

Recognized as an American National Standard (ANSI)

IEEE C37.99-1990

(Revision of ANSI/IEEE C37.99-1980)

IEEE Guide for the Protection of Shunt Capacitor Banks

Sponsor

**Power Relaying Committee
of the
IEEE Power Engineering Society**

Approved September 28, 1990
Reaffirmed December 13, 1994

IEEE Standards Board

Approved February 26, 1991

American National Standards Institute

Abstract: IEEE C37.99-1990, *IEEE Guide for the Protection of Shunt Capacitor Banks*, assists in the effective application of relays and other devices for the protection of shunt capacitors used in substations. It covers the protective considerations, along with recommended and alternate methods of protection for the most commonly used capacitor bank configurations. Capacitor bank design trade-offs are also discussed. This guide covers protection of filter tanks and very large EHV capacitor banks, but does *not* include a discussion of pole-mounted capacitor banks on distribution circuits or application of capacitors connected to rotating apparatus.

Keywords: Bank connections, bus voltage, capacitor units, delta-connected banks, equipment considerations, protection of banks, Y-banks, relaying methods

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

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Printed in the United States of America

ISBN 1-55937-071-8

Library of Congress Number 91-055206

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Foreword

(This Foreword is not a part of IEEE C37.99-1990, IEEE Guide for the Protection of Shunt Capacitor Banks).

This revision of ANSI/IEEE C37.99-1980 incorporates a number of additions and changes. Some of the more significant changes were made in the sections dealing with the protection of very large EHV capacitor banks and HVDC filter banks. Other changes were made to bring this guide up-to-date and more in line with present-day requirements.

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

C. J. Cook, Chair

H. N. Banerjee
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J. S. Komisarek
W. C. Kotheimer
R. W. Ohnesorge
G. C. Parr

L. J. Schulze
W. M. Strang
T. E. Wiedman

At the time this guide was approved, the Substation Protection Subcommittee membership was as follows:

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R. W. Dempsey, Vice Chair/Secretary

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E. A. Baumgartner
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S. P. Conrad
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IEEE Guide for the Protection of Shunt Capacitor Banks

1. Introduction

This guide has been prepared to assist in the effective application of relays and other devices for the protection of shunt capacitors used in substations. It covers the protective considerations, along with recommended and alternate methods of protection for the most commonly used capacitor bank configurations. Capacitor bank design trade-offs are also discussed since bank design influences protection. This guide covers protection of filter banks and very large EHV capacitor banks. This guide does not include a discussion of pole-mounted capacitor banks on distribution circuits or application of capacitors connected to rotating apparatus.

2. References

2.1 Standards References

This guide may be used in conjunction with the following publications:

[1] ANSI C37.06-1987, Preferred Ratings and Related Required Capabilities for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.¹

[2] IEEE Std 18-1980, IEEE Standard for Shunt Power Capacitors (ANSI).²

[3] IEEE Std 469-1988, IEEE Recommended Practice for Voice-Frequency Electrical-Noise Tests of Distribution Transformers (ANSI).

[4] IEEE C37.012-1979, (R 1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

[5] IEEE C37.04-1979, IEEE Standard Rating Structure for A.C High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

¹ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York NY 10018.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08855.

[6] IEEE C37.90-1989, IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus (ANSI).

[7] NEMA CPI-1976, Shunt Capacitors.³

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3. Basic Considerations

Relay protection of shunt capacitor banks requires an understanding of the capabilities and limitations of the individual capacitor units and associated electrical equipment including: individual capacitor-unit fuses, bank switching devices, power fuses, and voltage or current sensing devices. Applicable standards for this associated electrical equipment are referenced as discussed.

