTE 1—For *Vng* calculations, it is convenient to develop this equation based on an instant in time when the affected phase has 1 per-unit voltage and the other two phases have –0.5 per-unit voltage. For this condition, the two unaffected phases can be paralleled, and the voltage divider between –0.5 per-unit and +1 per-unit can be calculated for the midpoint voltage, which is recorded as *Vng*.

NOTE 2—Calculations above apply to both single and double wye-connected banks; double wye-connected banks calculations are applicable starting from the *Iy* value calculation onward.

8.7 Unfused capacitor banks

8.7.1 General considerations

This subclause covers the formulas for unbalance calculations for unfused capacitor banks built in the same way as conventional externally or internally fused banks (groups of capacitor units in parallel with each other and the groups connected in series from phase to neutral or ground) but with no fuses either internally or externally. These banks are normally of modest size; therefore, fuses or subdivision of the bank into multiple strings are not required to limit the energy into a fault within the bank.

Capacitor units in unfused capacitor banks are subject to overvoltage across elements within a unit as elements become shorted within the unit. The overvoltage on these remaining elements should be considered in the protection of unfused capacitor banks. Excessive voltage on remaining elements may lead to cascading violent failure during system transient overvoltages. This consideration of excessive voltage on remaining elements is in addition to the usual considerations of protection for external arcing within the bank and avoiding exposure of healthy capacitor units to voltages in excess of 110% of their rated voltage.

In an unfused capacitor bank, the unbalance detection gives an indication of the number of failed element groups within one capacitor unit. In practice, the actual number of failed elements throughout the bank can only be determined by a measurement of all series groups in a bank. This measurement may be recommended only when an alarm or relay trip has occurred and may or may not be a part of the regular maintenance schedule.

To calculate the overvoltage on the remaining element groups in a capacitor unit, the number of element groups in each capacitor unit should be specified. Sometimes the manufacturer will provide the number of elements in the series. See the capacitor unit nameplate or data sheet. If the number of series elements per capacitor unit is not available from the manufacturer, then the number may be estimated. Each element usually has a nominal voltage capability of between 1800 V and 2400 V. Dividing the capacitor unit voltage by 2400 and rounding up to the next integer will usually give a useable estimate for the unbalance calculations and settings. For instance, a 7960 V capacitor unit will probably have about 7960 / 2400 = 3.3, which rounds up to four series elements. (It may have five series elements per capacitor unit, which will make a small difference in the overvoltage and unbalance signals. However, the setting based on four series elements will still provide adequate protection for a five series element design.)

8.7.2 Using the calculated values

The trip level should be set as follows:

- The voltage on the remaining elements in the affected capacitor unit does not exceed the maximum recommended by the manufacturer.
- The voltage on the healthy capacitors does not exceed the contingency overvoltage capability of the capacitor units (usually 110% of rated voltage).

For simplicity, the protection may be set to trip on the shorting of the first element group.

The number of shorted element groups for trip and alarm can be determined by knowing the voltage on the remaining elements in the capacitor unit with the shorted element group(s) (for instance, the Ve value calculated in Table 11) and the capability of the capacitor units based on the information provided by the manufacturer. Based on the example calculated in Table 11, for capacitor units with an element capability of 125%, tripping should occur after the shorting of the third element group. At this point, the voltage on the remaining elements is 139%.

To ascertain reliable operation after the shorting of the third element, the trip level would be normally set midway between the unbalance signal associated with two operated elements and the unbalance signal with three shorted elements. Alternatively, the trip relay could be set at an unbalance that would result in 125% voltage on the remaining elements.

If the capacitor unit capability is not available from the manufacturer, then usually a value of about 125% on the stressed elements is reasonable if a restrike free switch or circuit breaker is being used or the installation is being protected with surge arresters at or below 2 per-unit. For an energizing transient voltage of 2 per-unit, the remaining element groups would be subjected to a stress of (2 × 1.25 =) 2.5 per-unit, which should be within the capability of standard capacitor units.

The alarm would be set above natural errors so that it would operate reliably on the shorting of the first element. This alarm set point would typically be 50% to 75% of the signal associated with one shorted element. For unbalance protection schemes with ambiguous indication, this alarm should seal in so that it should be manually reset after the removal of the failed capacitor units from the bank. It would be undesirable to have the alarm turn off after the shorting of a subsequent element that cancels the unbalance signal.

The actual unbalance signal will depend on the protection scheme employed for the bank. A wide variety of protection schemes is available for use on unfused shunt capacitor banks. The unbalance signals for some of the more common connections are given in Table 11.

The time delay for tripping should be minimized to decrease the probability of case rupture or excessive damage in the event of an internal capacitor unit fault to the case or an arcing fault in the capacitor bank. Practical limitations on the minimum time include the following:

a) To avoid tripping during a nearby system fault (for protection systems sensitive to unbalanced system voltages)
b) To avoid a bank that is operating in the alarm state from tripping on a system temporary overvoltage
c) To account for the settling time of the protection system on initial energization and for the transient response of certain capacitor voltage transformers, which may be a part of the unbalance protection system

Normally, a time delay of 0.01 s to 0.05 s is adequate for this coordination. With this intentional time delay in the trip relay, the additional time required for the lockout relay and breaker operation may result in total clearing times of the order of 0.1 s for a capacitor unit with an internal fault or a capacitor bank with an arcing fault. A time of 0.1 s is reasonably achievable to clear a capacitor bank with a problem but still may result in substantial damage. Once parts of a capacitor bank start to become damaged, further damage will escalate rapidly. Such escalation will increase the risk of major damage and fire and may result in increased damage to the capacitor bank. Keeping the clearing time short is important to minimize damage when a fault occurs within a bank.

The timing of the alarm should be long enough to avoid operation during system faults or temporary overvoltages but short enough in the case of ambiguous schemes to minimize the probability of two compensating fuse operations before the initiation of the alarm. Usually about a 10 s delay is appropriate for the alarm.

In managing the protection of an unfused capacitor bank, the unbalance protection should not be reset or “rebalanced” without first assuring that all capacitor units with failed elements have been removed from the bank and replaced with healthy capacitor units.

8.7.3 Introduction to capacitor bank unbalance calculations

The sample calculations in 8.7.4 provide the information required for setting the unbalance protection based on the following:

a) Neutral-to-ground voltage for ungrounded wye banks
b) Neutral current for ungrounded wye-wye banks
c) Neutral voltage difference for ungrounded wye-wye banks
d) Neutral-to-ground current for grounded wye banks
e) Voltage across low-voltage capacitors at the neutral end of each phase or in the neutral-to-ground connection of grounded wye banks
f) Difference in neutral-to-ground currents for grounded wye-wye banks
g) Delta and single-phase bank protection based on schemes similar to item a) through item f)

The system of units used for most of these calculations assumes every normal nonzero voltage, capacitance, and current is 1 per-unit under normal conditions, with no shorted elements.

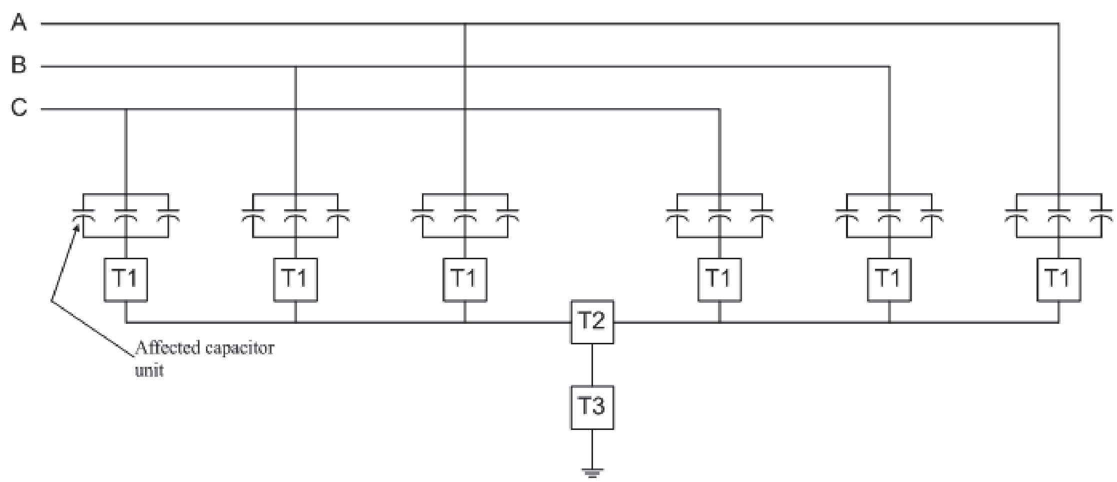
In addition to providing the necessary information for protective relay settings, this type of tabulation gives a good feel for the performance of the bank with varying numbers of shorted elements. Some manufacturers of unfused capacitor banks will provide this type of tabulation for the banks they propose or supply.

It is, of course, possible to combine the calculations of the various columns and to calculate only the voltage on the affected elements, the voltage on the affected unit (which is also the voltage on the parallel units), and the unbalance signal for the type of protection to be utilized. Because of the complexity of the configuration (for example, parallel elements and series groups in a capacitor unit, parallel capacitor units in a group, series groups in a string, and parallel capacitor units in a phase), the resulting equations become complex.

8.7.4 Unbalance calculations

Table 11 illustrates unbalance calculations for unfused capacitor banks when elements (element groups) are shorted in one capacitor unit. The principal equation for each calculated values is given in the second column of Table 11.

The row headings in the tabulations are based on wye-connected, three-phase capacitor banks. For delta-connected banks, the same formulas and tabulation(s) can be used by treating a leg of the delta as one phase of a grounded wye bank; all formulas are identical. For a delta bank, the currents shown as per-unit of-phase current become per-unit-of-leg current (phase current divided by √3). The difference current (equal wyes) becomes the difference in current between two equal delta-connected legs.



(Note: T1, T2, and T3 are the appropriate low voltage capacitors, current transformers, voltage transformers, etc., for the protection being used.)

Capacitor bank construction

S = 1 series groups
Pt = 6 parallel units per phase
Pa = 3 parallel units per phase in "left" wye
G = ? (0 = grounded, 1 = ungrounded)

Capacitor unit construction

Su = 10 number of series groups in capacitor unit

Figure 40 —Unfused wye-wye capacitor bank

Table 11 —Unbalance calculations for the unfused capacitor bank in Figure 40

Column title	**Formula and comment**	**G**	**Number of shorted capacitor elements *e*** [The number of elements (element groups) that have shorted inside one capacitor unit.]					
			0	**1**	**2**	**3**	**4**	**5**
Capacitor unit per-unit capacitance *Cu*	$Cu = \frac{Su}{Su-e}$ The capacitance of the affected capacitor unit based on number of shorted elements.	0	1.0000	1.1111	1.2500	1.4286	1.6667	2.0000
		1	1.0000	1.1111	1.2500	1.4286	1.6667	2.0000
Parallel group per-unit capacitance *Cg*	$Cg = \frac{Pa-1+Cu}{Pa}$ The capacitance of the group of capacitors that includes the affected unit. For all of the units in that group except the affected unit, the per-unit capacitance is 1. For the affected unit, the per-unit capacitance is *Cu*.	0	1.0000	1.0370	1.0833	1.1429	1.2222	1.3333
		1	1.0000	1.0370	1.0833	1.1429	1.2222	1.3333
Affected wye capacitance *Cs*	$Cs = \frac{S \times Cg}{Cg \times (S-1)+1}$ The per-unit capacitance of the (phase of) the wye that includes the affected capacitor unit. For the series group including the affected unit, the per-unit capacitance is *Cg*. For all other series groups, the per-unit capacitance is 1.	0	1.0000	1.0370	1.0833	1.1429	1.2222	1.3333
		1	1.0000	1.0370	1.0833	1.1429	1.2222	1.3333
Affected per-unit phase Capacitance *Cp*	$Cp = \frac{Cs \times Pa + Pt - Pa}{Pt}$ The per-unit capacitance of the phase (both wyes) that includes the affected unit. For this calculation, the capacitance of the affected wye is *Cs*. The capacitance of the other wye is 1 per-unit.	0	1.0000	1.0185	1.0417	1.0714	1.1111	1.1667
		1	1.0000	1.0185	1.0417	1.0714	1.1111	1.1667
Neutral-to-ground voltage (per-unit of *Vlg*) *Vng*	$Vng = G \times \left(1 - \frac{3}{2+Cp}\right)$ For grounded banks ($G = 0$), this voltage is always 0. For ungrounded wye banks, the calculation assumes the affected phase has a capacitance *Cp*, and the other two phases each have a per-unit capacitance of 1.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		1	0.0000	0.0061	0.0137	0.0233	0.0357	0.0526
Voltage on affected phase *Vln*	$Vln = 1 - Vng$ The voltage line to neutral across the phase that includes the affected unit. With unfused banks, the shorting of the elements increases the capacitance of that phase and decreases the voltage across the affected phase; therefore, the numbers are always less than 1.	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
		1	1.0000	0.9939	0.9863	0.9767	0.9643	0.9474
Voltage on affected unit *Vcu*	$Vcu = \frac{Vln \times Cs}{Cg}$ The actual per-unit voltage on the affected capacitor unit, based on the capacitance division of the actual voltage on the affected phase (*Vln*).	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
			1.0000	0.9939	0.9863	0.9767	0.9643	0.9474
Voltage on affected elements *Ve*	$Ve = Vcu \times Cu$ The actual per-unit voltage on the remaining elements in the affected capacitor unit, based on the actual voltage on the affected capacitor unit.	0	1.0000	1.1111	1.2500	1.4286	1.6667	2.0000
		1	1.0000	1.1043	1.2329	1.3953	1.6071	1.8947
Highest voltage on other units *Vh*	The highest voltage on capacitor units in the bank. For multiple-series groups, the capacitors are in the same phase and the per-unit voltage is $Vh = \frac{S-Vcu}{S-1}$ For single-series group banks, the overvoltage of interest is in the other two phases: $Vh = \sqrt{0.5^2 + \left(\sqrt{3} \div 2 + Vng\right)^2}$	0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
			1.0000	1.0053	1.0119	1.0202	1.0311	1.0459
Affected wye	$Iy = Cs \times Vln$	0	1.0000	1.0370	1.0833	1.1429	1.2222	1.3333

Column title	Formula and comment	G	Number of shorted capacitor elements *e* [The number of elements (element groups) that have shorted inside one capacitor unit.]					
			0	**1**	**2**	**3**	**4**	**5**
current *Iy*	The per-unit current in the affected phase of the affected wye.	1	1.0000	1.0307	1.0685	1.1163	1.1786	1.2632
Affected phase current *Iph*	$Iph = Cp \times Vln$ The per-unit current in the affected phase of the bank.	0	1.0000	1.0185	1.0417	1.0714	1.1111	1.1667
		1	1.0000	1.0123	1.0274	1.0465	1.0714	1.1053
Neutral-to-ground current *Ig*	$Ig = (1 - G) \times (1 - Iph)$ The neutral-to-ground current, which is used with protective relay schemes utilizing neutral-to-ground current, or the voltage across a low-voltage capacitor in the neutral or in each phase.	0	0.0000	–0.0185	–0.0417	–0.0714	–0.1111	–0.1667
	The per-unit change in current to ground is the per-unit change in voltage across a low-voltage capacitor in the affected phase. It is also the per-unit change in voltage across a low-voltage capacitor in the neutral-to-ground connection because the other two phase currents do not change in a grounded bank.	1	Not applicable					
Neutral current between wyes *In*	$In = \frac{3 \times Vng \times G}{2}$ The unbalance current for ungrounded wye-wye banks.	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	[The current is calculated assuming the neutral-to-ground (zero sequence) voltage is applied at the neutral of the unaffected wye, which is half the bank.]		0.0000	0.0092	0.0205	0.0349	0.0536	0.0789
Difference current, equal wyes *Id*	$Id = Vln \times (Cp - 1)$ For grounded wye-wye banks where the difference in the neutral current between the two equal wyes is used as a basis for protection. Values are per-unit of normal (total) phase current.	0	0.0000	0.0185	0.0417	0.0714	0.1111	0.1667
		1	Not applicable					

NOTE 1—For *Vng* calculations, it is convenient to develop this equation based on an instant in time when the affected phase has 1 per-unit voltage and the other two phases have –0.5 per-unit voltage. For this condition, the two unaffected phases can be paralleled, and the voltage divider between –0.5 per-unit and +1 per-unit can be calculated for the midpoint voltage, which is recorded as *Vng*.

