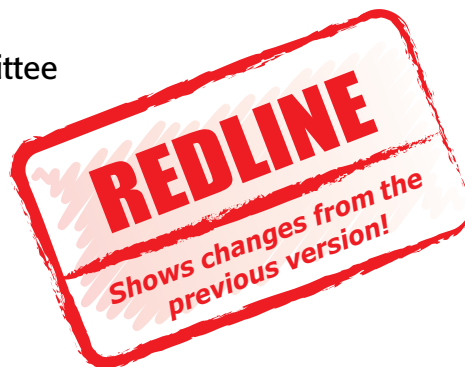


IEEE Guide for the Protection of Shunt Capacitor Banks

IEEE Power and Energy Society

Sponsored by the
Power System Relaying Committee



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3 Park Avenue
New York, NY 10016-5997
USA

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IEEE Guide for the Protection of Shunt Capacitor Banks

Sponsor

Power System Relaying Committee
of the
IEEE Power and Energy Society

Approved 5 December 2012

IEEE-SA Standards Board

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 1036TM-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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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 ~~a discussion~~ the protection of pole-mounted capacitor banks on distribution circuits or ~~application of~~ capacitors connected to the terminals of rotating ~~apparatus~~ 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. ~~Capacitor bank design trade-offs are also discussed because bank design influences~~ [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.](#)

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 If the following publications are superseded by an approved revision, the revision shall apply:~~

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

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

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

IEEE Std 18-~~1992~~ TM, IEEE Standard for Shunt Power Capacitors.²³

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

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

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

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

[IEEE Std 1531TM, IEEE Guide for Application and Specification of Harmonic Filters.](#)

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

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

IEEE Std C37.2-~~1996~~ TM, IEEE Standard ^{for} Electrical Power System Device Function Numbers, [Acronyms](#), and Contact Designations.

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

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

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[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-~~1989 (Reaff 1994)~~,TM IEEE Standard for Surge Withstand Capability (SWC) Tests for ~~Protective~~ 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-~~1996~~ TM, IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

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

IEEE Std C62.22-~~1997~~ TM, 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 ~~guide~~ [document](#), the following terms and definitions apply. [The IEEE Standards Dictionary Online](#) should be consulted for terms not defined in this clause.⁵

⁴ [NEMA publications are available from Global Engineering Documents \(http://global.ihs.com/\).](http://global.ihs.com/)

⁵ [The IEEE Standards Dictionary Online](http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html) subscription is available at http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

back-to-back capacitor bank switching (or back-to-back switching or back-to-back capacitor switching): Switching a capacitor bank ~~with and~~ 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. ~~It may be a collection of components assembled at the operating site or may include one or more piece(s) of factory assembled equipment.~~

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

capacitor element (or element): The basic component of a capacitor unit ~~A device~~ consisting ~~essentially~~ 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 ~~bank~~ 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 out rush current (or outrush current): The ~~high-frequency, high-magnitude current~~ transient discharge ~~of one or more capacitors into a short circuit, such as into a failed~~ current that flows when an energized capacitor ~~unit bank is initially~~ connected ~~in parallel with the discharging units, or into a breaker closing into a fault~~ 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 ~~residual~~ 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 ~~problems in~~ voltages and currents in the power system ~~such as reducing voltage distortion due to large rectifier loads or arc furnaces.~~

fixed capacitor bank: A capacitor bank ~~that does not have a capacitor control and must be manually switched~~ 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 ~~interrupting~~ 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 ~~between line and neutral (wye connection) or between line terminals (delta or single phase). See also: unfused capacitor bank.~~