3.1 Capacitor Unit Ratings

IEEE Std 18-1980 [2] specifies the standard ratings of capacitors designed for shunt connection to alternating current transmission and distribution systems. Some of the ratings most significant to the relay engineer are listed below:

- 1) Capacitors should be capable of continuous operation at up to 110% of rated terminal rms voltage, including harmonics, and at up to 180% of rated rms current, including fundamental and harmonic currents.
- 2) Capacitors should give not less than 100% and not more than 115% of rated reactive power at rated sinusoidal voltage and frequency, measured at a uniform case and internal temperature of 25 °C.
- 3) Capacitors mounted in multiple rows and tiers should be designed for continuous operation for a normal annual temperature of 25 °C (as defined in the reports of the U.S. Weather Bureau) and for a 24 h average temperature of 40 °C during the hottest day expected at that location.
- 4) Capacitors should be suitable for continuous operation at up to 135% of rated reactive power caused by the combined effects of:
 - a) Voltage in excess of nameplate rating at fundamental frequency, but not over 110% of rated rms voltage.
 - b) Harmonic voltages superimposed on the fundamental frequency.
 - c) Reactive power manufacturing tolerance of up to 115% of rated reactive power.

Capacitor units are available in standard voltage ratings shown in Table 1 and in standard reactive power ratings of 50, 100, 150, 200, 300, and 400 kvar at most standard voltage ratings.

3.2 Arrangement of Capacitor Units

Substation type shunt capacitor banks are commonly configured using one or more series groups of parallel-connected standard-voltage 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. Also available are capacitor units that employ internal fusible links on each capacitor pack or element. Use of this design can eliminate the need for external fuses altogether. Figure l(a) illustrates a typical capacitor bank utilizing conventional capacitor units with external fuses. Figure l(b) illustrates a typical capacitor bank utilizing internally-fused capacitor units. In general, banks employing internally-fused capacitor units are configured with fewer capacitor units in parallel, and more series groups of units than are banks employing externally-fused capacitor units.

In internally fused capacitors, a fusible link is connected in series with each capacitor pack or element. Each capacitor unit is constructed with a large number of packs or elements connected in parallel, and with only a few groups of parallel packs connected in series. This construction is just the opposite as that found in externally fused capacitors, which typically employ a large number of series groups of packs or elements, with correspondingly fewer packs connected in parallel per series group. With internally fused capacitors, when a capacitor pack or 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 pack or element.

3.3 Capacitor Bank Design

A capacitor bank of a given size and voltage rating may be made up of a number of series groups of capacitors, as indicated in Table 1, and a number of parallel capacitors per series group.

Use of capacitors with the highest possible voltage rating will result in a capacitor bank with the fewest number of series groups. This generally provides the simplest and most economical 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.

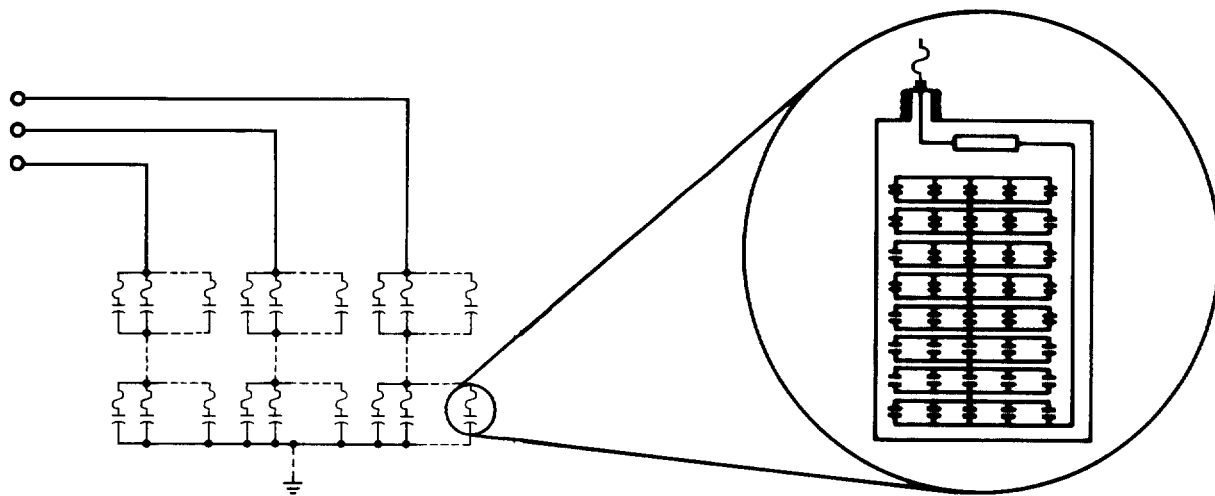
The number of capacitor units in parallel per series group is governed by both a minimum and a maximum limitation. The minimum number of capacitor units per group is determined by overvoltage considerations upon isolation of one capacitor unit in the group. The general rule is that isolation of one capacitor 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 rating of capacitor units per IEEE Std 18-1980 [2].