NOTE 2—Calculations above apply to both single and double wye-connected banks; double wye-connected banks calculations are applicable starting from the *Iy* value calculation onward.

9. Protection of capacitor filter banks

9.1 Filter bank protection

Capacitor units used in filter banks may be required to have more stringent ratings than typical capacitor units due to the harmonics normally present in the filter bank environment. In these applications, higher capacitor voltage ratings and fuse current ratings may be required. Generally, the additional overloading specifications on the various filter bank components should accommodate the higher peak voltages and the increased losses imposed on the reactors and resistor assemblies. For more details on applications, please refer to IEEE Std 1531™.

Figure 41 illustrates one possible primary protection scheme for a solidly grounded-wye connected filter bank (redundant protection is typically applied but is not shown in figure). Note that the "H" arrangement of the four C_2 capacitors results in an equivalent capacitance of C_2 and likewise that the "H" arrangement of the four C_1 capacitors results in an equivalent capacitance of C_1. The reactor L and capacitor C_2 are tuned to the fundamental frequency (f_o, typically 50 Hz or 60 Hz) to minimize the fundamental frequency losses in R.

$$f_0 = \frac{1}{2\pi\sqrt{LC_2}}$$

C_1 is selected so that its series combination with C_2 and L tunes to the frequency that is desired to be filtered.

$$f = \frac{1}{2\pi\sqrt{\frac{L\,C_1C_2}{C_1+C_2}}}$$

Figure 42 shows a similar protection scheme for an ungrounded-wye connected filter bank.

9.1.1 Overcurrent and overload protection

The overcurrent function (50/51) provides fast tripping for high-level short circuits near the circuit breaker terminal. In case of low-magnitude overcurrents, properly coordinated, time-delayed alarm and tripping signals are initiated due to the abnormal conditions in the filter bank. Special emphasis is given to the response of the overcurrent relays (50/51) to harmonic currents present because some types of relays operate on peak current measurements and improper use of these relays may result in undesired operations. This protection is redundant to the differential (87).

Thermal overload protection may be implemented using a thermal overcurrent relay (49) in each phase of the filter bank. This relay is responding to root-mean-square (RMS) current used with thermal analog modeling and ambient temperature and can be set to trip at RMS current values or temperature that will cause damage to the reactor. This sensitive protection is not achievable with fuses and is more sensitive than a traditional 51 relay.

9.1.2 Ground fault protection

A neutral (51N) overcurrent may be used to detect ground faults sensitively in the solidly grounded-wye bank. This relay would operate on the residual sum of each phase current ($I_R = I_A + I_B + I_C$). This 51N ground overcurrent relay is time-delayed and coordinated with system ground relaying to avoid undesired tripping for system ground faults as the grounded-wye filter bank is a path for ground fault current. It may be possible to supervise ("torque control") this element with a voltage element that monitors the zero sequence terminal voltage, 3V0. System ground faults in the vicinity of the filter bank generally produce substantial 3V0, while little 3V0 is produced for slight unbalances in the filter bank itself. Both phase and ground overcurrent relays provide backup to the differential protection. If it is determined that this phase differential is not sensitive enough for adequate ground fault protection, then a restricted earth fault (87N) differential can be applied. This relay compares the residual current at the terminals of the filter bank to the neutral current. With modern microprocessor relays, this element is easily achieved and implemented inside the three-phase 87 relay shown in Figure 41.

In the ungrounded-wye filter bank (Figure 42), the potential device connected from the neutral bus to the ground is typically a very high resistance divider rated for full line-ground potential. This scheme detects the neutral voltage shift resulting from capacitor failures in the high-voltage (C_1) or low-voltage (C_2) sections of the filter bank. The 59N relay can be compensated with the bus residual voltage (3V0) to accommodate existing system voltage unbalance for improved relay sensitivity. If not compensated, then this relay must be coordinated with the upstream ground fault relays so that it does not trip during upstream ground faults. The protection relay should be set to detect C_1 or C_2 failures and trip the bank for failed units in either capacitor bank.

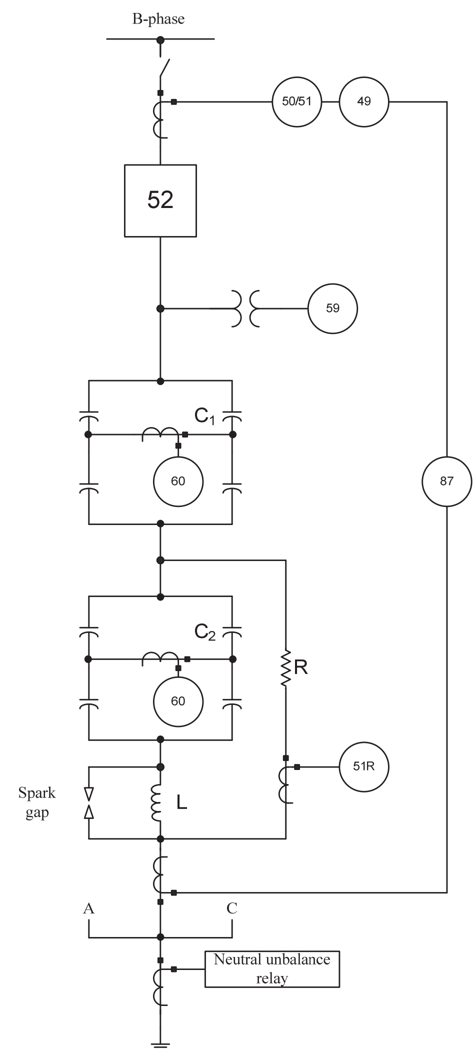


Figure 41—Sample protection scheme for a grounded-wye filter bank

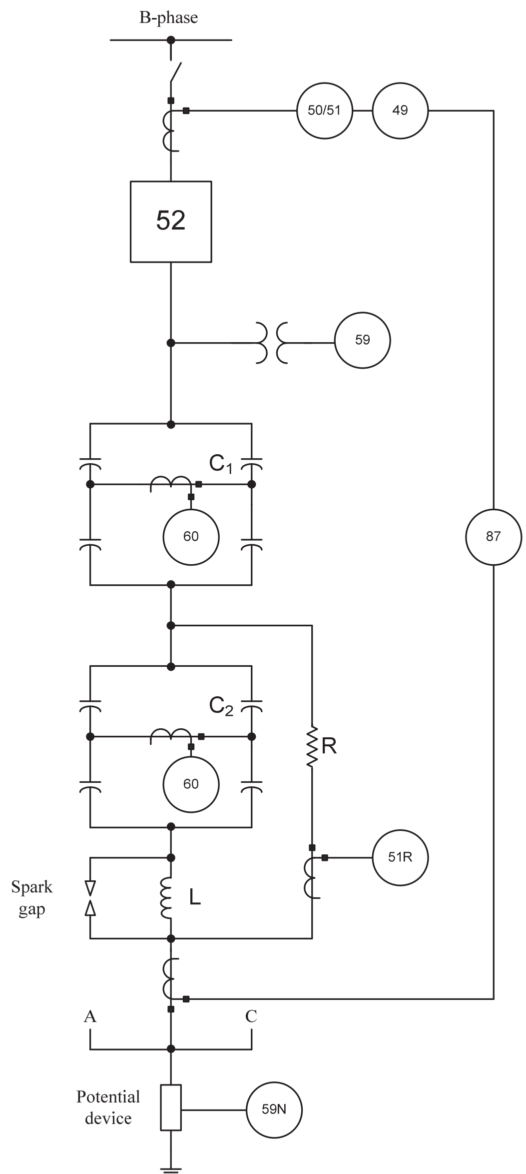


Figure 42 —Sample protection scheme for an ungrounded-wye filter bank

9.1.3 Resistor overload protection

The damping resistor R in each phase of the filter bank should also be protected against fundamental and harmonic overloads. The 51R relay shown in Figure 41 for this purpose should respond to the true RMS current flowing through the resistor. The time overcurrent curves should provide coordination with the I^2t overload capability of the resistor.

9.1.4 Overvoltage protection

Each filter is protected by an overvoltage relay that serves to protect the filter bank against continuous fundamental frequency overvoltages as well as against severe overvoltages. The continuous overvoltage protection should be time-delayed and coordinated with the system automatic voltage controls.

Severe overvoltages cause excessive stress on the capacitor units. Peak measuring relays are recommended for this application and should be set to coordinate with the withstand capability curves as specified by the capacitor manufacturers. Overvoltage and overload protection can be provided using current integration methods to calculate the true overvoltages imposed on the capacitor units.

9.1.5 Capacitor unbalance protection

The high-voltage C_1 and low-voltage C_2 capacitor banks of a typical filter (as shown in Figure 41 and Figure 42) are protected by separate unbalance protection schemes as detailed in Clause 8 of this guide. However, many other unbalance protection schemes can be applied on filter banks depending on the arrangement of the capacitors and on whether the system and bank unbalance compensation features are needed.

Another unbalance protection scheme is illustrated in the 51R and 60 discrete relays shown in Figure 41 and Figure 42. In this case, an unconventional capacitor unbalance scheme is provided by means of current measurements in the resistor branch or between legs of the high-voltage and low-voltage capacitor banks as a result of capacitor failures. Note that the 60 relay in bank C_1 (Figure 41) is only sensitive to imbalances in the C_1 bank and that the 60 in bank C_2 likewise is only sensitive to imbalances in the C_2 bank. Also, this protection may require that dual bushing capacitor units be provided so that the current through the two legs can be measured independently.

This unbalance protection scheme should carefully evaluate the effect on the protection of off nominal system frequency as well as deviations in capacitor values as a function of temperature (dC/dT). In this regard, the availability of the filter bank is considerably improved if compensation means are provided.

9.2 Multifrequency harmonic filter protection considerations

Multifrequency filter banks are normally applied in applications such as high-voltage dc converter stations where two or more harmonics are to be shunted off the system. The high-voltage capacitor can be used for both frequencies. The low-voltage section is tuned so that more than one frequency can be shunted off the system. Standard protection may be applied to the high-voltage and low-voltage sections. Figure 43 illustrates one possible primary protection scheme for a multifrequency filter bank.

Neutral unbalance protection may be used (59N), but it is important to verify that the relay has a narrow fundamental (e.g., 60 Hz) frequency band-pass filter. There may be a high level of harmonics present, which could cause false alarms and trips if the relay operates on anything other than the fundamental frequency. The filter bank likely would be large and, therefore, should have a compensation circuit to handle system unbalance and the inherent unbalance of the bank as described for the 59N function in 9.1.2. This protection will detect a shorted turn in the reactors as well as failed capacitor units. Note that the low-voltage capacitor shown in Figure 43 may actually be the parallel combination of two or more low-voltage capacitors. The high-voltage and low-voltage capacitor banks (C_1 and C_2) can be protected using an H connection as described in 9.1.5 (60 relay).

Voltage differential protection is not recommended for a multifrequency filter bank because the voltage is normally connected from the bus to the ground. The low-voltage section makes it difficult to balance the two voltage sources because the voltage change will be different if a high-voltage capacitor unit fails as compared to a low-voltage capacitor unit. The voltage across a section of the high-voltage bank may be compared to the bus voltage, but a special voltage transformer would be required to accommodate the required basic impulse level (BIL).

The low-voltage section may be protected by connecting voltage transformers across the low-voltage capacitor, summing the three voltages, and measuring only the fundamental frequency component (59U in Figure 43). The relay can be balanced or nulled when the bank is energized to accommodate manufacturing tolerances. This protection is sensitive and can easily detect a low-voltage capacitor unit failure as well as a shorted turn in the low-voltage reactor. It can also detect a major impedance change in the high-voltage section. One advantage of this scheme is that only single-bushing capacitor units are required.

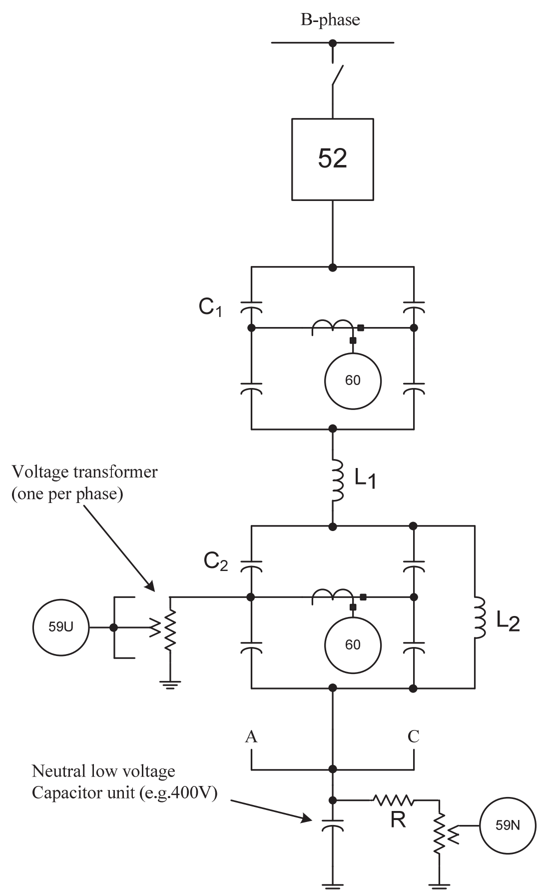


Figure 43—Multifrequency protection scheme

Digital relays may be influenced by harmonic distortions if the predominant orders of harmonic oscillations are not predicted. The digital band-pass filter response provided in the relay may have a low attenuation factor at a given harmonic frequency and may cause undesired tripping of the filter banks.

The expected reliability of the relay protection depends on the protection technology used, the design and manufacturing approaches, and the environment in which the relays are applied. To improve the availability of filter banks, appropriate data and experience related to harmonic distortion should be considered in the selection of the protection scheme.

9.3 Static var compensator (SVC) capacitor protection

SVCs are used in strategic installations to compensate reactive power rapidly for maintaining an acceptable system voltage profile and for improving the overall stability of the power system. Voltage flicker is also reduced in industrial applications (such as steel mill arc furnaces) when SVCs and harmonic filters are provided. An example of an SVC installation is illustrated in Figure 44.

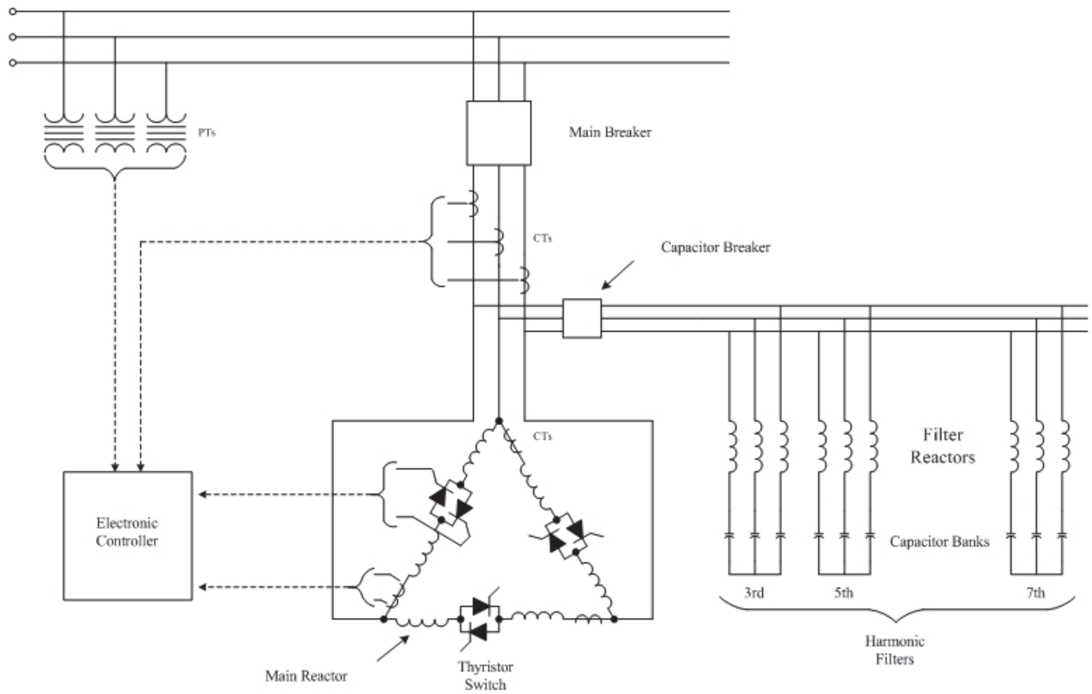


Figure 44—Typical SVC schematic

Protection of SVCs is provided by a combination of conventional protective relays and protective functions contained in the SVC control system (IEEE Power System Relay Committee [B7]). These functions are made up of a number of zones to include the SVC step-down transformer, low-voltage buses, reactor branches, capacitor branches, filters, and thyristors.