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

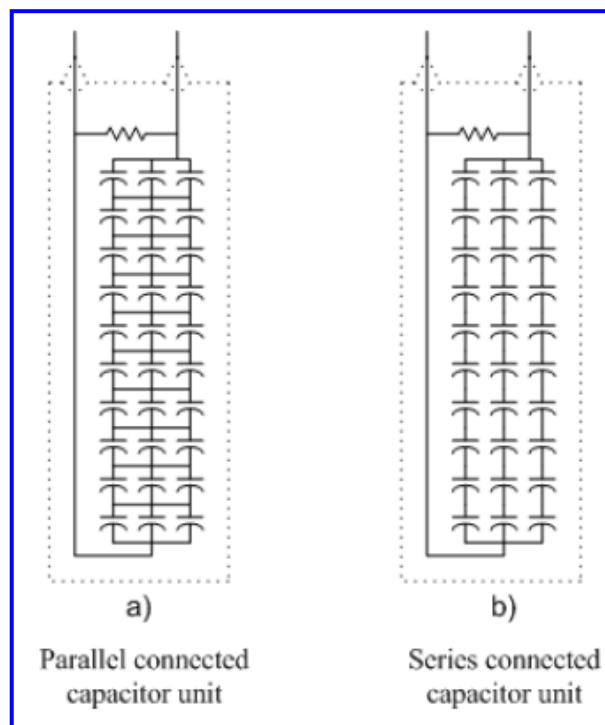
internal fuse of a capacitor: A fuse connected inside a capacitor unit, in series with an element or a group of elements.

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.

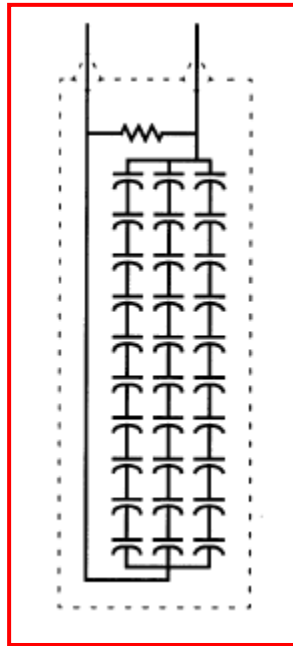
parallel-(element)-connected capacitor (unit): A capacitor unit with the elements connected in parallel groups, with the parallel groups connected in series between the line terminals ([Figure 1](#)). ~~A capacitor unit that has only one string of capacitor elements between the capacitor terminals is considered to be parallel-connected.~~

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.



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Figure 1—Capacitor unit design



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

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).

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

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

thyristor-controlled reactor (TCR): ~~The~~ A reactor whose effective value ~~of the reactor~~ is changed by ~~using thyristors to~~ 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.