The minimum recommended number of capacitor units in parallel per series group, listed in Table 2, may limit the maximum capacitor unit kvar rating that can be used for relatively small banks. Moreover, it emphasizes the desirability of using capacitor units with the highest possible voltage rating and minimum number of series groups in order to obtain an adequate number in each group.

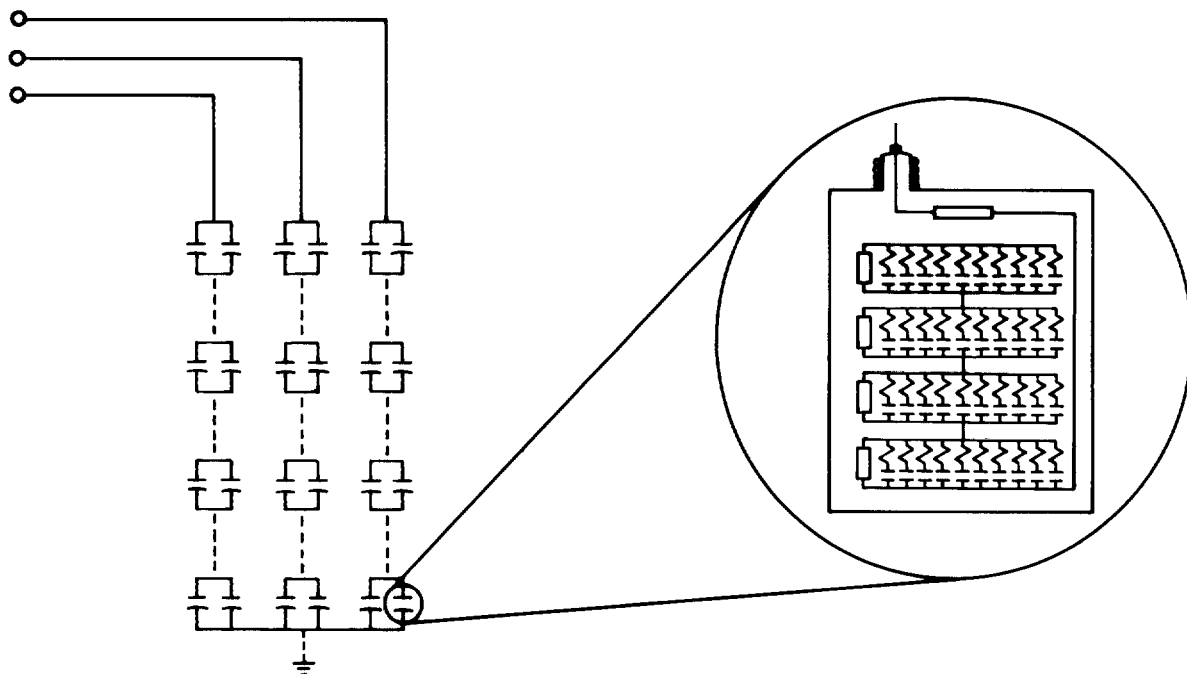
The maximum number of capacitor units that may be placed in a parallel per series group is governed by a different consideration. When a capacitor unit fails, other capacitors in the same parallel group will contain some amount of charge. This charge will then drain off as a high-frequency transient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