This guide applies equally to the protection of the fixed or thyristor-switched capacitor (TSC) banks provided as an integral part of an SVC installation. In this regard, Clause 7 and Clause 8 describe various protection methods that can be applied by conventional relays to shunt capacitor banks along with additional methods illustrated in Table 12 and Figure 45.

Table 12—Suggested SVC protection methods

Protected zone	Protection device	Protection function	Notes
TSC	60C	Unbalance	H-bridge unbalance measurement
TSC/TCR	50/51	Overcurrent	Branch fault of limiting reactor overloads
TCR	46	Negative phase sequence	Unbalance
TSC/TCR	60	Phase unbalance	Unbalance in lieu of 46
TSC	59	Overload	Capacitor overvoltage using current measurement
TSC/TCR	50N	Ground overcurrent	Branch faults

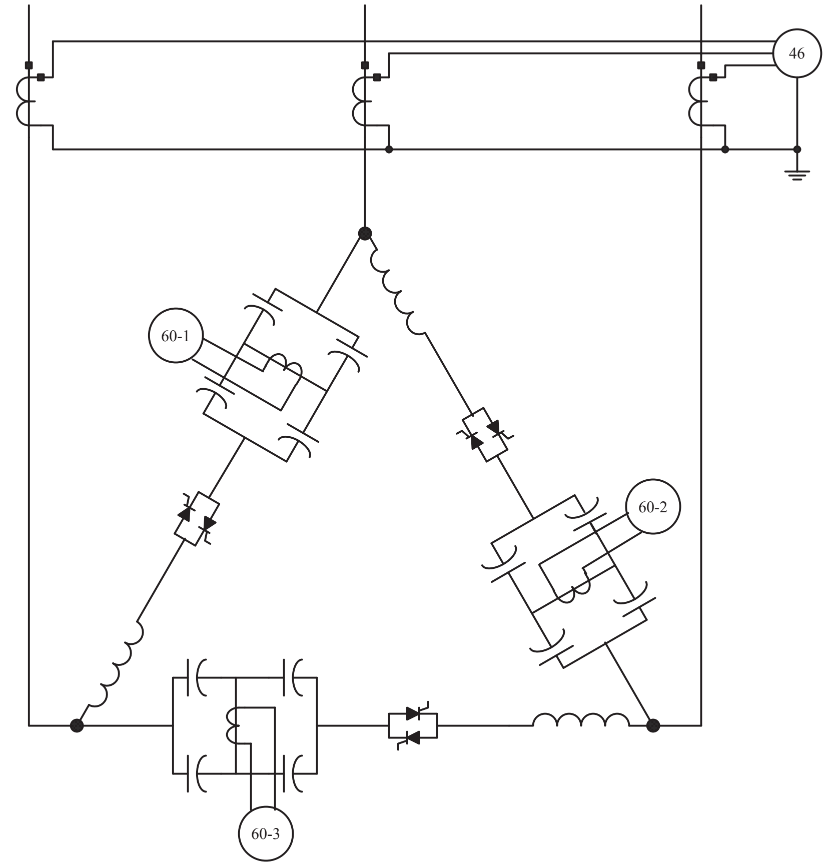


Figure 45—Capacitor unbalance protection in the TSC mode

SVC capacitor banks in the TSC mode are provided with air-core reactors connected in series to limit the inrush generated from thyristor switching. The selection and setting of the overcurrent protection should consider a misfire in the TSC valve (accounting for the magnitude and time duration of inrush and outrush currents) and should coordinate with other protective functions provided in the controls.

Harmonics are an important factor to consider in the protection of capacitors in the TSC mode. Adequate overcurrent and overvoltage protection types and settings should be provided to counter the effect of harmonics generated by the thyristor-controlled reactors (TCRs) and by other unusual harmonic distortion such as those resulting from geomagnetic disturbances (Benmouyal et al. [B3]). In this regard, true RMS-based overcurrent relays are required to protect the series limiting reactors adequately against overloads, while peak-measuring voltage relays should be provided for the protection of capacitors against overvoltages (see Table 1).

9.4 SVC filter protection

Harmonics are produced by the switching elements of SVCs, which may require harmonic filtering. For instance, a six-pulse, phase-controlled reactor unit employs three TCRs connected in delta. Odd harmonics (e.g., 5th, 7th, 11th, and 13th) will be injected into the power system during balanced steady-state conditions.

If filters are required, the effectiveness of such filtering depends mainly on the system impedance normally referred to by an R-X locus, which may determine the need for additional single- or double-tuned shunt filters. These filters will operate as an equivalent shunt capacitor bank generating reactive power at system frequency. Some of the protection methods discussed in Clause 7 and Clause 8 are applicable to SVC filter bank protection. However, as noted in 9.1 and 9.2, the unbalance protection can be more demanding, depending on the filter configuration (single-frequency tuned or multifrequency tuned) and the system voltage to which the harmonic filters are connected.

10. Capacitor bank equipment considerations

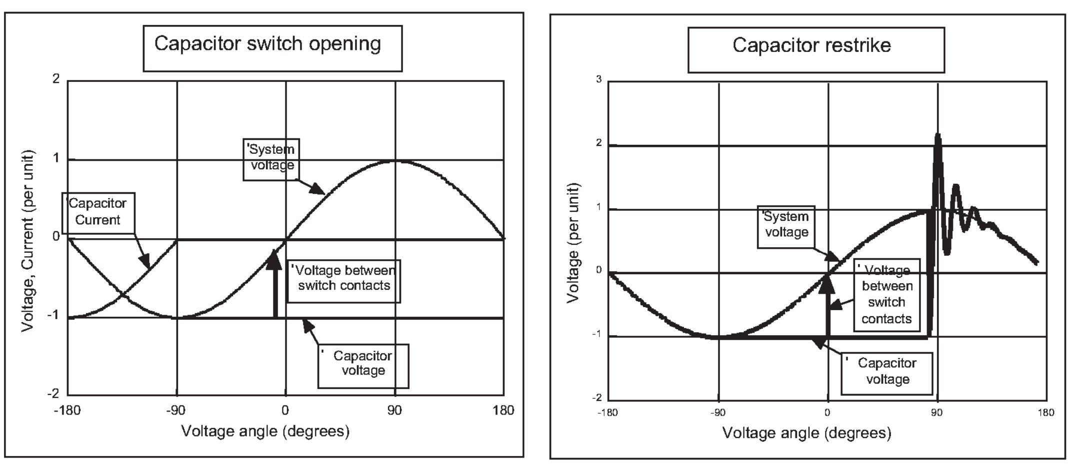
10.1 Capacitor bank switching devices

Capacitor switching devices require special attention because more severe switching duties exist for the interruption of shunt capacitor banks than for other forms of switching. The various devices that may be used for capacitor switching include the following:

Circuit breakers	Circuit switcher	Interrupter switches
SF_6 Vacuum Oil Air-magnetic Air	SF_6	Oil SF_6 Vacuum Thyristor

All capacitor switching devices should be applied within their maximum voltage, frequency, and current ratings, including transient inrush current and frequency. Reference should be made to IEEE Std C37.04, ANSI C37.06, IEEE Std C37.012™, and IEEE Std C37.66™ for rating and application information.

The current rating of the switching device should include the effects of system overvoltage (<110%), capacitor-unit capacitance tolerance (<115%), and system harmonics (<110%) to provide adequate margins for most capacitor switching duties.



(a) No restrike (b) One restrike

Figure 46—Opening the circuit to a single-phase capacitor in one step

An important consideration involving application of circuit breakers or circuit switchers for capacitor switching is the transient overvoltage that may be generated by restrikes during the opening operation. At current zero, the capacitor is left charged to nearly full-peak line voltage. Little recovery voltage appears across the switching device contacts at this instant, and the capacitance-current arc is usually interrupted at the first current zero after the switching device contacts open. After interruption, the normal frequency alternation of the voltage on the source side of the switching device results in a recovery voltage across the open contacts, 0.5 cycle later, approaching twice the peak line voltage [see Figure 46(a)]. If a breakdown were to occur at 90° as shown in Figure 46(b), the capacitor voltage immediately attempts to equalize with the system voltage. The circuit is oscillatory. At the first peak of the transient, the capacitor voltage will, depending on damping, overshoot by an amount approaching the difference between the two voltages immediately prior to the restrike. This high transient overvoltage may damage equipment. If the current is interrupted at the first high-frequency current zero, then the transient voltage peak is trapped on the capacitor bank. The recovery voltage reaches a value greater than that following the first interruption. However, the contacts have moved farther apart, and the buildup of dielectric may prevent additional restrikes.

If the gap between the open contacts breaks down less than 0.25 cycles after current zero, then the amplitude of the voltage oscillation will not exceed the normal transient voltage that occurs when the bank is first energized. The breakdown is defined as reignition rather than as a restrike.

In Figure 46(b), the restrike is shown to occur a full 0.5 cycle after current interruption. This condition is the worst possibility for the first restrike because the recovery voltage has reached its maximum and the resultant surge voltage can, theoretically, reach three times normal line-to-ground crest voltage. In actual practice, it seldom exceeds 2.5 times normal. Additional restrikes can produce higher crest voltages, and the sudden voltage changes and high-frequency oscillations may produce other relatively higher voltages elsewhere on the system. Therefore, to protect the entire system, it is desirable to limit restrikes and the voltage phenomena resulting from them.

Under special circuit arrangements, it may be possible for some switching devices to interrupt the transient current caused by a prestrike when energizing a capacitor bank. Overvoltages may result when the contacts close after an interruption of the transient current. The resulting transient can produce overvoltages.

In a station where large capacitor banks are connected to a common bus, it may be prudent to verify that the transient capacitor discharge current into a nearby fault does not exceed the capability of any circuit breakers or circuit switchers connected to the bus.

The peak discharge current of an individual capacitor bank is:

$$I_{\text{pk}} = \frac{\sqrt{2}}{\sqrt{3}} \times 10^3 \times kV_{\text{LL}} \sqrt{\frac{C_B}{L_S}} = \sqrt{\frac{1000}{3\pi f}} \times \sqrt{\frac{\text{kvar}(3\varphi)}{L_S}}$$

where

I_{pk}	is the peak discharge current (A)
C_B	is the capacitance (F)
L_S	is the total inductance, capacitor bank to fault (H)
kV_{LL}	is the line-to-line voltage (kV)
f	is the power frequency (Hz)

For a 60 Hz system, the peak discharge current is:

$$I_{\text{pk}} = 1.33 \sqrt{\frac{\text{kvar}(3\varphi)}{L_S}}$$

In addition to involving the contact capability, the transient inrush current through a switching device may also cause secondary flashover of bushing current transformers (BCTs). The voltage developed in the secondary circuit is proportional to the frequency and magnitude of the transient inrush current:

$$V\_BCT_{sec} = (I_{pk} / BCTR) \times (X_{sec}) \times (f_{hf} / f)$$

where

V_BCT_{sec}	is the secondary voltage crest on the bushing current transformer
I_{pk}	is the peak transient current on the primary side
BCTR	is the bushing current transformer turns ratio
X_{sec}	is the reactance of the secondary burden at power system frequency
f_{hf}	is the oscillation frequency of the transient

NOTE—The current transformer burden reactance is the sum of the reactances of the current transformer, the leads, and the relay.

The switching equipment manufacturer should be consulted if the *dI*/*dt* or crest values of the inrush current exceed the limits specified in Table 1A through Table 3A of ANSI C37.06-2000.

10.2 Inrush control devices

Energizing a capacitor bank will result in a transient inrush current. The magnitude and frequency of this inrush current are a function of the applied voltage (point on the voltage wave at closing), the capacitance of the circuit, the inductance of the circuit, the initial charge of the capacitor bank at the instant of closing, and the damping of the circuit due to closing resistors or other resistance in the circuit. See Annex D for inrush current calculations.

The transient inrush current to a single isolated bank is less than the available short-circuit current at the capacitor location. Because a switching device should meet the momentary current requirement of the system, transient inrush current is not a limiting factor in applying switching devices on isolated capacitor banks. However, it is important to check the momentary rating of other switching devices not intended for fault current interruption.

When capacitor banks are switched back to back (that is, one or more energized when another is connected to the same bus), transient currents of high magnitude and high frequency may flow between the banks on closing of the switching device or in the event of a restrike on opening. The oscillatory current is limited only by the impedance of the capacitor banks and the circuit between them, and the peak inrush may be much higher than the peak of the available short-circuit current at the bus. The transient current usually decays to zero in a fraction of a cycle of the power frequency. The component supplied by the power source is usually so small it may be neglected.

The magnitude of inrush current and its subsequent effects to a switched capacitor bank may be greatly reduced by use of inrush-current-limiting reactors. A capacitor switching device furnished with preinsertion resistors or inductors or a switch that uses zero-crossing controls minimizes the switching inrush transient, but it does not help the outrush transient for close in faults. When used for daily switching of back-to-back capacitor banks, the life of the switching device contacts can be extended by increasing the inductance between banks by adding in current-limiting reactors. The reactors will also reduce the outrush currents (see IEEE Std C57.16™). Evaluate the effect of the outrush on the components that will be affected before adding a reactor.

Capacitor bank installations using series reactors to control back-to-back capacitor bank switching transients are potentially subject to capacitor terminal faults as well as faults between the capacitor bank and its series reactor that may be problematic to clear due to the excessive rate of rise of transient recovery voltage (RRRV) across the capacitor breaker contacts. See 6.1 for discussions on the use of current-limiting reactors. Refer to the IEEE Std 1036 for more information.

The phenomenon of inrush to a single switched shunt capacitor bank and to a bank switched back to back with a parallel energized bank or banks is discussed in 6.1. In a given application, the currents and voltages associated with inrush to a capacitor bank may precipitate undesirable resonant effects with other parts of the system, induce hazardous surges in station control cable, and interfere with communication facilities in the area.

Closing resistors or inductors on the bank switching device, or current-limiting reactors installed in series with a switched capacitor bank, will serve to alter the frequency of the inrush transients and reduce the magnitude of the transients. The reactors applied should have a sufficiently high BIL rating so that gaps or surge arresters required for reactor protection will not short out the reactors during energization of the capacitor bank. Synchronous or zero voltage closing of the switched bank can also reduce the severity of the switching transients (see 6.1).

In back-to-back switching applications, the addition of even a minimal amount of inductance between banks will significantly reduce the magnitude of inrush currents flowing from the energized bank(s) to the bank being energized.

Grounded wye shunt capacitor banks (as well as other substation equipment capable of generating or transmitting high-frequency transients to the ground mat) should be installed as far away as practical from the control building and cable trenches.

10.3 Surge arresters

Lightning surges and the switching of capacitors can result in significant system overvoltages. The ability of the surge arrester to dissipate energy that results during capacitor switching operations is of particular importance to assure proper surge arrester selection. Restrikes of the capacitor bank switching device generally cause the highest transient overvoltages, particularly for isolated banks. Significant transient overvoltages can also occur at the capacitor bank due to surge magnification of resonant circuits on the power system associated with switching of a remote capacitor bank, cable, or transmission line. Metal-oxide surge arresters are generally better than silicon-carbide surge arresters because they usually have a higher energy duty for the same arrester rating and typically absorb less energy per transient event.

Refer to the surge arrester application guides in IEEE Std C62.2™ (for gap silicon carbide surge arresters) and IEEE Std C62.22™ (for metal oxide surge arresters) for further information on surge arrester application.

10.4 Voltage-sensing devices

If a voltage transformer, capacitor-coupled voltage transformer, or potential device connected from the bank neutral to ground is used for unbalance detection, then it should be capable of withstanding switching surge voltages of 0.5 to 2.5 times system phase-to-neutral voltage without malfunction (Harner and Owen [B6]). At higher system voltages, higher ratio voltage transformers are required. The use of these higher ratio voltage transformers can make the neutral voltage unbalance detection methods become insensitive. Special relaying techniques may be required (see Clause 8).