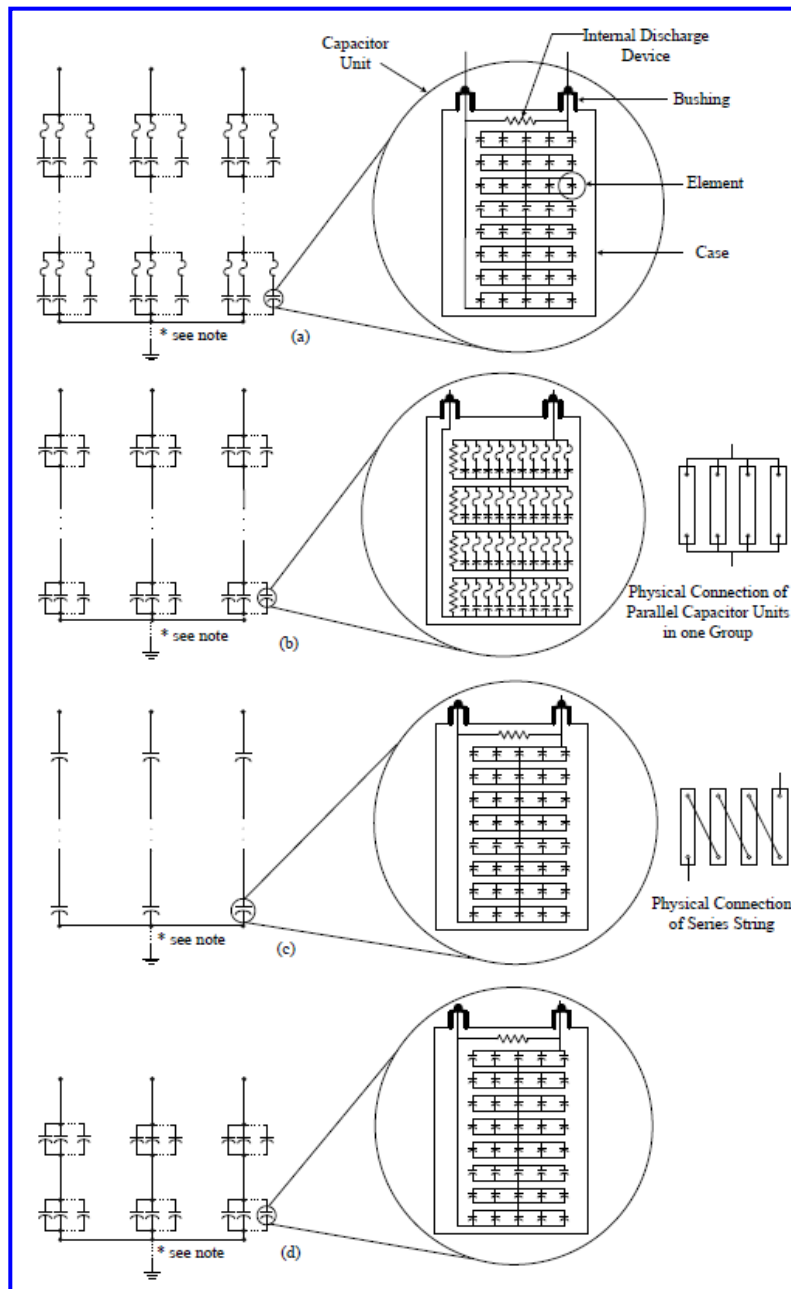
4. Basic considerations

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

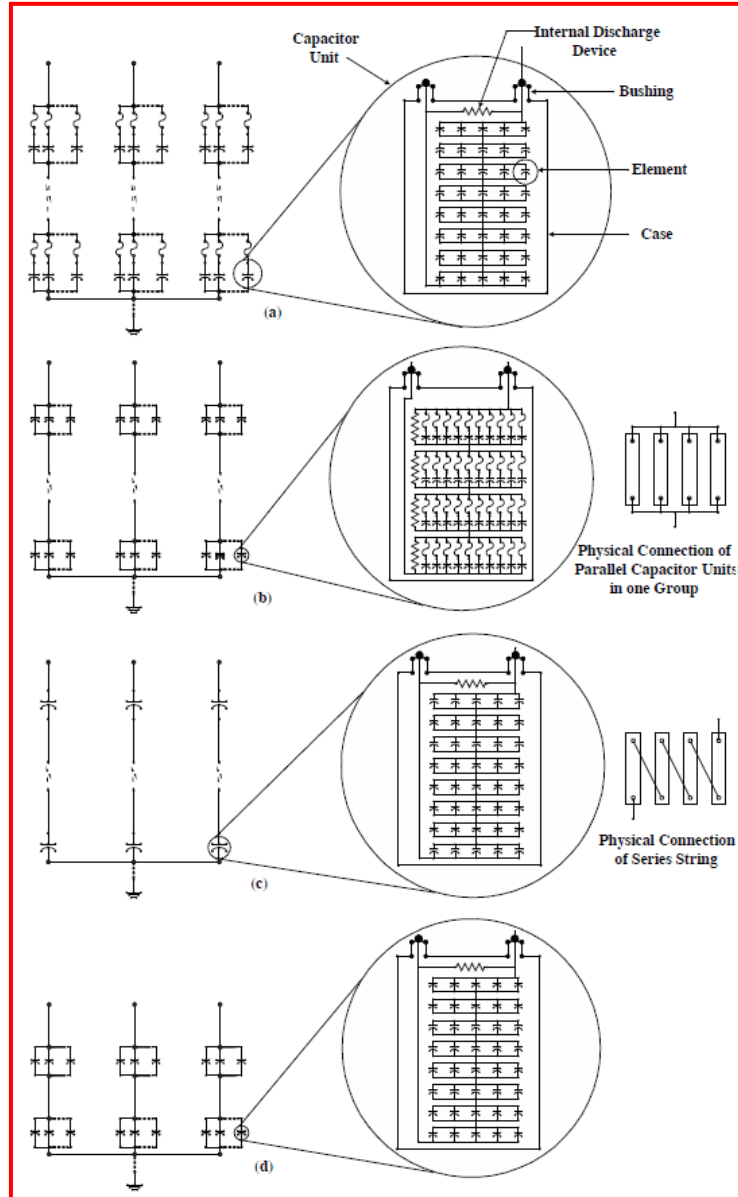
- a) Externally fused, with individual fuses for each capacitor unit.
- b) Internally fused, with each element fused inside the capacitor unit.
- c) Fuseless, with capacitor units connected in series strings between line and neutral (or between line terminals)
- d) Unfused, with ~~the~~ capacitor units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

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

See Clause 2 ~~for~~ [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.