The discharge transient from a large number of paralleled capacitors can be severe enough to rupture the failed capacitor unit or the expulsion fuse holder, which may result in damage to adjacent units or cause a major bus fault within the bank. To minimize the probability of failure of the expulsion fuse holder, or rupture of the capacitor case, or both, the total energy stored in a parallel-connected group of capacitors should not exceed 15 000 J for all-film capacitor units (10 000 J for older capacitor units) at maximum peak voltage (rated voltage $\cdot 1.1 \cdot \sqrt{2}$). For 60 Hz applications, the maximum recommended limit for parallel-connected kvar per series group is 4650 kvar for all-film capacitor units (3100 kvar for older capacitor units). Refer to NEMA CP1-1976 [7].

If a capacitor bank having the minimum number of series groups requires more than 4650 kvar per series group, capacitors of a lower voltage rating requiring more series groups and fewer units in parallel per group may be a suitable solution. However, this may reduce the sensitivity of the unbalance detection scheme, or it may result in the bank being removed from service for a fewer number of isolated capacitor units due to the voltage across the remaining units exceeding 110% of their rated voltage. Splitting the bank into two sections, as a double Y, may be the preferred arrangement and may permit a better unbalance detection scheme. Another possibility is the use of current limiting fuses in a single-Y configuration.



(a)



(b)

Figure 1—Y-Connected Capacitor Bank
(a) Externally-Fused Capacitor Units
(b) Internally-Fused Capacitor Units

Table 1—Y-Connected Capacitor Banks, Number of Series Groups*

V_{LL} kV	V_{LN} kV	Available Capacitor Voltages (kV per unit)												
		21.6	19.92	14.4	13.8	13.28	12.47	9.96	9.54	8.32	7.96	7.62	7.2	6.64
500.0	288.7	14	15	20	21	22		29	30	35	36	38		
345.0	199.2		10			15	16	20	21	24	25	27		
230.0	132.8					10			14	16	17	18		20
161.0	92.9					7							13	14
138.0	79.7		4	6	6	6		8			10		11	12
115.0	66.4					5			7	8	9	9		10
69.0	39.8		2		3	3		4			5			6
46.0	26.56					2								4
34.5	19.92		1					2						3
24.9	14.4			1									2	
23.9	13.8				1									
23.0	13.28					1								2
14.4	8.32									1				
13.8	7.96										1			
13.2	7.62											1		
12.47	7.2												1	

*This table shows, for a particular system voltage, the number of series-connected capacitors per phase of a Y-connected bank that operates near rated capacitor unit voltage.

Table 2—Minimum Recommended Number of Units in Parallel per Series Group to Limit Voltage on Remaining Units to 110% with One Unit Removed

Number of Series Groups	Grounded Y or Δ	Ungrounded Y	Double Y (Equal Sections)
1	—	4	2
2	6	8	7
3	8	9	8
4	9	10	9
5	9	10	10
6	10	10	10
7	10	10	10
8	10	11	10
9	10	11	10
10	10	11	11
11	10	11	11
12 and over	11	11	11

3.4 Overvoltage on Remaining Capacitor Units

The overvoltage that occurs when an individual capacitor unit is isolated decreases as the number of capacitor units per series group is increased. For a given bank size, use of larger individual unit capacitor kvar ratings decreases the number of capacitor units per series group and increases the overvoltage change due to isolation of a single capacitor. Failure of additional capacitors is most likely to occur in the same series group as the first failure, since these remaining capacitor units have the highest voltage stress. However, if two capacitors fail in the same phase but not in the same series group, the overvoltage percentage is less than that of two capacitors failing within the same series group.

4. Bank Connections

There are five common capacitor bank connections. The connection selected depends upon the best utilization of the standard voltage ratings of capacitor units, fusing, and protective relaying. Virtually all substation banks are connected in **Y**. Distribution capacitor banks, however, may be connected **Y** or Δ .