10.5 Current-sensing devices

A reasonably conservative voltage rating for the neutral wound primary current transformer to withstand the surge voltages appearing at the bank neutral is 0.2 times the system line-to-line voltage (Harder [B5]). However, window-type current transformers rated 0.1 of system voltage (even 600 V rated CTs) have been applied without trouble. On small banks, these current transformers are often wound primary types with low ratios. During switching, the bank neutral transient voltage rise can stress the insulation across the current transformer's wound primary. It can also stress the insulation between the case (which is usually grounded to a local support structure) and the secondary winding due to the fact that the secondary neutral is usually grounded at the remote end (that is, at the relay location) for safety reasons. Although the voltage stress between the grounded case and the secondary winding could be eliminated by grounding the secondary circuit at the current transformer location, this alternative is not recommended. To do so would impress the bank transient potential rise on the secondary cable and present hazardous voltages at the relay location. Refer to IEEE Std C57.13.3 for more information. Generally, the secondary winding can withstand these short-duration transients without difficulty. Also, coupling of this transient voltage to the secondary cable can be greatly reduced by routing the cable closely parallel to the primary ground conductor down to the ground mat and then closely paralleling the ground mat conductors en route to the relay location. In special instances where excessive neutral transient voltages are encountered, it may be necessary to insulate the transformer case from the local ground to allow connection of one side of the secondary winding to the transformer case. This approach will eliminate the stress between the secondary winding and the core and will increase the stress between the primary winding and the core. However, the primary insulation can generally be expected to be more robust than the secondary insulation.

To protect the primary winding insulation of a wound primary current transformer, it is common practice to install a rod gap of 1.2 mm to 1.6 mm connected directly across the primary terminals (Harder [B5]). This arrangement will limit the voltage impressed across the winding and prevent primary turn-to-turn breakdown. A high-energy, gas-filled protector tube or low-voltage surge arrester (varistor) should be connected across the secondary terminals to protect the secondary winding from turn-to-turn breakdown. (Failure of an inadequately rated varistor is likely to short-circuit the current transformer and cause the unbalance protection to be inoperative.) This device should be insulated from local ground, again to avoid impressing the bank transient potential on the secondary circuit. The surge arrester should be chosen to limit the current transformer secondary voltage to coordinate with the secondary circuit insulation voltage rating.

Nonsimultaneous making and breaking times of the three poles of the capacitor bank switching device may allow full phase current to flow in the neutral current transformer and relay during the switching time. This current can flow for an indefinitely long period of time if one or two poles of the bank switching device fail to operate. For this reason, it may be desirable to select a neutral current transformer that can accommodate this current without damage or malfunction. For more information on surge protection of current transformers, see 10.6.1.

10.6 Transient currents

It is well documented that the switching of capacitive currents produces transients that are markedly different from those produced by other power system switching operations (Greenwood et al. [B4]). For capacitor bank switching, the differences are as follows:

a) Highly damped, nonoscillatory, transient-current pulses may be produced when preinsertion resistors are employed in the bank switching device. Peak currents range from 1000 A to 3000 A. The rise time is about 1 µs, and the fall time is about 600 µs. Initial dI/dt is about 3000 A/µs.

b) When the main contacts of the capacitor bank switching device close, shorting the preinsertion resistor, oscillatory transient currents may be produced that have a frequency of 1000 Hz to 20 000 Hz, current of 1000 A to 2500 A, and a subsequent dI/dt of about 100 A/µs.

c) If resistor preinsertion is not employed, then the transient may be oscillatory at frequencies in the range of 1000 Hz to 20 000 Hz and the initial dI/dt will be about the same as with resistor preinsertion: 1000 A/µs. However, the peak current will be much greater, especially during back-to-back switching. Similar transient current components can be superimposed on 60 Hz fault current waveforms for faults in the bank, for bus faults in the station, and for close-in line faults.

If preinsertion inductors are utilized, then peak transient currents are generally less than 3000 A. The oscillatory frequency is on the order of several hundred hertz. The maximum dI/dt is, therefore, less than 10 A/µs. One source (Abdulrahim et al. [B1]) has pointed out that additional very high-frequency switching transients of several megahertz (due to traveling waves on the capacitor bank bus) will also be produced and superimposed on the transients already described. This transient is similar, if not identical, to the transients generated by switching a length of high-voltage bus with a disconnect switch.

The rate of change of the current (dI/dt) is a useful indicator of the potential for inducing interference in nearby control circuits. Although switching with preinsertion resistors reduces the peak current and eliminates the oscillation, it does not reduce the initial dI/dt. This rate of change is determined only by the voltage across the switch before closing and the circuit-loop inductance:

$$dI/dt = V/L$$

Surge protection techniques for capacitor bank applications should take into consideration the different character of the transient currents produced during bank switching (higher peak currents and lower oscillation frequencies) than are experienced with other power system switching operations.

The circulating paths of the transient currents are also important. These currents flow into the capacitor bank buses, bank ground connections, and capacitor bank ground grid. For some conditions, the currents also flow into the bus interconnections between the main switching station and the capacitor bank, as well as into the main station buses and ground grid. Due to the combination of high current and high frequency, significant transient potential differences can appear across portions of the ground grid due to the grid inductance. The currents are also accompanied by strong high-frequency magnetic fields. Therefore, control cables in these areas are prone to inductive interference and require careful attention to routing, shielding, and grounding.

10.6.1 Surge protection for current transformers

When the transient currents produced during capacitor bank switching pass through the primary of the current transformer, its secondary circuit can experience a large transverse-mode interference voltage. It is not induced through stray coupling but by the normal transformer action of the current transformer. This can present a serious problem for both the current transformer and the equipment and instruments that make up its secondary burden, such as protective relays and data transducers. The reactance of the burden components at these frequencies can be more than 100 times their 60 Hz values. As a consequence, high-frequency transient currents, which can be a few hundred amperes, can produce extremely high voltages across inductive burdens.

The suggestion is sometimes made that current transformer saturation will prevent the production of such high secondary voltages. This suggestion is not true for this situation, however. The secondary volt-second product for each half cycle of the high-frequency oscillation is small compared to that required to produce current transformer core saturation at 60 Hz. Therefore, voltage limiting by current transformer saturation is not likely to occur.

Overvoltage protection of the current transformer secondary circuit is thus required to prevent damage to the current transformer winding and the connected burdens. This protection usually takes the form of high-current-rated varistors or spark gaps connected directly across the current transformer secondary terminals. If the current transformer has a wound primary, then a gap or a surge arrester may also be needed across the primary (Harder [B5]). Varistors applied to the secondary should be selected with a sufficient energy-absorbing rating to withstand the secondary current oscillations (see 10.5). Also, to maintain voltage-limiting action, the varistor size should be selected so that the peak current does not drive it deep into the voltage turn-up region on the varistor's V/I curve. Figure 47 illustrates this point. Manufacturers of varistors can supply V/I characteristic curves suitable for checking this condition.

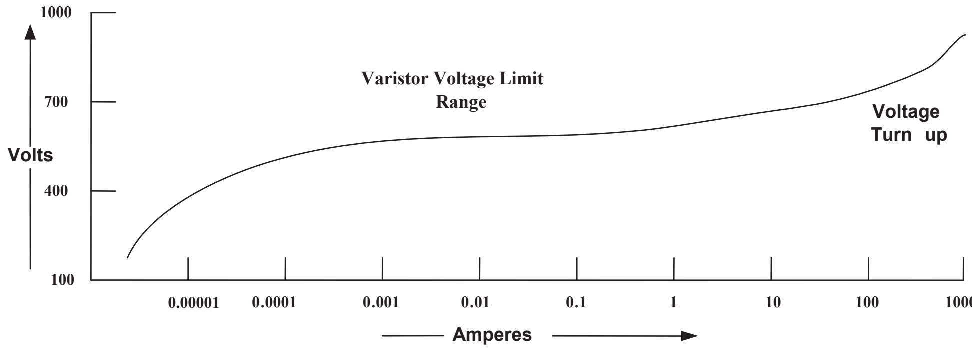


Figure 47—Varistor V/I curve showing voltage turn up

To a degree, the secondary high-voltage problem can be minimized by selecting the current transformer ratio and burden to reduce the level of the secondary current. Also, eliminating inductive components in the secondary burden will reduce the secondary voltage. Solid-state relays are particularly beneficial in this respect because their current burdens are low and essentially resistive.

The foregoing discussion is best illustrated by a numerical example. Figure 48 shows a one-line diagram for a 230 kV station with a shunt capacitor bank. The bank is rated 40 000 kvar and is wye connected with a grounded neutral. In the figure, the line circuit breakers have 1200/5 ratio current transformers, and the capacitor bank is in service when a phase-to-ground fault occurs on line 3 just outside the station. The distance along the 230 kV circuit from the capacitor bank to the fault is about 150 m.

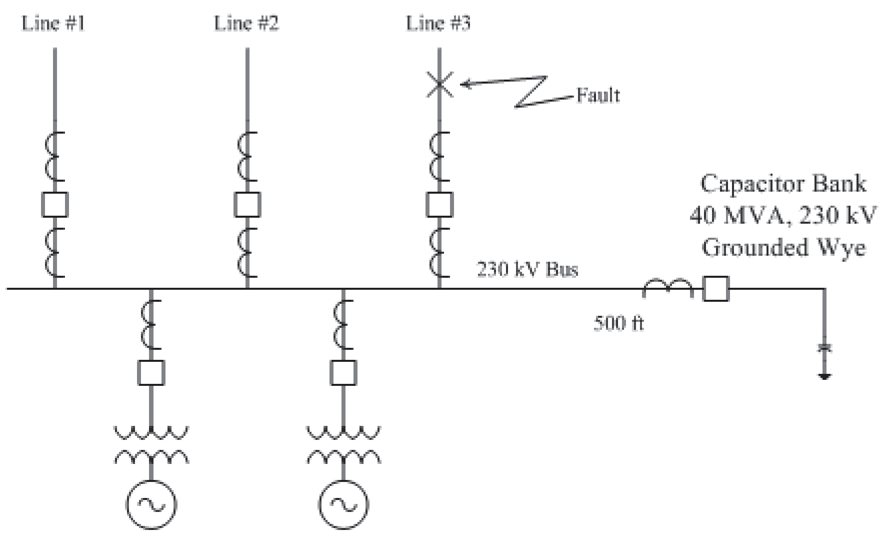


Figure 48—One-line diagram of 230 kV station with a shunt capacitor bank

Upon occurrence of the fault, the capacitor bank discharges through the bus-ground loop inductance, which is about 350 µH. Because there is little resistance in the loop, the current is oscillatory. The frequency of the oscillation depends on the loop inductance and on the bank capacitance. The capacitance of the bank can be found from its voltage rating and its power frequency kilovar rating:

$$C_B = 2.65 \times \text{kvar} \times \left(\frac{1}{KV_{\text{LL}}}\right)^2 \ \mu\text{F}$$

$$C_B = 2.65 \times [40\ 000] \times \left(\frac{1}{230}\right)^2\ \mu\text{F}$$

$$C_B = 2.0\ \mu\text{F}$$

The frequency of oscillation (f) is:

$$f = \frac{10^6}{2\pi\sqrt{L_S \times C_B}}\ \text{Hz}$$

$$f = \frac{10^6}{2\pi\sqrt{350 \times 2.0}}\ \text{Hz}$$

NOTE—The capacitance is in microfarads (μF) and the inductance is in microhenries (μH).

$$f = 6105\ \text{Hz}$$

The peak current is:

$$i_{\max} = \frac{\sqrt{2}}{\sqrt{3}} \times 10^3 \times kV_{\text{LL}} \sqrt{\frac{C_B}{L_S}}\ \text{A}$$

$$i_{\max} = \frac{\sqrt{2}}{\sqrt{3}} \times 10^3 \times 230 \sqrt{\frac{2.0}{350}}\ \text{A}$$

The peak secondary current is:

$$i_{\max} = (\text{secondary}) = 14\ 196 / (1200{:}5\ )$$

$$= 59.1\text{A @ } 6015\ \text{Hz}$$

The current transformer secondary burden impedance, at 60 Hz, is 1 + j1 Ω. At 6015 Hz, the burden impedance is about 1 + j100 Ω. The peak magnitude of the oscillatory voltage transient across the secondary of the current transformer is then:

$$\text{V}_{\max} = \sqrt{[59.1 \times (1)^2] + [59.1 \times (100)^2]}$$

$$= 5910\ \text{V @ } 6015\ \text{Hz}$$

This voltage is too much to allow across the relay and instrument burdens or the current transformer secondary winding insulation. Some means to clamp or limit the voltage to a lower amount is required, such as a spark gap or high-current varistor. Protective relays operating from these current transformers or from the bank-tie current transformers should also have a filter to exclude the 6 kHz discharge current calculated previously or be designed to ignore its presence.

The peak voltage, peak current, and frequency produced in a given installation will vary from this example depending on the bank capacitance, current transformer ratios, system voltage, and burden impedance.

10.6.2 Surge protection of voltage transformer, capacitor-coupled voltage transformers, and resistance potential devices

Voltage signal sources of various types are used in capacitor bank protection schemes to detect abnormal conditions in the bank. Because they are located close to the capacitor bank, these devices can be directly exposed to the transients or surges produced during capacitor bank switching. Surge protection of these devices is mainly to prevent overstress in the primary-to-secondary insulation and the secondary-to-ground (case) insulation by the transient ground potential differences produced in the bank area during switching.

A peninsula grounding arrangement for the capacitor bank (along with proper control cable shielding, grounding, and routing) provides better surge protection for ac voltage signal sources than the single-point grounding scheme. The higher cost of peninsular grounding may be justified for large EHV capacitor bank installations.

With the single-point grounding arrangement, the bank neutral transient potential will be about 0.25 that on the capacitor bank bus (20 kV to 60 kV or higher). In this case, a voltage transformer connected to measure the capacitor bank voltage, bus to neutral, would need to be a two-bushing design so the case could be safely grounded to the station ground grid (refer to 6.1).

Use of a single bushing transformer, with the case (primary ground) connected to the bank neutral, would impress the neutral transient voltage between the case and the secondary winding, which is grounded through the control cable at the relay location. Failure of the secondary winding insulation would be a strong possibility. Figure 49 and Figure 50 illustrate the situation.

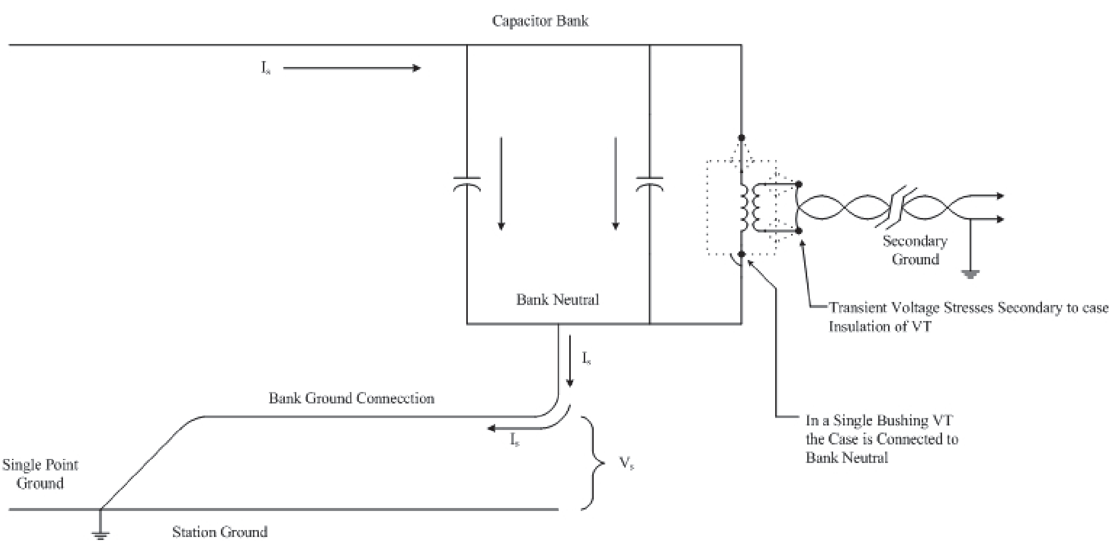


Figure 49 —Single-point grounded bank with single-bushing voltage transformer

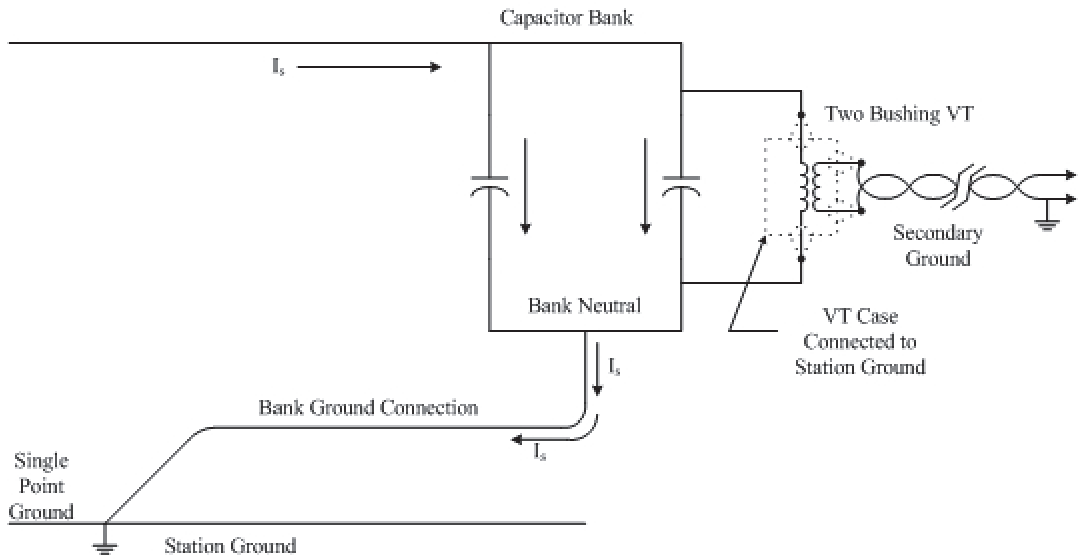


Figure 50 —Single-point grounded bank with two-bushing voltage transformer

Conventional high-voltage and EHV magnetic voltage transformers often have primary winding self-resonant frequencies in the range of 500 Hz to 2000 Hz. If the bank switching frequency coincides with this self-resonance, then the capacitor bank transient may be strongly amplified in the voltage transformer output voltage. There is probably little risk of damage to the voltage transformer, but the operation of relays and controls connected to the voltage transformer may be adversely affected. A resistor in series or parallel with the secondary of the transformer can be used to dampen the oscillation. The resistor value should be such that it does not influence the signal level to the relay.