[\(New\)](#)



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- (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-~~1992~~³ TM specifies the standard ratings of the capacitors designed for shunt connection to ac transmission and distribution systems.⁶ IEEE Std 1036-~~1992~~ TM 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 ~~and frequency~~. Capacitors ~~are~~ shall be capable of continuous operation under the contingency system and bank conditions provided none of the following limitations are ~~not~~ exceeded:

- 1) 110 % of rated RMS voltage
- 2) 120% of rated peak voltage (i.e., peak ~~crest~~ voltage not exceeding $1.2\sqrt{2}$ times the ~~of~~ rated RMS voltage, including harmonics, but excluding transients,
- 3) ~~The capacitor should also be able to carry~~ 135% of nominal RMS current based on rated kvar and rated voltage ~~capability of any series element of a capacitor unit shall be considered to be its share of the total capacitor unit voltage capability.~~
- 4) 135% of rated kvar

⁶ Information on references can be found in Clause 2.

- b) ~~The~~ capacitance of a unit ~~shall~~ ~~should not give less than 100% nor~~ ~~not vary~~ more than ~~-0%~~ to +10% of the nominal value based on rated kvar, 115% (110% for capacitor units manufactured in conformance with IEEE Std 18-1992 after the year 2000) of rated reactive power at rated sinusoidal voltage, and frequency, measured at ~~a~~ 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 24 h average ambient air temperature of 40 °C during the hottest day ~~or~~ Capacitors shall be capable of both continuous operation and switching operations at a minimum ambient temperature of -40 °C ~~during the coldest day expected at the location.~~
- 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 (~~240~~ 216 V to 24 940 V) and sizes (2.5 kvar to about ~~1000~~ 800 kvar). Capacitor units designed for special applications can exceed these ratings (see IEEE Std 18-~~1992~~). See IEEE Std 1036-~~1992~~ for capacitor short- time overvoltage capability.
- d) ~~Capacitor units should be suitable for continuous operation at up to 135% of rated reactive power caused by the combined effects of~~
- ~~1) Voltage in excess of the nameplate rating at fundamental frequency, but not over 110% of rated rms voltage.~~
 - ~~2) Harmonic voltages superimposed on the fundamental frequency.~~
 - ~~3) Reactive power manufacturing tolerance of up to 115% of rated reactive power.~~

4.2 Capacitor unit ~~connections~~ ~~capabilities~~

Depending on the application, any of the four ~~connections~~ 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 ~~substation~~ shunt capacitor banks are configured using one or more series groups of parallel connected capacitor units per phase. ~~Each capacitor unit is typically protected by~~ An individual fuse, externally mounted between the capacitor unit and the capacitor bank fuse bus. ~~See,~~ 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 ~~are~~ is required to allow the bank to remain in service with one ~~fuse or~~ 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.

Figure 2(b) illustrates a typical capacitor bank utilizing internally fused capacitor units. The capacitor units ~~are~~ normally have a large ~~because~~ 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 ~~to~~ [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.](#) ~~Another advantage is that the unbalance protection does not have to be delayed to coordinate with the fuses.~~

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 voltage across the remaining elements will increase more than in the fuseless design.~~ The unfused approach ~~would normally~~ [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 ~~does~~ [may](#) not require as many capacitor units in parallel as an externally fused bank. ~~See~~ [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 ~~also having~~ [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-~~1992~~.

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

The maximum number of capacitor units that may be placed in parallel per series group is governed by a different consideration. When a capacitor unit fails, other capacitors in the same parallel group will contain some amount of charge. This charge will drain off as a high-frequency transient current that flows through the failed capacitor unit and its fuse. The fuse holder and the failed capacitor unit should withstand this discharge transient [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 $\times 1.1 \times \sqrt{2}$). For 60 Hz applications, NEMA CP1-~~1988~~ recommends a total parallel kilovar limit of 4650 kvar for all-film dielectric capacitor units (3100 kvar for older capacitor units). All-film dielectric capacitor banks have been applied up to 9600 kvar in parallel with expulsion fuses (Mendis et al. [B ~~(9)~~(10)]⁷). Consult the capacitor and fuse manufacturer before exceeding the 4650 kvar limit to ~~ensure~~ [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.