The various types of connections illustrated in Fig 2 are:

- 1) Δ
- 2) Grounded **Y**
- 3) Grounded double **Y**
- 4) Ungrounded **Y**
- 5) Ungrounded double **Y**

4.1 Delta-Connected Banks

Delta-connected banks are generally used only at distribution voltages and are configured with a single series group of capacitors rated for line-to-line voltage. Wye-connected banks are less complicated and more economical, since Δ -connected banks require either two-bushing capacitors with a grounded rack or single-bushing units with an insulated rack. The greatest use of Δ -connected banks is at 2400 V, since this is the lowest standard capacitor voltage rating. Capacitor units for **Y** connection at 2400 V are not available as a standard unit size.

With only one series group of units, no overvoltage occurs across remaining capacitor units from isolation of a faulted capacitor unit and, 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 in a Δ -connected capacitor bank. Additionally, where one series group per phase is used, the individual capacitor fuses should be capable of interrupting the system short-circuit phase-to-phase fault current. This often necessitates a current-limiting fuse. Such fuses are significantly more costly than expulsion fuses.

4.2 Grounded-Y Connected Banks

Grounded-**Y** capacitor banks are most commonly used for voltages of 34.5 kV and above, and are composed of two or more series groups of parallel connected standard voltage capacitor units per phase. Figure 1 shows a typical bank arrangement. A number of series group combinations are given in Table 1.

Grounded capacitor banks provide a low-impedance path to ground for lightning surge currents and give some protection from surge voltages. Sometimes the bank may be operated without surge arresters, taking advantage of this self-protective feature.

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

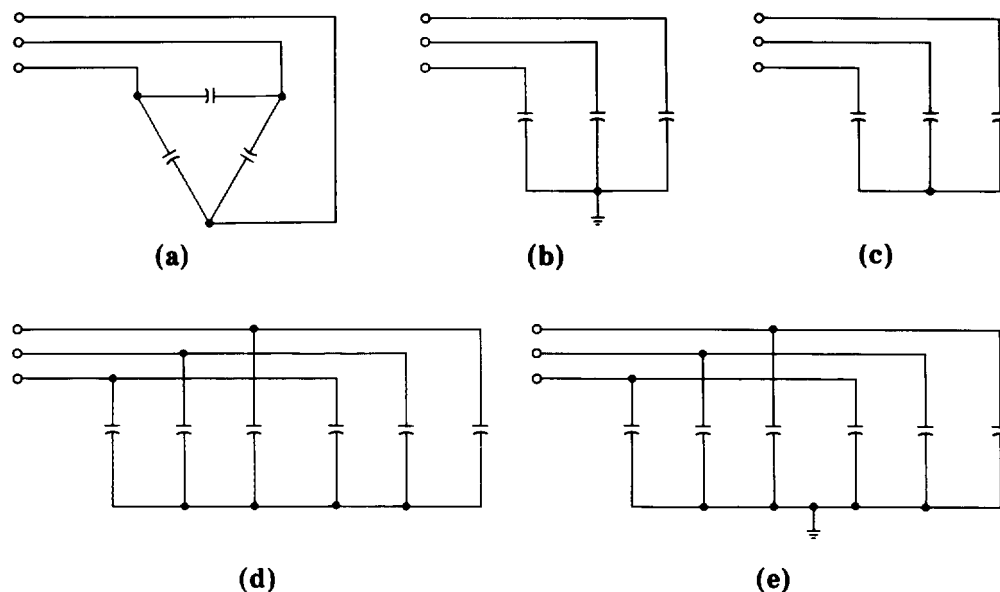


Figure 2—Basic Capacitor Bank Connections
 (a) Delta (b) Grounded Y (c) Ungrounded Y
 (d) Ungrounded Double Y-Neutrals (may or may not be tied)
 (e) Grounded, Double Y

When the neutral is grounded, recovery voltages encountered during switching are reduced, however, careful consideration should be given to the effect of inrush current on protective relay performance (see Section 10) and the method of grounding (see 5.2).