Finally, all types of voltage transducers, voltage transformers, capacitor-coupled voltage transformers, and resistance potential devices can, with some loss in fidelity, reproduce the capacitor bank switching transient voltage. It will appear in the transverse mode at the output terminals of the device. This voltage, too, may affect the operation of relay systems.

10.6.3 Surge protections of relay systems associated with capacitor banks

It has already been mentioned that capacitor bank switching produces the same megahertz transients that occur in other high-voltage switching operations, as well as its characteristic high-energy kilohertz transients. Protective relay systems for capacitor bank applications should have incorporated in their design surge protection that is effective for both types of interference.

Experience has shown that interference in control circuits caused by high-voltage switching operations is always stronger in the common mode than in the transverse mode. Surge protection techniques have been directed mostly toward reducing the common mode. Some of these techniques (such as control cable routing, cable shielding and grounding, and isolation), which are highly effective at megahertz frequencies, are also effective against the kilohertz common mode interference due to capacitor bank switching and are, therefore, recommended for such installations.

On the other hand, the surge filters [for example, passive electromagnetic interference filters] used in the inputs to relay systems, although highly effective at megahertz frequencies, are ineffective against capacitor bank switching transients in the kilohertz frequency range. Passive kilohertz surge filters for relay input circuits would require much larger inductors and capacitors, which could present severe loading problems for current transformers and voltage transformers. Such filters are often not practical.

In capacitor bank switching, the kilohertz interference in the secondary circuits is strongest in the transverse mode because, as already described, it is coupled to the secondary circuits of current transformers and voltage transformers by the normal transformer action of these devices. Because it is not practical to use passive kilohertz filters in the current transformer and voltage transformer secondary ac relay input circuits, the required filtering action should be achieved by other means. One approach is to design active filters as an integral part of the relay analog signal processing circuits.

Finally, all ac input connections to the relay system should be protected against overvoltages by using varistors or spark gaps.

10.7 Control cables

IEEE Std 525™ provides guidance on routing of control cables. IEEE Std 1143™ provides guidance on shielding of low-voltage cables. The following information is extracted from these guides.

All control cable duct runs, cable trenches, or direct buried control cables not specifically associated with capacitor controls or protection should be removed from the immediate area around the capacitor bank. This step is to avoid induction of surges into relaying systems or possible control cable failure during capacitor bank switching.

The routing of control cables from neutral current transformers or voltage transformers should be kept at right angles with respect to the common neutral for single-point grounding and in parallel with the tie to the substation ground for peninsular grounding to minimize induction. These induced voltages can also be minimized by shielding the cables and using a radial configuration for circuits (circuits completely contained within one cable so that inductive loops are not formed).

Control cables entering the capacitor bank area should be kept as close as possible to the ground grid conductors (that is, #4/0 AWG copper minimum) in the cable trench, or on top of the duct run, or alongside a ground grid conductor if direct buried. This grounding arrangement is mandatory if a peninsula ground is used. Multiple control cable shield grounds are recommended: one at the cable termination in the capacitor area, another where the cable enters the main cable trench or duct run, and another where the cable enters the control house, or at the final termination on the relay panel. All spare or unused conductors of control cables should be grounded at least at one end.

The induced voltages [common mode (between a signal pair and ground) and transverse mode (between the signal wires)] will be affected by the cable construction (for example, shielded twisted pairs or random lay without shielding) and by whether the shields and unused conductors are grounded. The outer shield should normally be grounded at both ends to reduce the common and transverse induced voltage.

If the spare conductors and internal shields are grounded at both ends, then the induced common mode voltage will be reduced, but the induced transverse mode voltage can be increased due to the current flow through the spare conductors coupling to the other cable conductors.

11. System considerations

11.1 Resonance

A shunt capacitor bank forms a resonant circuit with system inductive elements. The natural resonant frequency may be excited while switching a remote capacitor bank and give rise to excessive voltages and currents and the possible failure of equipment such as other capacitors, surge arresters, instrument transformers, and fuses. These undesirable resonant effects are more likely to occur if the capacitor bank switching device has a long arcing time and multiple restrike characteristics.

The natural resonant frequency of a single-capacitance shunt capacitor bank (not a filter bank) is simply related to the inductance of the system and the capacitance of the bank:

$$f = \frac{1}{2\pi\sqrt{\mathrm{LC}}}$$

This is the frequency at which the magnitude of the system inductive reactance equals that of the capacitive reactance of the bank presenting a low-impedance path for current flow at that frequency. If the fundamental frequency of the power system is f_0, then the resonant frequency can be expressed as:

$$\omega = \frac{1}{\sqrt{\mathrm{LC}}} = n\omega_0$$

where n is a positive number, $\omega_0 = 2\pi f_0$ and $\omega = 2\pi f$.

$$n = \frac{1}{\omega_0\sqrt{\mathrm{LC}}}$$

Carrying this further, an expression for the harmonic resonance of a particular capacitor bank in terms of its size and the short-circuit capacity of the system can be developed as follows:

$$n = \frac{1}{\omega_0\sqrt{\mathrm{LC}}} = \sqrt{\frac{1}{\omega_0^2\mathrm{LC}}} = \sqrt{\frac{1/\omega_0\mathrm{C}}{\omega_0\mathrm{L}}} = \sqrt{\frac{X_\mathrm{C}}{X_\mathrm{L}}}$$

Neglecting resistance, the impedance can be approximated to the reactance: ZC ≈ XC and ZSYS ≈ XL:

$$n \approx \sqrt{\frac{Z_\mathrm{C}}{Z_\mathrm{SYS}}} = \sqrt{\frac{\frac{V/\sqrt{3}}{I_\mathrm{CAP}}}{\frac{V/\sqrt{3}}{I_\mathrm{SC}}}} = \sqrt{\frac{I_\mathrm{SC}}{I_\mathrm{C}}} = \sqrt{\frac{\sqrt{3}VI_\mathrm{SC}}{\sqrt{3}VI_\mathrm{C}}} = \sqrt{\frac{\mathrm{mva_{SC}}}{\mathrm{mvar}}}$$

So, a 50 mvar shunt, single-capacitance bank applied to a power system bus with 1350 mva of short circuit available will be tuned near the fifth harmonic:

$$n = \sqrt{\frac{1350}{50}} = 5.2$$

$$\%\,\mathrm{rise} \approx \frac{Z_\mathrm{SYS}}{Z_\mathrm{C}}$$

It is interesting to note that this equation can be related to the equation for the percentage voltage rise produced by the capacitor bank as well:

$$n = \sqrt{\frac{1350}{50}} = \frac{10}{\sqrt{\%\mathrm{rise}}}$$

What this means in practical terms is that a single-capacitance shunt bank installed in the power system to produce a 2% voltage rise would naturally be resonant near the seventh harmonic. Likewise, a 4% rise would tune near the fifth harmonic. Refer to Figure 51 for a plot of the harmonic number against the percentage voltage rise.

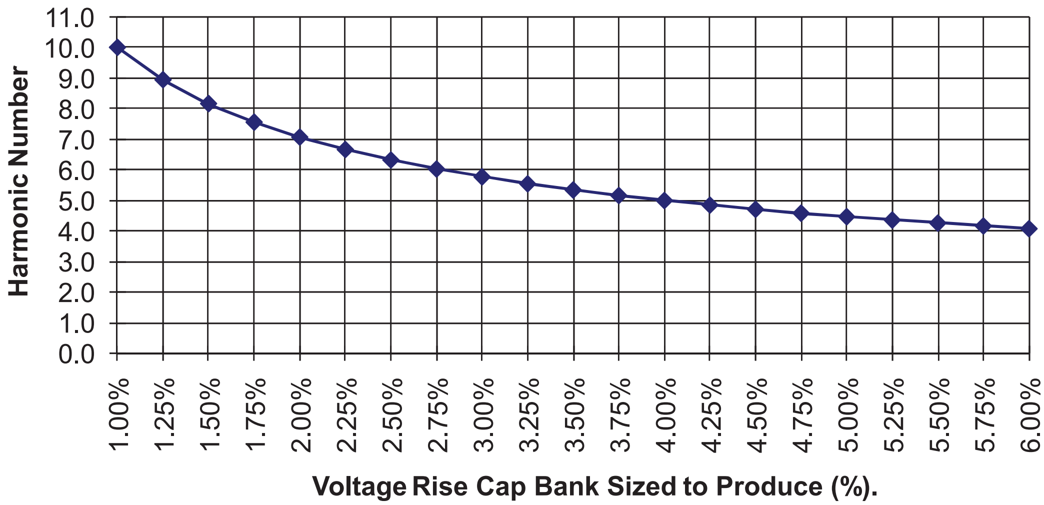


Figure 51 —Single-capacitance shunt bank harmonic tuning as function of percentage voltage rise

11.2 Harmonics

The capacitor bank may also resonate with harmonic currents produced elsewhere, such as remote loads. The use of thyristors in industry to derive variable potential dc from an ac source is extensive and growing. Such phase-controlled thyristors generate harmonics, particularly third, fifth, seventh, and eleventh. More instances of parallel resonance are occurring due to this cause. Some examples of harmonic series resonance with utilities, due to adjacent utility loads, have been noted. These resonant circuits also include utility distribution circuits with capacitors that supply medium-voltage industrial and commercial loads. In most instances, some form of harmonic voltage and high-harmonic capacitor currents are involved. Capacitors rated for higher voltage may be used (Steepes and Stratford [B12]; Miller [B11]; McCauley et al. [B9]).

Arc furnaces, in the melt part of their cycle, produce a similar array of troublesome harmonics, including even-ordered harmonics. While the large furnaces are connected to stiff high-voltage sources, small installations on distribution circuits nevertheless produce the same effect.

11.3 Telephone interface

Another objection to harmonics in the power system is the noise interference produced in communications circuits. Voice frequency noise interference comes primarily from the residual or zero-sequence currents that are odd multiples of the third (the ninth and fifteenth harmonic of the fundamental frequency). Grounded capacitor banks provide a low impedance path for these currents to flow.

The measure of the capability of a power circuit to act as a noise source is the telephone influence factor (IEEE Std 469™). Before attempting to apply corrective measures to a capacitor bank that is suspected of causing interference, the source of the noise should be located. The best corrective measures are usually applied at the source. If corrections should be made at the capacitor bank, then modifications to change the resonant frequency can be made.

12. Commissioning, operation, and maintenance

12.1 Preparation for initial energizing

Before energizing power equipment, there are the usual pre-commissioning checks for instrument transformer ratio, polarity, and excitation; circuit dielectric withstand; proper operation of protective devices; and visual verification of proper connections and clearances, clean insulators, and so on. The nameplate information and wiring should be checked to verify that the construction is correct and agrees with the construction drawings. Test trip and verify the logic of the schemes. In addition, some recommended checks specific to capacitors are addressed in 12.1.1 through 12.1.6.

12.1.1 Visual and switching device inspection

Inspect all capacitor unit fuses (if used) for proper connections and clearance. The bank switching device and ground switch (if used) should be checked for proper operation. Capacitor unit nameplates should be checked for the correct voltage for the desired number of units in series (fuseless design) or units in series groups with parallel capacitor units per series group. Secondary circuits should be checked for proper grounding of cable shields and spare control wires (see 10.7).

12.1.2 Capacitance testing

The capacitance of each capacitor unit should be checked to verify that it is within specified tolerance and for future testing reference. Usually, the capacitor manufacturer will maintain capacitor tolerances to within ±2% of each other within a given bank. For fuseless designs, measuring and comparing the capacitance of each series string of units is adequate.

12.1.3 Relay protection testing

All relaying associated with the capacitor installation should be checked for proper operation. Where possible, this step should be done by putting the appropriate signal on the primary terminals of the sensing device (CT and/or VT), and checking for appropriate operation of the relays and circuit breakers.

The unbalance relay installation that detects the change in capacitance should be calibrated to verify both proper pickup current and proper time delay. (Excessive time delay in the trip operation can result in severe damage to the capacitor bank and associated equipment.) The lockout and trip operation should also be checked.

Backup or redundant overcurrent relays should be tested to verify proper pickup current and time delay. The settings used should be compared with the desired values that have been calculated.

12.1.4 Special recording

The oscillographic recording capability of a microprocessor relay or a portable recorder can assist in diagnosing problems associated with initial energization of a large capacitor bank. The following parameters should be recorded:

- All three phase currents
- All three phase voltages (if voltages are available)
- Capacitor bank neutral current (or voltage)
- The outputs of the capacitor bank sensing devices

A calibration trace should be run on each channel used.

12.1.5 Initial energization

Verify that all relaying systems are operational prior to energizing the capacitor bank. The oscillographic equipment should be started immediately before the circuit breaker, circuit switcher, or equivalent switching device is closed. If the relay protection operates to trip immediately after initial closing, then the following procedure should be initiated:

a) Perform the procedures of 12.2.1 through 12.2.4.
b) If no problem is found with the capacitor bank or relay installation, review the setting of the relay that tripped with the oscillographic data and revise the setting, if appropriate.
c) If the sensitive unbalance relay is operating on the inherent unbalance of the capacitor bank, it may be necessary to raise its setting until the capacitor bank remains energized to adjust the relay properly.

With the bank energized, it may be necessary to calibrate the protection equipment with actual system voltages and currents applied, especially if compensation for inherent unbalance is involved. Secondary currents from the current transformers should be recorded along with phase angles to verify that the installation is correct and to provide for future reference.

12.1.6 Additional tests (optional)

After the capacitor bank has been energized and all protection has been properly adjusted, the alarm level (if used) and the lockout operation may be checked. Depending on the bank construction, it may be possible to check for proper trip and alarm performance in operation by removing or adding appropriate capacitors in the bank. Modify the bank to create an alarm situation. Measure the unbalance and verify that the level measured is close to the expected value. The alarm should pick up. Verify operation of any remote displays, if used.

Modify the bank to create a trip situation. Energize the bank. Modifying units from different groups, series strings, or phases instead of all from one group, string, or phase tests the unbalance protection and produces less stress on the remaining units. Verify proper relay targets and remote displays, if used.

12.2 Response to alarm or lockout (trip)

12.2.1 Oscillographic records

If available, review oscillographic records to determine the magnitude of the unbalance current or voltage on the phase.

12.2.2 Inspection (after deenergization)

Immediately inspect the bank for blown fuses (if applicable), possible flashover damage, and obvious capacitor unit failures.

12.2.3 Testing

In externally fused banks, test capacitors that are not obviously defective but have blown fuses. In cases where a large number of the capacitor units in the bank have blown fuses (for example, 25% or more), it is advisable to test all capacitor units and verify fuse ratings. Measure the capacitance in other types of banks. Measure the series strings in the fuseless design and the individual capacitor units in the internally and unfused designs.