⁷ The numbers in brackets correspond to those of the bibliography in Annex [A](#) ~~B~~.

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 ~~can~~ [will also](#) result in the removal of the bank. ~~Another possibility is~~ 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 ~~should~~ [typically](#) recommends the maximum number of capacitor units to be connected directly in parallel.

If a proposed capacitor bank having the minimum number of series groups has too many capacitor units in parallel, [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 ~~require a high~~ [are usually used at a higher](#) system voltage (~~about~~ [at or above](#) 34.5 kV ~~minimum~~). Capacitor units are connected in series strings. The capacitor units usually have two bushings and may have additional insulation between the capacitor elements and the case. Each string usually has more than 10 elements in series to ~~ensure~~ [assist in ensuring](#) that the remaining elements do not exceed 110% [of the nominal](#) rating if an element in the string shorts. ~~If a large fuseless bank is required, several strings can be connected in parallel.~~

4.3.4 Unfused [shunt capacitor](#) banks

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

4.4 Overvoltage on remaining capacitor units

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

4.4.1 Externally fused [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 ~~higher the voltage for the bank, the more~~ 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 ~~absorb the additional~~ be subject to overvoltage. The voltage ~~additional voltage~~ increase on each element will be approximately equal to $E/(E-1)$, where E is the original number of capacitor elements in the string⁵. 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

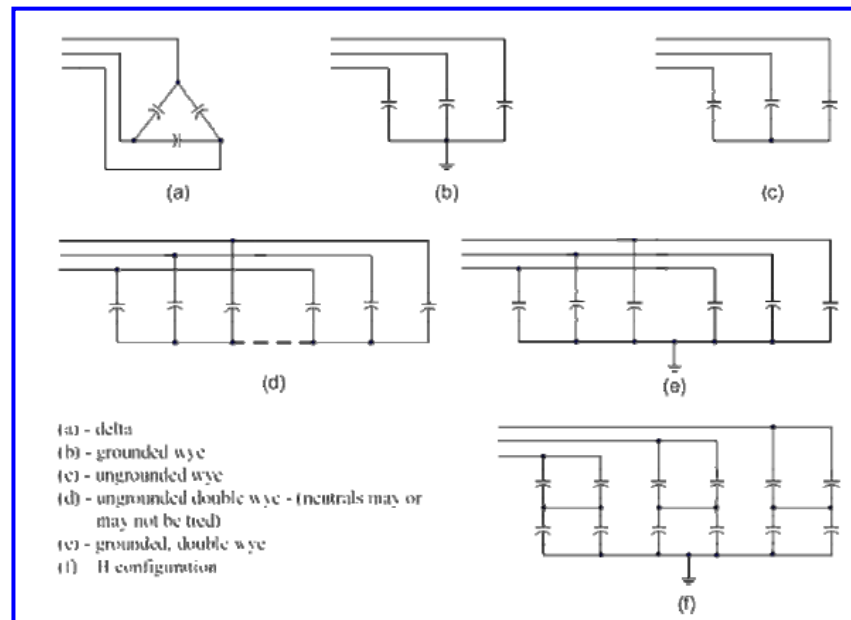
The unfused capacitor bank has no fuses. Unbalance protection should be applied so that following failures, the resulting voltage on the remaining healthy capacitor units does not exceed 110% of their rating or the recommended level specified by the manufacturer.