4.2.1 One Series Group Per Phase

As with Δ -connected banks, no overvoltage across remaining capacitor units occurs from isolation of a faulted capacitor unit, and, therefore, unbalance relay protection is not required. Similarly, the individual capacitor fuses should be capable of interrupting the system available fault current.

4.2.2 Multiple Series Groups Per Phase—Single Y

Grounded-Y 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 capacitor fuses are usually not required unless the parallel kvar exceeds 4650 kvar.

4.2.3 Multiple Series Groups Per Phase—Double Y

When a capacitor bank becomes too large for the 4650 kvar per group maximum for expulsion fuses, or is large enough to meet the minimum units-per-group requirement as outlined in 3.2, the bank may be split into two Y sections. The characteristics of the grounded double-Y bank are similar to a single grounded Y bank. The two neutrals should be directly connected, with a single connection to ground.

4.3 Ungrounded Y-Connected Banks

Ungrounded **Y** banks do not permit third harmonic currents or large capacitor discharge currents during system ground faults. The neutral, however, should be insulated for full-line voltage, since 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.

4.3.1 One Series Group Per Phase

For systems with line-to-neutral voltages corresponding to standard capacitor ratings, **Y**-connected capacitor banks with a single series group per phase may be used. The capacitor bank neutral is usually not grounded in order to avoid the need for power fuses to interrupt system short-circuit fault current (see 6.1). This also requires that single-bushing capacitor units be mounted on an insulated rack. However, if two-bushing capacitor units with a grounded rack are used, the capacitor-unit fuse should be capable of interrupting system phase-to-ground fault current. If lower rated fuses are used, a fault to the capacitor case may not be cleared by the capacitor-unit fuse and will require that the fault be cleared by the capacitor bank overcurrent protective devices. Ungrounded **Y** capacitor banks usually do not require current limiting capacitor-unit fuses since current through a faulted capacitor unit is limited to three times normal phase current. However, caution needs to be exercised when re-fusing a bank of this type since faulted capacitors in different phases could result in a phase-to-phase system fault.

4.3.2 Multiple Series Groups Per Phase—Single Y

Wye banks with multiple series groups may also be ungrounded. Such a bank cannot, in and of itself, provide any surge voltage protection, and provides no path to ground for third harmonic currents. The entire bank, including the neutral, should be insulated for line over-voltage.

4.3.3 Multiple Series Groups Per Phase—Double Y

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 3.2, the bank may be split into two **Y** sections. When the two neutrals are ungrounded, the bank has some of the characteristics of the ungrounded single-**Y** bank. These two neutrals may or may not be tied together. As for any ungrounded **Y** bank, the neutral should be insulated from ground for the full line-to-line voltage.

5. Other Considerations

The performance of the protection method can be influenced by the design of the capacitor bank. Therefore, protection begins with bank design (see 3.3). In general, shunt capacitor bank design requirements necessitate an increase in minimum bank size with system voltage. The higher the system voltage, the larger the bank investment and risk of costly damage. Although capacitors having larger kvar ratings may reduce the overall cost of the bank, they may also reduce the choice of different capacitor combinations.

5.1 Parallel Banks

Where two or more grounded **Y** banks are at the same location, the neutrals should be directly connected, with a single connection to ground. 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-type grounding (see Fig 3).

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, which flow between banks during back-to-back switching, from flowing in the ground grid. Unfortunately, in the event of a nearby ground fault, this arrangement does not eliminate those 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) is 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 [19]. Although this arrangement allows the capacitor bank neutral potential (and associated current transformers and voltage transformers) to rise during capacitor bank switching, it does provide the lowest possible impedance between capacitor banks (see Fig 3).

If single-point grounding is used, there will be substantial voltages (tens of kV) 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 tap sensing voltage transformers, will be subjected to this voltage, increasing the possibility of failure. Two bushing voltage transformers should be used with the primary connected to the capacitor bank neutral.