12.2.4 Capacitor unit removal and replacement

Replace the defective capacitor units and/or fuses. When capacitors are arranged in parallel, units can be removed or relocated from other phases to rebalance the series-parallel groups for capacitance and voltage. Relocation of capacitor units and changes to the bank configuration may require a change in the unbalance relay settings.

If only the fuse(s) is (are) blown, then make sure that the capacitor unit(s) is (are) checked for the capacitance value and visual deformation such as bulging. If the capacitance is out of tolerance or if the unit is bulged, then it is recommended to replace both the fuse(s) and the capacitor unit(s).

12.2.5 Returning bank to service after lockout

If only a few capacitor units have been replaced, then the bank can be returned to service with a minimum of readjustment of the unbalance relay. These adjustments can be performed after the bank is energized.

If a large number of the capacitor units have been replaced, then attention may have to be given to recalibration of the sensitive protection after the bank is reenergized. Refer to 12.1.5.

Additional tests, as noted in 12.1.6, may be performed to verify the protection scheme.

12.2.6 Servicing bank following alarm condition

When system conditions permit, the bank should be taken out of service to replace defective capacitor units and/or capacitor fuses. If replacement capacitor units are not available, then for some bank designs, it may be possible to rebalance the bank by disabling corresponding units from all phases. Such rebalancing, or other changes to the bank configuration, may require a change in unbalance relay settings.

13. Microprocessor-based control and protection schemes

In addition to their protective functions, microprocessor relays and programmable logic devices can provide enhanced monitoring and control of a shunt capacitor bank. These devices are capable of providing automatic switching based on time of day, system voltage, and power factor, or any combination thereof. During system contingencies, these devices can provide fast bank switching and coordinate device operation. These relays may also provide detailed operational data from the capacitor bank, including but not limited to annunciation of capacitor can failure and bank unbalance conditions.

In addition to the features mentioned, modern relays provide the following features:

- Easy unbalance compensation adjustment for inherent system unbalance or capacitance tolerance and instrument transformer errors
- Dynamic compensation adjustment for slow variations in capacitance due to unequal solar heating of capacitor units in a bank
- Easy setting of two different types of unbalance detection to avoid protection blind zones as discussed in 8.3.3
- Blocking differential functions on loss of measuring inputs and alarming such events

Annex A

(informative)

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Annex B

(informative)

Symbol definition

Cg	is the per-unit capacitance of the affected parallel group of capacitor units.
Chn	is the capacitance from H leg or tap point to neutral or reference end of a capacitor bank.
Ci	is the per-unit capacitance of the affected group in an internally fused capacitor unit.
Cp	is the per-unit capacitance of the phase (leg if the bank is delta-connected) with the affected capacitor unit(s).
Cs	is the per-unit capacitance of a string (or leg) of capacitor units with affected capacitor unit(s).
Cst	is the capacitance of a string of capacitor units with shorted elements.
Ctn	is the capacitance from tap to neutral or reference end for a tapped capacitor bank.
Cy	is the per-unit capacitance of the parallel strings in the phase of the wye with affected elements.
Cu	is the per-unit capacitance of a capacitor unit.
ΔC	is the per-unit variation of capacitance between phases.
$dVtg$	is the change in tap voltage, per-unit of normal tap voltage.
ΔVLG	is the variation of VLG between phases, per-unit.
e	is the number of shorted elements in a string of capacitor elements.
E	is the total number of series elements in a string of capacitor elements.
f	is the number of blown fuses (eliminated elements) in one group of an internally fused capacitor unit.
Φ	is the variance of phase angle between two phases from 120°.
G	is the grounding of bank: 0 = grounded, 1 = ungrounded.
Id	is the difference in neutral-to-ground current between two equal grounded wye banks.
Ig	is the neutral-to-ground current for a grounded wye bank.
Ih	is the current through the H leg (current transformer) of an H-bridge.
In	is the neutral current between wyes for wye-wye banks, per-unit of normal total phase current.

Iph	is the current in affected phase, per-unit of normal phase current.
Ist	is the current in affected string, per-unit of normal string current.
Iu	is the current in the affected capacitor unit.
Iy	is the current in affected phase of the affected wye.
N	is the number of parallel elements in one group of an internally fused capacitor unit.
n	is the number of external fuses blown in one series group.
P	is the number of parallel capacitors per series group (in the affected group of units).
Pa	is the parallel units on the left (affected) wye or side of H.
Pb	is the parallel units on the right (unaffected) wye or side of H.
Pt	is the total parallel units in a bank (*Pt* = *Pa* + *Pb*).
S	is the number of series groups in a bank (phase-to-neutral for wye-connected banks and phase to phase for delta-connected banks).
Sl	are the parallel strings in the left wye.
Sp	is the the total number of parallel strings of units in one phase (leg) of a fuseless capacitor bank.
St	is the number of series groups, sensing tap to ground or reference end for tapped banks and sensing H leg to ground or reference end for H-bridge banks.
Su	is the number of series groups of capacitor elements in a capacitor unit.
Vcu	is the voltage across capacitor units in affected series group (per-unit of normal voltage).
Ve	is the voltage across affected elements in an internally fused capacitor unit (per-unit of normal voltage).
Vg	is the voltage across affected elements in an internally fused capacitor unit due to unbalance within the unit (per-unit of actual unit operating voltage).
Vh	is the highest voltage on other units in the bank when this is higher than the voltage on the parallel units *Vcu* or in the same string *Ve*.
Vhn	is the voltage of the H leg of the H-bridge.
VLG or *Vlg*	is the line-to-ground voltage (use maximum value where appropriate).
Vln	is the line-to-neutral voltage of affected phase, per-unit of normal line to neutral voltage.
VNG or Vng	is the neutral-to-ground voltage or per-unit of normal line to ground voltage.
VNN or Vnn	is the voltage between neutrals.
VTG or Vtg	is the voltage between intermediate tap point and ground.

Annex C

(informative)

Equations for effect of inherent unbalances

Table C.1 is intended as a rule of thumb for determining the effect of inherent unbalances on the displacement of various bank protection schemes.

Table C.1—Effect of inherent unbalance on displacement signal

Shunt capacitor bank configuration	Effect of capacitor manufacturing tolerance	Effect of system voltage magnitude changes	Effect of system voltage phase angle change
Grounded wye with neutral current sensing	$I_N = \frac{\Delta C \times \text{var}_B}{3V_{LG}}$	$I_N = \frac{(\Delta V_{LG}) P \times \text{var}_U}{S(V_C)^2}$	$I_N = \frac{2P \times V_{LG}\left(\sin\frac{\Phi}{2}\right)\text{var}_U}{S \times V_C}$
Ungrounded wye with neutral potential sensing	$V_{NG} = \frac{\Delta C \times V_{LG}}{3}$	$V_{NG} = \frac{\Delta V_{LG}}{3}$	$V_{NG} = \frac{2}{3}\left(\sin\frac{\Phi}{2}\right)V_{LG}$
Ungrounded double wye with neutral differential current sensing	$I_N = \frac{\Delta C \times \text{var}_B}{6V_{LG}}$	$I_N = 0$	$I_N = 0$
Ungrounded double wye with neutral differential potential sensing	$\Delta V_{NN} = \frac{\Delta C \times V_{LG}}{3}$	$\Delta V_{NN} = 0$	$\Delta V_{NN} = 0$
Grounded wye with differential potential sensing	$\Delta V_{TG} = \Delta C(V_{LG})\left[\frac{S_T}{S^2}(S - S_T)\right]$	$\Delta V_{TG} = 0$	$\Delta V_{TG} = 0$
NOTE 1—I_N is neutral current, ΔC is per-unit variation of capacitance between phases, var_B is capacitor bank reactive power rating, var_U is individual capacitor-unit reactive power rating, V_C is rated capacitor voltage, Φ is variance of phase angle between two phases from 120°, and ΔV_{TG} is per-unit variation of the voltage between the intermediate tap point and the ground. NOTE 2—See Annex B for other symbols.			

Annex D

(informative)

Inrush current and frequency during capacitor bank switching

D.1 Energizing an isolated bank with no previous charge

$$i_{\max}\left(\mathrm{A}\right)=\sqrt{2I_{\mathrm{SC}}\times I_1}$$

or

$$i_{\max}\left(\mathrm{A}\right)=\frac{\sqrt{2}}{\sqrt{3}}\times kV_{\mathrm{LL}}\times 10^3\times\sqrt{\frac{C_B}{L_S}}$$

or

$$i_{\max}\left(\mathrm{A}\right)=10^3\times\sqrt{\frac{1000}{3\pi f_s}}\times\sqrt{\frac{\mathrm{kvar}}{L_S}}$$

$$f\left(\mathrm{hz}\right)=f_s\sqrt{\frac{I_{\mathrm{SC}}}{I_1}}=\frac{10^6}{2\pi\sqrt{L_S\times C_B}}$$

D.2 Energizing a bank with another on the same bus with no charge on the bank being switched

$$i_{\max}\left(\mathrm{kA}\right)=\sqrt{\frac{10^3}{3\pi f_s}}\times\sqrt{\frac{\mathrm{kvar}_1\times\mathrm{kvar}_2}{L_{\mathrm{eq}}\times\mathrm{kvar}_{\mathrm{T}}}}$$

$$f\left(\mathrm{kHz}\right)=9.5\times\sqrt{\frac{f_S\times kv_{\mathrm{LL}}\times\left(I_1+I_2\right)}{L_{\mathrm{eq}}\times\left(I_1\times I_2\right)}}$$

where

C_B	is the bank capacitance (μF)
L_S	is the system inductance (μH)
f_S	is the system frequency (Hz)
L_{eq}	is the total equivalent inductance per phase between capacitor banks (μH)
I_1	is the load current of the capacitor bank being switched (A)
kV_{LL}	is the line-to-line voltage (kV)
kvar_1	is the 3 φ kVA of the capacitor bank being switched
I_2	is the load current of the capacitor bank already energized (A)
kvar_2	is the 3 φ kVA of the capacitor bank already energized
$i_{\max}$	is the peak current without damping (actual value about 90%)

$kvar_T$ is $kvar_1 + kvar_2$
I_{SC} is the symmetrical rms short-circuit current (A)

NOTE—The previous expressions for inrush current apply only for energizing uncharged capacitors. If capacitors are charged, as during a restrike across an interrupting switch, then the inrush current may be twice these values.

D.3 Typical values of inductance between capacitor banks

See IEEE Std C37.012-2005.

Rated maximum voltage (kV)	**Inductance per phase of bus (μH/m)**	**Typical inductance between banks[a] (μH)**
17.5 and below	0.702	10 to 20
36	0.781	15 to 30
52	0.840	20 to 40
72.5	0.840	25 to 50
123	0.856	35 to 70
145	0.856	40 to 80
170	0.879	60 to 120
245	0.935	85 to 170

[a] Typical values of inductance per phase between capacitor banks. This value does not include inductance of the capacitor bank itself. Values of 5 μH for banks below 52 kV and of 10 μH for banks above 52 kV are typical for the inductance of the capacitor banks.

Annex E

(informative)

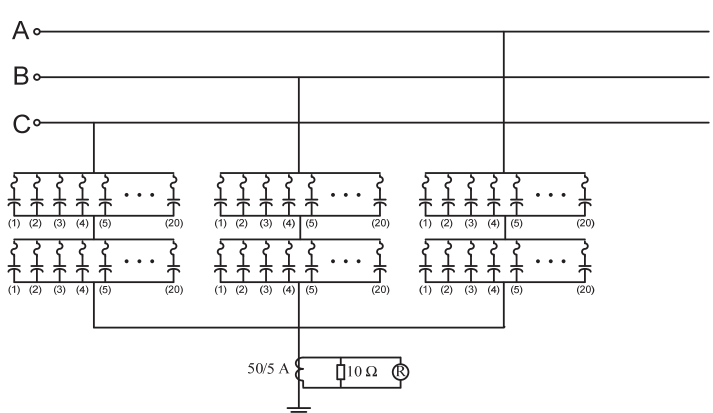
Unbalance relay setting examples

E.1 Grounded wye externally fused bank

Externally fused bank—neutral unbalance calculations

E.1.1 Technical data/ratings

Bank rating:		
kV	69 kV	
mvar	18.0 mvar	
Connection	Grounded wye	
Rated current	150.79 A	kvar / (1.73 × kV)
Series groups/phase, *S*	2	
Number of cans per Series group, *Pt*	20	
Capacitor unit rating:		
kV	19.9 kV	
kvar	150 kvar	
Protection system rating:		
Neutral CT	50/5 A	
Resistor	10 ohms	



S = 2 series groups line to neutral
Pt = 20 parallel units per phase
n = ? blown fuses
G = 0 “0” if grounded, “1” if ungrounded

Figure E.1—Sample grounded wye externally fused capacitor bank

E.1.2 Unbalance calculations (8.4.4)

Series groups/phase, S	2
Number of cans per series group, Pt	20
Grounding, G (grounded)	0
Neutral CT ratio—50/5 A	10

Assume the system is operating at 69.0 kV nominal voltage.

The nominal capacitor parallel group voltage is (69.0 kV / √3) / 2 series groups = 19.92 kV.

Alarm and trip criterion:

As per the statement in 8.4.1, the unbalance relays are set on the basis of the maximum system operating voltage. The maximum system operating voltage is 72.5 kV for a 69 kV system:

"Where possible, the unbalance relay should be sensitive enough to alarm for the loss of one unit within a group. It should also trip and lock out on the loss of additional capacitor units that cause a group overvoltage in excess of 110% of capacitor unit rated voltage (or the capacitor unit manufacturer's recommendation)."

From Figure 28 and Figure 29, and from Table 2 and Table 3:

Vcu is the voltage on the affected series group, in per-unit
Cp is the phase-to-neutral capacitance of the series/parallel group that includes the blown fuses, in per-unit
Cg is the capacitance of the parallel group of capacitors that includes the blown fuses, in per-unit

From Table 2 and Table 3 (note that in Table 3, $Pt = Pa$ and $C_s = C_p$ for a single wye bank):

$$Vcu = \frac{Cp}{Cg},\ Cp = \frac{SCg}{Cg(S-1)+1},\ \text{and}\ Cg = \frac{Pt-n}{Pt}$$

This simplifies to:

$$Vcu = \frac{S}{\left[\frac{Pt-n}{Pt}\right](S-1)+1}$$

For the loss of one individual capacitor unit, the voltage of the affected group will be:

$$Vcu(1) = \frac{2}{\left[\frac{20-1}{20}\right](2-1)+1} = 1.026\ \text{pu}$$

At maximum system voltage, $Vcu(1)$ would be 1.026 × [72.5 / 69] = 1.078 pu.

The neutral unbalance protection will be programmed to alarm for this condition. The alarm setting will be equal to 50% of the value as suggested in 8.4.2.

For the loss of two individual capacitor units, the voltage of the affected group will be:

$$Vcu(2) = \frac{2}{\left[\frac{20\ -\ 2}{20}\right](2-1)\ +\ 1} = 1.053\,\text{pu}$$

At maximum system voltage, $Vcu(2) = 1.053 \times [72.5 / 69] = 1.106$ pu.

This exceeds the continuous maximum rating of the capacitor units when the system is operating at maximum system voltage.

The neutral unbalance protection will be programmed to trip for this condition. The setting would be halfway in between the trip and alarm setting as discussed in 8.4.2.

Neutral unbalance:

The equation from Table 2 is used to determine the neutral unbalance current, Ig, following the loss of capacitor units:

$$Ig = (1-G)\times(1-Iph)$$

where

$$Iph = Cp\ ,\ Cp = \frac{SCg}{Cg(S-1)+1}\text{, and } Cg = \frac{Pt-n}{Pt}$$

This simplifies Ig to:

$$Ig = 1 - \frac{S(Pt-n)}{(Pt-n)(S-1)+Pt}$$

The unbalance alarm will be set to detect the loss of one individual capacitor unit. For the loss of one unit, the neutral current will be:

$$Ig(1) = 1 - \frac{2(20-1)}{(20-1)(2-1)+20} = 0.026\,\text{pu} = 0.026\times 150.79 = 3.92\,\text{Apri}$$

At maximum system voltage, $Ig(1) = 3.92 \times [72.5 / 69] = 4.12$ A.

The resulting secondary CT current will be 4.12 / 10 = 0.412 As, and the voltage applied to the unbalance relay will be 4.12 V. Set the relay alarm pickup at 50% of this value, 2.06 V.