5. Bank connections

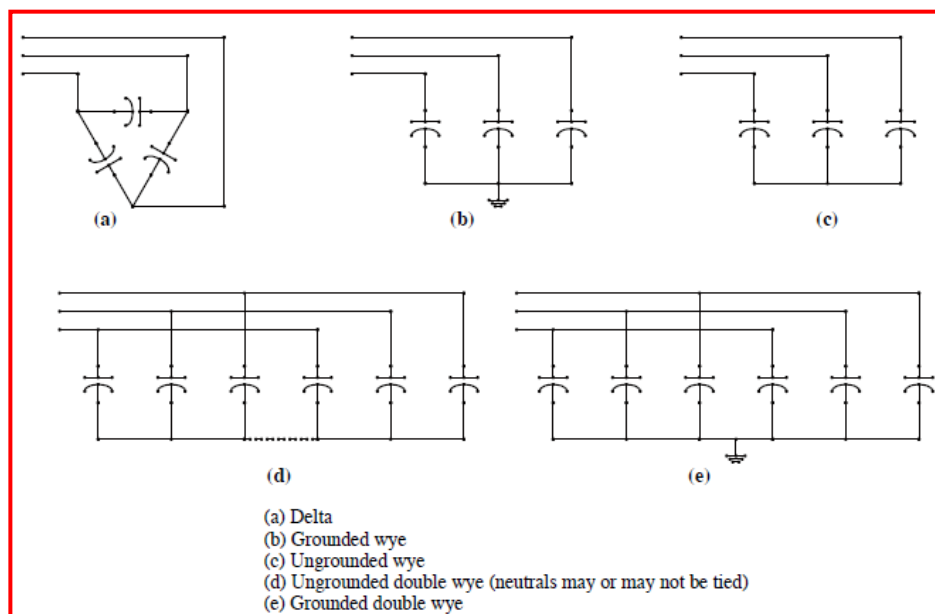
~~Five~~ Six common capacitor bank connections are shown in Figure 3. The optimum connection depends on the best utilization of the available voltage ratings of capacitor units, fusing, and protective relaying. These connections can be used for externally fused capacitor bank design, internally fused 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.

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

The various types of connections are illustrated in Figure 3



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Figure 3—**Basic** ~~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 ~~shall~~ should be capable of interrupting the system available fault current.

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

5.1.2 Multiple units in series phase to ground—single wye

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

Internally fused capacitor units should be arranged in the bank design ~~to ensure~~ 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 ~~shall~~ 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 becomes too large, making to maintain the parallel energy of a series group within the limits of capacitor units or fuses, the bank may be split into two wye sections. The characteristics of the grounded double wye are similar to a grounded single wye bank. The two neutrals should be directly connected with a single connection to ground.

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

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 ~~in order~~ to avoid the need for power fuses to interrupt the system short-circuit fault current or to minimize the flow of triplen harmonics, which can cause telephone interference. This design requires that single-bushing capacitor units be mounted on an insulated rack. If two-bushing capacitor units are used with a grounded rack, 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 ~~three~~ [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.

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

5.2.3 Multiple units in series phase to neutral—double wye

When a capacitor bank becomes too large for the 4650 kvar per group maximum for expulsion fuses and is large enough to meet the minimum units per group requirement as outlined in 4.3, the bank may be split into two wye sections. When the two neutrals are ungrounded, the bank has the same characteristics ~~of~~ 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 ~~as should the phase terminals~~, for full line-to-ground voltage.

5.3 Delta-connected banks

Delta-connected banks are generally used only at distribution voltages and are 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 ~~per leg~~ of capacitors is used, the individual capacitor fuses ~~shall~~ 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™.