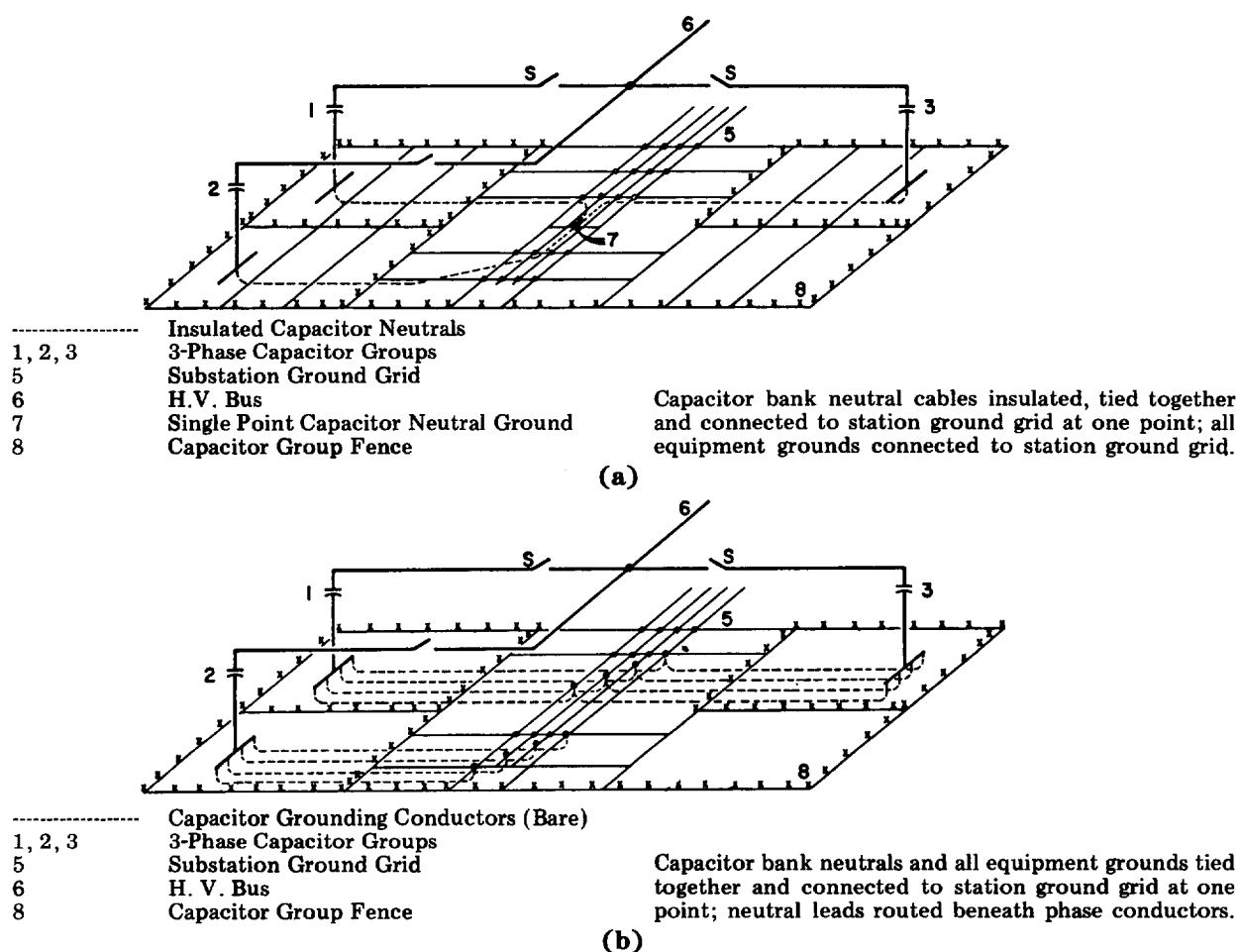


Figure 3—Methods of Neutral Grounding
(a) Single Point Grounding (b) Peninsula Grounding

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

Single-point grounding and peninsula grounding are not compatible. All capacitor banks of the same system voltage should use the same grounding scheme in the same substation.