The unbalance trip will be set to trip for the loss of two individual capacitor units assuming maximum system operating voltage. For the loss of two units, the neutral current will be:

$$Ig(2) = (1 - \frac{2(20-2)}{(20-2)(2-1)+20})\times[72.5/69] = 0.0553\ \text{pu} = 8.338\ \text{Apri}$$

The resulting secondary CT current will be 8.64 / 10 = 0.833 As, and the voltage applied to the unbalance relay will be 8.33 V. Set the relay to trip at 8.0 V.

The relay will not trip for the loss of one capacitor unit and will trip only if the current unbalance reaches a value that results in 110% voltage on the capacitor units. Note that the tripping is delayed to coordinate with other relays in the system as described in 8.3.4.

E.2 Ungrounded wye externally fused bank

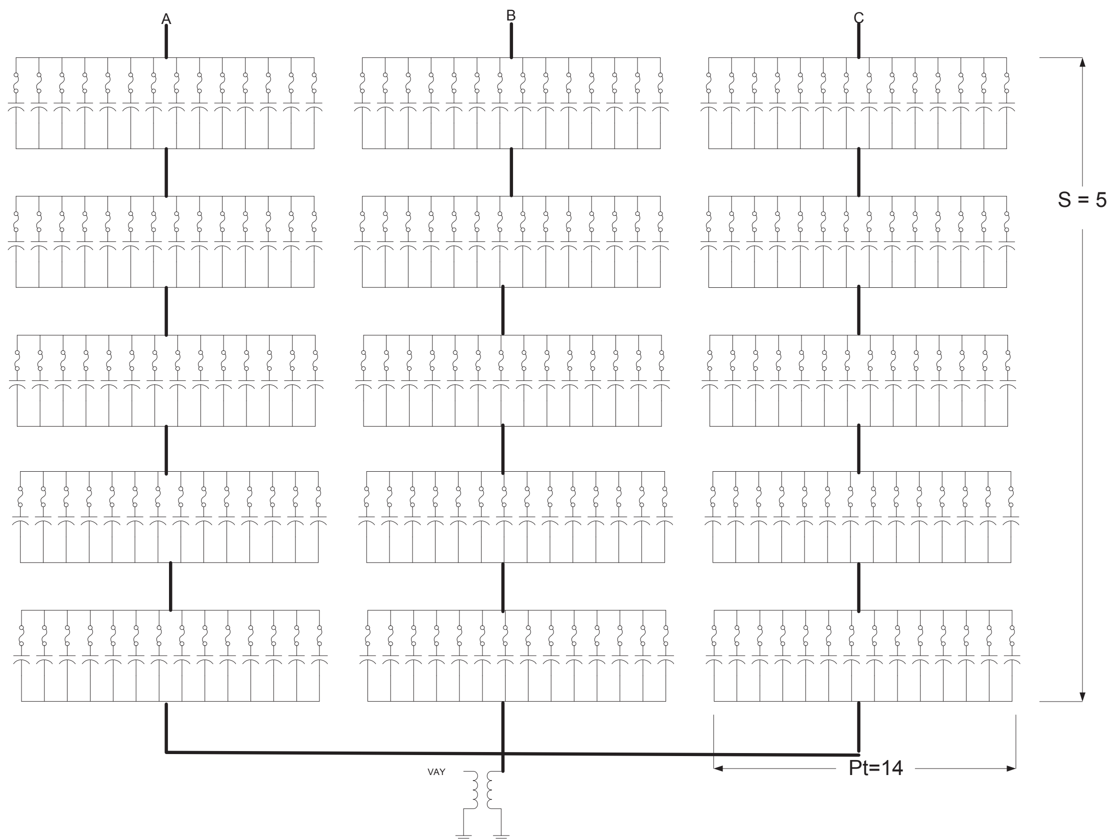


Figure E.2—Sample ungrounded wye externally fused capacitor bank

System nominal phase-phase voltage = 138 kV	Rated bank system voltage = 151 kV
Rated three-phase kvar = 50 000	Neutral-to-ground PT ratio = 300
# Series groups (*S*) = 5	Grounded/ungrounded = 1 (ungrounded)
# Parallel units per phase (*Pt*) = 14	
# Parallel units per phase in left wye (*Pa*) = 14	

Bank rating:

kV	151 kV
mvar	50.0 mvar
Connection	Ungrounded wye

Rated current kvar / (1.73 × kV) 191.4 A

Series groups/phase, *S* 5

Number of parallel units per series group, *Pt* 14

Capacitor unit rating:

kV (151 / 1.73) / 5 17.4 kV

kvar (50 × 10^6/total units) 238.1 kvar

Protection system rating:

Neutral PT 300:1

Maximum system operating voltage 105% (145 kV)

Alarm and trip criteria:

As stated in 8.4.1:

"The unbalance relay should coordinate with the individual capacitor unit fuses so that the fuses operate to isolate a defective capacitor unit before the protection switches the bank out of service. [A reliable fuse operation provides a convenient, visual means for locating the defective capacitor unit(s).]

Where possible, the unbalance relay should be sensitive enough to alarm for the loss of one unit within a group. It should also trip and lock out on the loss of additional capacitor units that cause a group overvoltage in excess of 110% of capacitor unit rated voltage (or the capacitor unit manufacturer's recommendation)."

110% of the capacitor unit rated voltage is 17.4 kV × 1.1 = 19.14 kV.

Unbalance calculations in 8.4.4 and Table 3:

NOTE—Calculated values for the following situations are pasted from the output of a MathCAD document.

*For zero fuse failures (*n *= 0)—normal condition:*

$Cg := \dfrac{Pa - n}{Pa}$	Parallel group capacitance	$Cg = 1$
$Cs := \dfrac{S \times Cg}{Cg \times (S - 1) + 1}$	Affected wye capacitance	$Cs = 1$
$Cp := \dfrac{(Cs \times Pa) + Pt - Pa}{Pt}$	Affected phase capacitance	$Cp = 1$
$Vng := G \times \left\lvert \dfrac{3}{(2 + Cp)} - 1 \right\rvert$	Neutral-to-ground voltage	$Vng = 0$
$Vln := 1 + Vng$	Voltage on affected phase	$Vln = 1$
$Vcu := \begin{cases} \dfrac{Vln \times Cs}{Cg} & \text{if } Cg > 0 \\ Vln \times S & \text{otherwise} \end{cases}$	Voltage on affected series group	$Vcu = 1$
$Iu := Vcu \times 1$	Current through affected capacitor(s)	$Iu = 1$
$Iy := Cs \times Vln$	Current in affected wye	$Iy = 1$

Convert per-unit quantities, above to primary system quantities:

SYSVLN = Maximum system voltage L-L/SQRT3 = $145 \times 10^3 / 1.732$ = 83.718 kV

UVOLTS = Normal unit voltage at maximum system voltage = SYSVLN/S = 16.74 kV

UIRATE = Normal unit current at maximum system voltage = UVAR/UVOLTS = $238.1 \times 10^3 / 16.74 \times 10^3$ = 14.22 A

*Vng*PRI = *V*ng × SYSVLN	Voltage neutral to ground	*Vng*PRI = 0
*Vln*PRI = *V*ln × SYSVLN	Voltage on affected phase	*Vln*PRI = 83.72 kV
*Vcu*PRI = *V*cu × UVOLTS	Voltage on affected group	*Vcu*PRI = 16.74 kV
*Iu*PRI = Iu × UIRATE	Current through affected capacitor(s)	*Iu*PRI = 14.22 A

Capacitor rated voltage is 17.4 kV. Voltage on group with no fuse failures is 16.74 kV. At 105% system voltage, the capacitor units are operating at 96.2% of rated voltage.

For one fuse failure within a parallel group (n = 1):

$Cg := \dfrac{Pa - n}{Pa}$	Parallel group capacitance	$Cg = 0.929$
$Cs := \dfrac{S \times Cg}{Cg \times (S - 1) + 1}$	Affected wye capacitance	$Cs = 0.985$
$Cp := \dfrac{(Cs \times Pa) + Pt - Pa}{Pt}$	Affected phase capacitance (Same as Cs for a single wye bank)	$Cp = 0.985$
$Vng := G \times \left\lvert \dfrac{3}{(2 + Cp)} - 1 \right\rvert$	Neutral-to-ground voltage	$Vng = 5.076 \times 10^{-3}$
$Vln := 1 + Vng$	Voltage on affected phase	$Vln = 1.005$
$Vcu := \begin{cases} \dfrac{Vln \times Cs}{Cg} & \text{if } Cg > 0 \\ Vln \times S & \text{otherwise} \end{cases}$	Voltage on affected series group	$Vcu = 1.066$
$Iu := Vcu \times 1$	Current through affected capacitor(s)	$Iu = 1.066$

$Vng\mathrm{PRI} = Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 424.95\ \mathrm{V}$
$Vln\mathrm{PRI} = \mathrm{V}ln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 84.14\ \mathrm{kV}$
$Vcu\mathrm{PRI} = Vcu \times \mathrm{UVOLTS}$	Voltage on affected group	$Vcu\mathrm{PRI} = 17.85\ \mathrm{kV}$
$Iu\mathrm{PRI} = Iu \times \mathrm{UIRATE}$	Current through affected capacitor(s)	$Iu\mathrm{PRI} = 15.159\ \mathrm{A}$

With one fuse blown within a parallel group, the voltage on the affected group (the group experiencing the fuse failure) rises to 17.85 kV. This is 102% of the capacitor unit voltage rating. The primary neutral-to-ground voltage is 425 V. A reliable alarm threshold for detecting this condition would be set at 80% of the calculated voltage level.

Alarm threshold = (0.8 × 425) / 300 = 1.13 V secondary (340 V primary).

*For two fuse failures within a single group (*n *= 2):*

$Cg := \dfrac{Pa - n}{Pa}$	Parallel group capacitance	$Cg = 0.857$
$Cs := \dfrac{S \times Cg}{Cg \times (S - 1) + 1}$	Affected wye capacitance	$Cs = 0.968$
$Cp := \dfrac{(Cs \times Pa) + Pt - Pa}{Pt}$	Affected phase capacitance	$Cp = 0.968$
$Vng := G \times \left\lvert \dfrac{3}{(2 + Cp)} - 1 \right\rvert$	Neutral-to-ground voltage	$Vng = 0.011$
$Vln := 1 + Vng$	Voltage on affected phase	$Vln = 1.011$
$Vcu := \begin{cases} \dfrac{Vln \times Cs}{Cg} & \text{if } Cg > 0 \\ Vln \times S & \text{otherwise} \end{cases}$	Voltage on affected series group	$Vcu = 1.141$
$Iu := Vcu \times 1$	Current through affected capacitor(s)	$Iu = 1.141$
$Iy := Cs \times Vln$	Current in affected wye	$Iy = 0.978$

$Vng\text{PRI} = Vng \times \text{SYSVLN}$	Voltage neutral to ground	$Vng\text{PRI} = 909.954\ \text{V}$
$Vln\text{PRI} = Vln \times \text{SYSVLN}$	Voltage on affected phase	$Vln\text{PRI} = 84.63\ \text{kV}$
$Vcu\text{PRI} = Vcu \times \text{UVOLTS}$	Voltage on affected group	$Vcu\text{PRI} = 19.11\ \text{kV}$
$Iu\text{PRI} = Iu \times \text{UIRATE}$	Current through affected capacitor(s)	$Iu\text{PRI} = 16.23\ \text{A}$

With two fuses blown within a single group, the voltage on the affected group rises to 19.11 kV, which is 109.7% of rated voltage. Set the trip threshold for the bank halfway between the 1 and 2 fuse blown neutral-to-ground voltage levels for reliable detection of the second fuse failure.

Trip threshold = (910 V – 425 V) / 2 + 425 V = 667.5 V primary, 2.225 V secondary.

E.3 Grounded wye—fuseless bank

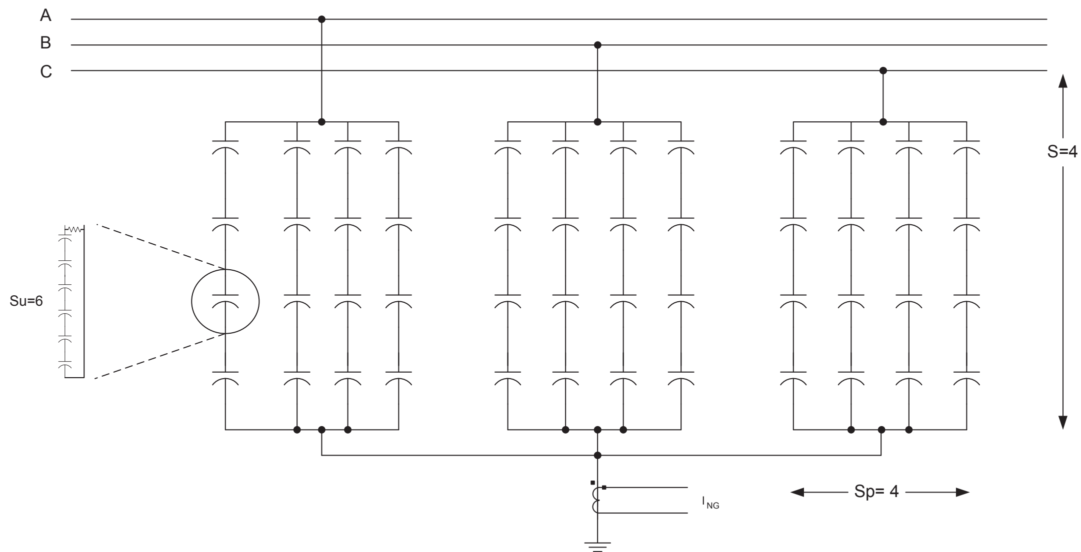


Figure E.3—Sample grounded wye fuseless capacitor bank

System nominal voltage = 69 kV # Parallel strings in left wye (same as # strings per phase = 4)

Rated bank system voltage = 69 kV Grounded/ungrounded = 0 (grounded)

Rated 3-phase kvar = 12 000 # Series elements per-unit (*Su*) = 6

Series groups (*S*) = 4

Parallel strings per phase = 4

Bank rating:

kV	76 kV
mvar	12.0 mvar
Connection	Grounded wye
Rated current kvar / (1.73 × kV) 91.27 A	
Series groups/phase, S	4
Number of parallel strings	4
Number of parallel strings in left wye	4
Number of series elements per-unit 6	

Capacitor unit rating:

kV (76 / 1.73) / 4	11.0 kV

kvar (12×10^3/total units)	250.0 kvar
Capacitor element rating:	
kV (11.0 / 6)	1.83 kV
Protection system rating:	
Neutral CT ratio	50:5
Maximum system operating voltage	105% (72.5 kV)

Alarm and trip criteria:

As stated in 8.6.2:

"The number of shorted elements for trip and alarm can be determined by knowing the voltage on the affected elements (for instance, the *Ve* value calculated in Table 10) and the capability of the elements (either 110% of rating based on industry standards or the information provided by the capacitor manufacturer)."

110% of capacitor element rated voltage is 1.83 kV × 1.1 = 2.02 kV.

*For zero failed elements (*e *= 0):*

$E = S.\mathrm{Su}$	Total elements in a string	$E = 24$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1$
$Cp = \frac{(Cy \cdot Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1$
$Vng = G \times \left(1 - \frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 1$
$Ve = Vln \times \frac{E}{E-e}$	Voltage on affected elements	$Ve = 1$
$Iy = Cy \times Vln$	Current in affected wye	$Iy = 1$
$Iph = Cp \times Vln$	Current in affected phase	$Iph = 1$
$I_g = (1-G) \times (1-Iph)$	Ground current	$Ig = 0$
$In = \frac{3 \times Vng \times G \times (Sp-Sl)}{Sp}$	Neutral current between wyes	$In = 0$
$Id = Vln \times (1-Cp)$	Difference current	$\lvert Id \rvert = 0$

$\mathrm{ING} := \lvert Ig \rvert \times \frac{Iph\mathrm{PRI}}{2} \times Sl$	Neutral-to-ground	$\mathrm{ING} = 0$
$Vn\mathrm{PRI} := Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 0$
$In\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times In$	Neutral current between wyes	$In\mathrm{PRI} = 0$
$Id\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times \lvert Id \rvert$	Difference current between equal wyes	$Id\mathrm{PRI} = 0$
$Vln\mathrm{PRI} := Vln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 43.88\ \mathrm{kV}$
$Ve\mathrm{PRI2} := Ve \times \frac{Vln\mathrm{PRI}}{E}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 1.828\ \mathrm{kV}$

With zero element failures, the voltage on the elements is 1828 V, which is 91.35% of rated voltage.