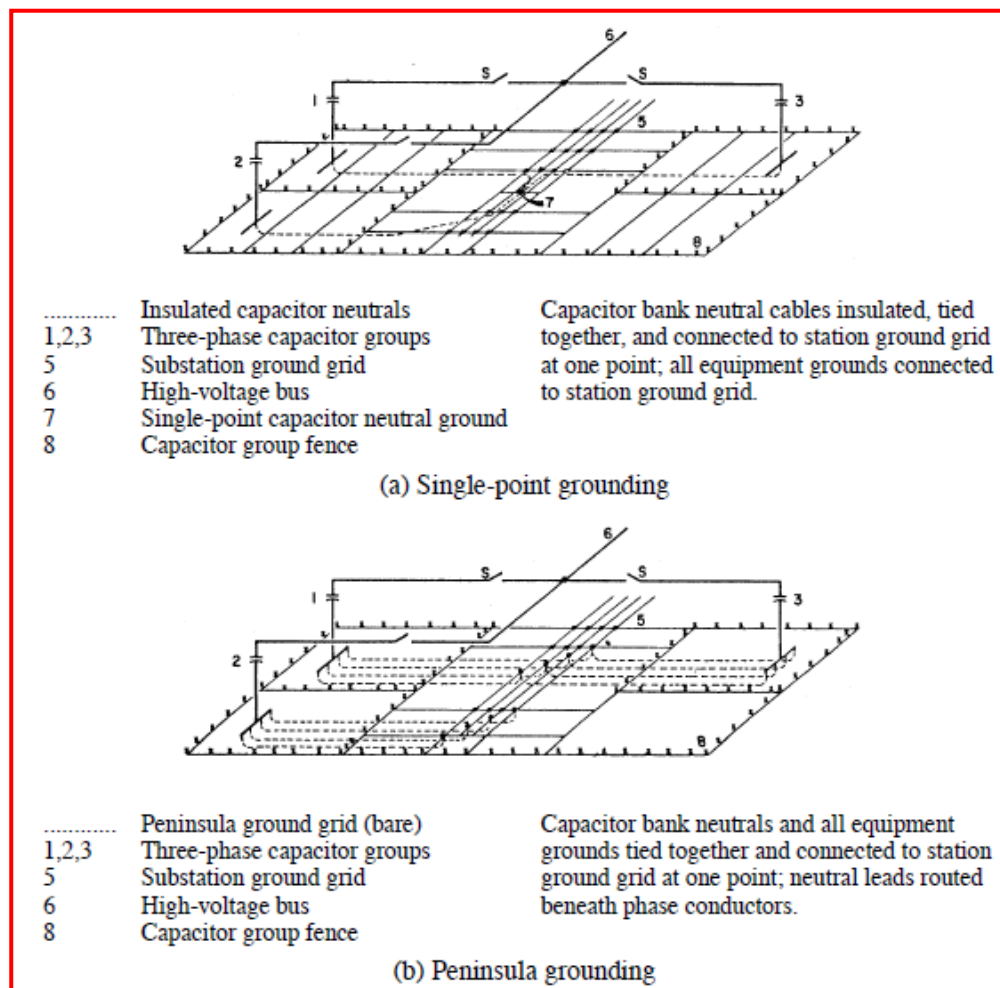
6.1 Single-point and peninsula grounding

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

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

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

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



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Figure 4—Single-point and peninsula grounding

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

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

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

~~Because the severity of parallel bank switching is caused by the very sudden high current, which initially is limited only by the very low resistance and inductance of the circuit between the banks, it can be reduced by the addition of inductance to the circuit. An inductance with a 60-Hz reactance as low as 0.5–1% of the 60-Hz capacitive reactance of the banks placed in series with them will greatly reduce both the rate of rise and the peak value of the inrush current. This inductance greatly reduces the severity of the switching device duty. Additional inductance may be obtained by increasing the length of the bus between the capacitor banks or adding current-limiting reactors. The reactors may be air core or consist of magnetic cores surrounding the leads or bus.~~

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

~~—Minimize the possibility of induced voltages affecting the relaying.~~

~~—Avoid damaging other equipment (Rogers and Gillies [B12]; Alexander [B2]; McCauley et al. [B8]).~~

6.2 Neutral grounding

The application of large shunt capacitor banks with switched parallel banks in high-voltage transmission systems involves a number of considerations, one of which is grounding. It is generally recommended that the neutral of capacitor banks be grounded only ~~to~~ 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 ~~of the~~ main advantage associated with neutral grounding ~~concerns the~~ 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-~~1979~~TM and ANSI C37.06-~~1997~~ 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 ~~applied~~ connected to tertiaries of power transformers that are connected to the line or possibly to the bus. Grounding the neutral of ~~the~~ 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 ~~source~~ 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 X_0/X_1 , depending on system, transformer, and capacitor bank parameters. If the neutral is to be grounded on a system that is not effectively grounded, then the application should be thoroughly analyzed for proper application of surge arresters, bank configuration, bank switching devices, ~~etc~~ 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](#) ~~a shutdown~~ of the bank in case of faults that may lead to a catastrophic failure, and alarms to indicate unbalance within the bank.

System protection schemes are provided to protect the capacitor bank from stresses that may be caused by the system and to protect the substation and system from stresses that may be caused by the operation of the capacitor bank. System protection may include items such as a means to limit overvoltage and excessive transient overcurrents and to disconnect the bank in the event of a major fault within the capacitor installation [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 ~~of the~~ 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)

Bank protection		
Condition	Type of protection	Remarks
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.