*For a single element failure in a string (*e *= 1):*

$E = S.Su$	Total elements in a string	$E = 24$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1.043$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1.011$
$Cp = \frac{(Cy \times Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1.011$
$Vng = G \times \left(1 - \frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 1$
$Ve = Vln \times \frac{E}{E-e}$	Voltage on affected elements	$Ve = 1.043$
$Iy = Cy \times Vln$	Current in affected wye	$Iy = 1.011$
$Iph = Cp \times Vln$	Current in affected phase	$Iph = 1.011$
$Ig = (1-G) \times (1 - Iph))$	Ground current	$Ig = -1.0110$
$In = \frac{3 \cdot Vng \times G \times (Sp - Sl)}{Sp}$	Neutral current between wyes	$In = 0$
$Id = Vln \times (1 - Cp)$	Difference current	$\lvert Id \rvert = 0.011$

$\mathrm{ING} := \left\lvert Ig \right\rvert \times \frac{Iph\mathrm{PRI}}{2} \times Sl$	Neutral-to-ground current	$\mathrm{ING} = 1.982$
$Vng\mathrm{PRI} := Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 0$
$In\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times In$	Neutral current between wyes	$In\mathrm{PRI} = 0$
$Id\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times \left\lvert Id \right\rvert$	Difference current between equal wyes	$Id\mathrm{PRI} = 1.002$
$Vln\mathrm{PRI} := Vln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 43.88\ \mathrm{kV}$
$Ve\mathrm{PRI2} := Ve \times \frac{Vln\mathrm{PRI}}{E}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 1.908\ \mathrm{kV}$

With one element shorted in the string, the voltage on the remaining elements in the string is 1908 V, which is 94.5% of the rated element voltage. Primary neutral-to-ground current is 1.982 primary or 0.198 A secondary. Set the alarm threshold to 80% of this level for reliable detection of a single element failure within a string.

Alarm threshold = 1.98× 0.8 = 1.584 primary, 0.158 A secondary.

*For four failed elements within a string (*e *= 4):*

$E = S.\mathrm{Su}$	Total elements in a string	$E = 24$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1.2$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1.05$
$Cp = \frac{(Cy \times Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1.05$
$Vng = G \cdot \left(1 - \frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 1$
$Ve = Vln \times \frac{E}{E-e}$	Voltage on affected elements	$Ve = 1.2$
$Iy = Cy \times Vln$	Current in affected WYE	$Iy = 1.05$
$Iph = Cp \times Vln$	Current in affected phase	$Iph = 1.05$
$Ig = (1-G)\times(1-Iph))$	Ground current	$Ig = -0.05$

$In = \frac{3 \times Vng \times G \times (Sp - Sl)}{Sp}$	Neutral current between wyes	$In = 0$
$Id = Vln \times (1 - Cp)$	Difference current	$\lvert Id \rvert = 0.05$

$\mathrm{ING} := \lvert Ig \rvert \times \frac{Iph\mathrm{PRI}}{2} \times Sl$	Neutral-to-ground current	$\mathrm{ING} = 9.116$
$Vng\mathrm{PRI} := Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 0$
$In\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times In$	Neutral current between wyes	$In\mathrm{PRI} = 0$
$Id\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times \lvert Id \rvert$	Difference current between equal wyes	$Id\mathrm{PRI} = 4.786$
$Vln\mathrm{PRI} := Vln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 43.88\ \mathrm{kV}$
$Ve\mathrm{PRI2} := Ve \times \frac{Vln\mathrm{PRI}}{\mathrm{Ts}}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 2.194\ \mathrm{kV}$

With four failed elements, the voltage on the affected elements is 109.6%. To trip the bank for this level of unbalance reliably, set the unbalance current element halfway between the neutral-to-ground current for four element failures, and for three element failures:

Trip threshold = (9.116 – 6.511) / 2 + 6.511 = 7.836 A primary, 0.78 secondary (50:5 CT ratio).

E.4 Undergrounded wye fuseless bank

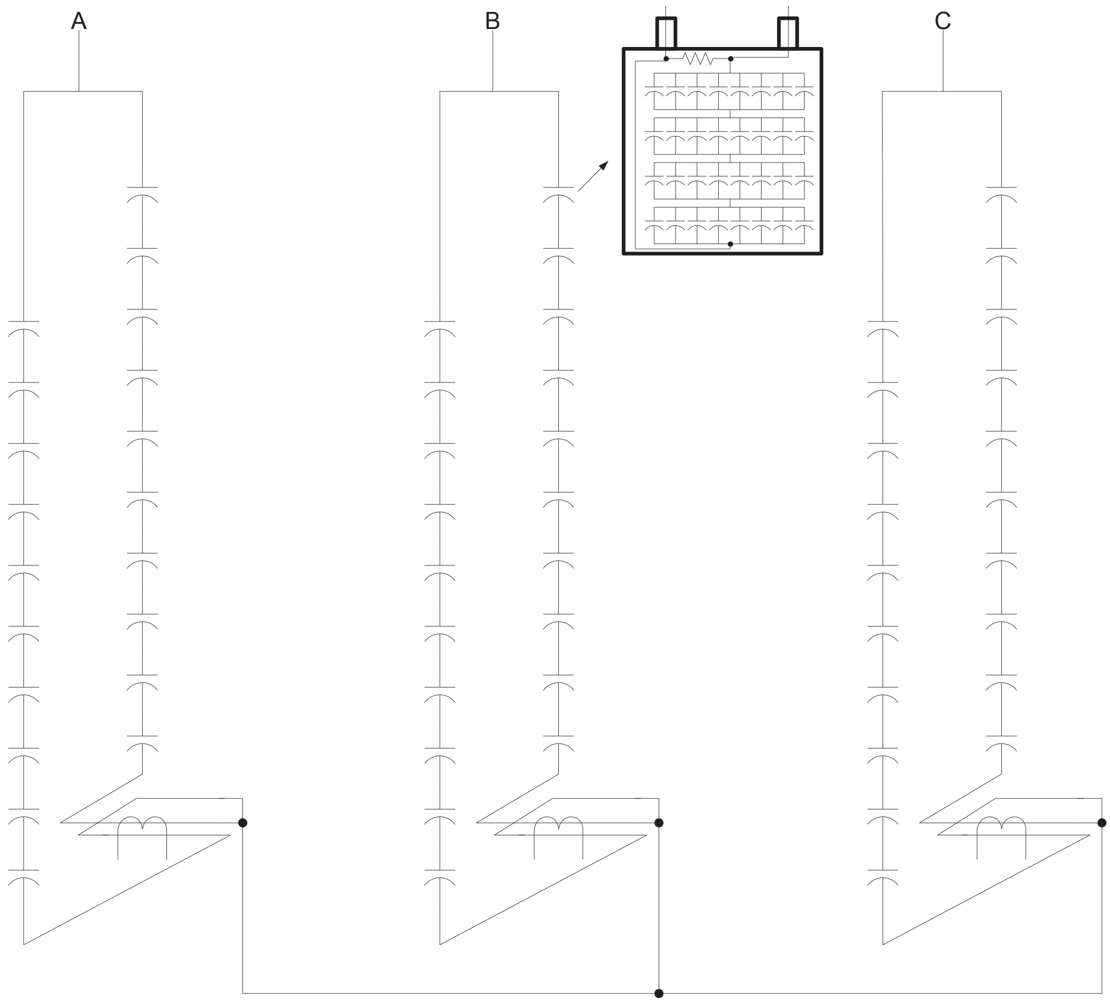


Figure E.4—Sample ungrounded wye fuseless capacitor bank

System nominal voltage = 230 kV

Rated bank system voltage = 250 kV

Rated 3 phase kvar = 60 000

Series groups (*S*) = 10

Parallel strings per phase (*Sp*) = 2

Parallel strings in left wye (*Sl*) = 1

Grounded/undgrounded = 1 (ungrounded)

Series elements per-units (*Su*) = 4

Parallel elements per group (*N*) = 8

Bank rating:

kV	250 kV
mvar	50.0 mvar
Connection	Ungrounded wye

Rated current kvar / (1.73 × kV) 115.5 A	
Series groups/phase, *S*	10
Series element groups in capacitor unit, *Su*	4
Parallel elements per group (*N*)	8

Capacitor unit rating:

kV (250 / 1.73) / 10	14.4 kV
kvar (50 × 10^3/total units)	833.33 kvar

Capacitor element rating:

kV (14.4 / 4)	3.6 kV

Protection system rating:

Phase imbalance CT ratios	5:5
Maximum system operating voltage	105% (241.5 kV)

Alarm and trip criteria:

As stated in 8.6.2:

"The number of shorted elements for trip and alarm can be determined by knowing the voltage on the affected elements (for instance, the *Ve* value calculated in Table 10) and the capability of the elements (either 110% of rating based on industry standards or the information provided by the capacitor manufacturer)."

110% of capacitor element rated voltage is 3.6 kV × 1.1 = 3.96 kV.

*For zero failed units (*e *= 0):*

$E = S.Su$	Total elements in a string	$E = 40$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1$
$Cp = \frac{(Cy \times Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1$
$Vng = G \times \left(1-\frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 1$
$Ve = Vln \times \frac{E}{E-e}$	Voltage on affected elements	$Ve = 1$

$Iy = Cy \times Vln$	Current in affected wye	$Iy = 1$
$Iph = Cp \times Vln$	Current in affected phase	$Iph = 1$
$Ig = (1 - G) \times (1 - Iph)$	Ground current	$Ig = 0$
$In = \frac{3 \times Vng \times G \times (Sp - Sl)}{Sp}$	Neutral current between wyes	$In = 0$
$Id = Vln \times (1 - Cp)$	Difference current	$\lvert Id \rvert = 0$

$\mathrm{ING} := \lvert I_g \rvert \times \frac{Iph\mathrm{PRI}}{2} \times Sl$	Neutral-to-ground current	$\mathrm{ING} = 0$
$Vng\mathrm{PRI} := Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 0$
$In\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times In$	Neutral current between wyes	$In\mathrm{PRI} = 0$
$Id\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times \lvert Id \rvert$	Difference current between equal wyes	$Id\mathrm{PRI} = 0$
$Vln\mathrm{PRI} := Vln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 139.4\ \mathrm{kV}$
$Ve\mathrm{PRI2} := Ve \times \frac{Vln\mathrm{PRI}}{\mathrm{Ts}}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 3.486\ \mathrm{kV}$

The voltage on each element with zero failed elements is 3486 V at 105% nominal system voltage. This is 96.8% of the rated element voltage.

*For a single failed element in a string (*e *= 1):*

$E = S.Su$	Total elements in a string	$E = 40$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1.026$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1.026$
$Cp = \frac{(Cy \times Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1.013$
$Vng = G\times\left(1-\frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0.00425$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 0.996$
$Ve = Vln \times \frac{E}{E-e}$	Voltage on affected elements	$Ve = 1.021$
$Iy = Cy \times Vln$	Current in affected wye	$Iy = 1.021$
$Iph = Cp \times Vln$	Current in affected phase	$Iph = 1.009$
$Ig = (1-G)\times(1-Iph))$	Ground current	$Ig = 0$
$In = \frac{3\times Vng \cdot G \times (Sp-Sl)}{Sp}$	Neutral current between wyes	$In = 0$
$Id = Vln \times (1-Cp)$	Difference current	$\|Id\| = 0.0013$

$\mathrm{ING} := \|Ig\| \times \frac{Iph\mathrm{PRI}}{2} \times Sl$	Neutral-to-ground current	$\mathrm{ING} = 0$
$Vng\mathrm{PRI} := Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 593.32$
$In\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times In$	Neutral current between WYES	$In\mathrm{PRI} = 0.718$
$Id\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \cdot \|Id\|$	Difference current between equal wyes	$Id\mathrm{PRI} = 1.436$
$Vln\mathrm{PRI} := Vln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 1.388 \times 10^5$
$Ve\mathrm{PRI2} := Ve \times \frac{Vln\mathrm{PRI}}{\mathrm{Ts}}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 3.545 \times 10^3$

For a single failed element, the voltage on the affected elements rises to 3545 V, which is 98.5% of the rated element voltage. To detect this condition reliably, set the phase unbalance elements to 80% of the calculated difference current between equal wyes.

Alarm threshold = 1.436 A × 0.8 = 1.148 A primary.

*For seven failed elements (*e *= 7):*

$E = S.Su$	Total elements in a string	$E = 40$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1.212$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1.212$
$Cp = \frac{(Cy \cdot Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1.106$
$Vng = G \times \left(1 - \frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0.034$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 0.966$
$Ve = Vln \times \frac{E}{E-e}$	Voltage on affected elements	$Ve = 1.171$
$Iy = Cy \times Vln$	Current in affected wye	$Iy = 1.171$
$Iph = Cp \times Vln$	Current in affected phase	$Iph = 1.068$
$Ig = (1-G) \times (1 - Iph))$	Ground current	$Ig = 0$
$In = \frac{3 \times Vng \cdot G \times (Sp - Sl)}{Sp}$	Neutral current between wyes	$In = 0.051$
$Id = Vln \times (1 - Cp)$	Difference current	$\lvert Id \rvert = 0.102$

$\mathrm{ING} := \lvert Ig \rvert \times \frac{Iph\mathrm{PRI}}{2} \times Sl$	Neutral-to-ground current	$\mathrm{ING} = 0$
$Vng\mathrm{PRI} := Vng \times \mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 4.761 \times 10^{3}$
$In\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times In$	Neutral current between wyes	$In\mathrm{PRI} = 6.103$
$Id\mathrm{PRI} := Iph \times Iph\mathrm{PRI} \times \lvert Id \rvert$	Difference current between equal wyes	$Id\mathrm{PRI} = 12.207$
$Vln\mathrm{PRI} := Vln \times \mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 1.347 \times 10^{5}$
$Ve\mathrm{PRI2} := Ve \times \frac{Vln\mathrm{PRI}}{Ts}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 3.942 \times 10^{3}$

With seven failed elements, the voltage on each element rises to 3942 V. This is 109.5% of the rated element voltage.

*For eight failed elements (*e = *8):*

$E = S.Su$	Total elements in a string	$E = 40$
$Cst = \frac{E}{E-e}$	Shorted capacitor elements	$Cst = 1.25$
$Cy = \frac{Sl-1+Cst}{Sl}$	Shorted per-unit capacitance	$Cy = 1.25$
$Cp = \frac{(Cy\times Sl)+Sp-Sl}{Sp}$	Affected phase capacitance	$Cp = 1.125$
$Vng = G\times\left(1-\frac{3}{2+Cp}\right)$	Neutral-to-ground voltage	$Vng = 0.04$
$Vln = 1 - Vng$	Voltage on the affected phase	$Vln = 0.96$
$Ve = Vln\times\frac{E}{E-e}$	Voltage on affected elements	$Ve = 1.2$
$Iy = Cy\times Vln$	Current in affected wye	$Iy = 1.2$
$Iph = Cp\times Vln$	Current in affected phase	$Iph = 1.08$
$Ig = (1-G)\times(1-Iph))$	Ground current	$Ig = 0$
$In = \frac{3\times Vng\times G\times(Sp-Sl)}{Sp}$	Neutral current between wyes	$In = 0.06$
$Id = Vln\times(1-Cp)$	Difference current	$\lvert Id\rvert = 0.12$
$\mathrm{ING} := \lvert Ig\rvert\times\frac{Iph\mathrm{PRI}}{2}\times Sl$	Neutral-to-ground current	$\mathrm{ING} = 0$
$Vng\mathrm{PRI} := Vng\times\mathrm{SYSVLN}$	Voltage neutral to ground	$Vng\mathrm{PRI} = 5.577\times 10^{3}$
$In\mathrm{PRI} := Iph\times I\mathrm{phPRI}\times In$	Neutral current between wyes	$In\mathrm{PRI} = 7.228$
$Id\mathrm{PRI} := Iph\times Iph\mathrm{PRI}\times\lvert Id\rvert$	Difference current between equal wyes	$Id\mathrm{PRI} = 14.456$
$Vln\mathrm{PRI} := Vln\times\mathrm{SYSVLN}$	Voltage on affected phase	$Vln\mathrm{PRI} = 1.339\times 10^{4}$
$Ve\mathrm{PRI2} := Ve\times\frac{Vln\mathrm{PRI}}{\mathrm{Ts}}$	Voltage on affected elements	$Ve\mathrm{PRI2} = 4.016\times 10^{3}$

With eight failed elements, the voltage across the remaining elements in the string rises to 4016 V. This is 111.5% of the rated element voltage. To determine the trip threshold, find a current unbalance point halfway between seven and eight unit failures.

Trip threshold = (14.456 – 12.207) / 2 + 12.207 = 13.33 A primary.