When de-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 to 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 that may be damaging to the contacts or structure.

Since 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 of as little as 1/2 to 1% of the 60 Hz capacitive reactance of the banks, and placed in series with them, will greatly reduce both the rate of rise and the peak value of the inrush current that, in turn, 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 of the wound type, or may consist of magnetic cores surrounding the leads or bus. Preinsertion resistors or inductors on the capacitor switching device will also effectively limit the inrush current.

5.2 Neutral Grounding

The application of large shunt capacitor banks with switched parallel banks in high-voltage transmission systems involves a number of considerations, one of which is grounding. It is generally recommended that the neutral of capacitor banks be grounded only to systems that are effectively grounded. A grounded capacitor bank neutral in an otherwise ungrounded system will allow phase-to-phase voltage to appear across two phases of the bank, in the event of a phase-to-ground fault in the remaining phase.

One of the main advantages associated with neutral grounding concerns the severity of the recovery voltage across the first pole to clear of a switch interrupting the charging current of a 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 2 times normal peak voltage when the bank is grounded. On an ungrounded bank, the magnitude of the first peak of the recovery voltage can be as high as 3 times the peak system line-to-ground voltage when the bank is switched.

Since recovery voltage is a most important factor in determining the capability of a switching device to switch capacitive reactive power, it may be desirable, in terms of switch rating and cost, to ground the neutral of large shunt banks rated above 100 kV. In fact, IEEE C37.04-1979 [5] and ANSI C37.06-1987 [1] require both the shunt capacitor bank and the system to be grounded at voltage levels of 121 kV and above. The circuit breaker manufacturer should be consulted for application of a breaker if these conditions are not met.

While many shunt capacitor banks are directly connected to a high-voltage substation bus, switched capacitor banks may be applied to tertiary of power transformers that are connected to the line, or possibly to the bus. Grounding the neutral of the wye-connected capacitor bank should be done with caution. Since the A tertiary of the auto transformer represents an isolated source, grounding the capacitor bank neutral would make this side of the transformer capacitive grounded. Overvoltages may be experienced during line-to-ground faults for certain ratios of XO/X1 depending on system, transformer, and capacitor bank parameters. In those situations where the neutral is grounded, the application should be specifically analyzed for proper application of surge arresters, bank configuration, and bank switching devices.

6. Capacitor Bank Protection

To ensure availability of a capacitor bank for service requires reliable protection. This ensures minimal damage to the bank in the event of a fault. The bank should be removed from the system before it is severely damaged, or before a fault is established on the system. When a single capacitor unit fails within a bank, the capacitor unit should be isolated without transferring problems to adjacent units.

The design of the capacitor bank protective system should reflect consideration of the influence of the following seven basic conditions:

- 1) Overcurrents due to capacitor bank bus faults;
- 2) System surge voltages;
- 3) Overcurrents due to individual capacitor unit failure;
- 4) Continuous capacitor unit overvoltages;
- 5) Discharge current from parallel capacitor units;
- 6) Inrush current due to switching; and
- 7) Arc-over within the capacitor rack.

Table 3 summarizes the type of protection and preventive measures. Bus-fault and surge-voltage protection are conventional in nature. Capacitor unit overcurrent protection is obtained through proper fuse coordination. Capacitor manufacturers usually assist in this task, but a thorough understanding by the user, of capacitor unit and bank fusing, is recommended. Consideration of discharge current from parallel capacitor units influences selection of fuse type. Unbalance relay protection is covered in detail in Section 7.

Each of the several types of faults or abnormalities should be considered when the protection for a shunt capacitor bank is evaluated.

6.1 Capacitor-Unit Fusing

The first line of protection for a capacitor bank is the individual capacitor-unit fuse. The job of the fuse is to operate in response to the failure of a single capacitor unit, and remove the unit from service fast enough to prevent case rupture and damage to adjacent units. Removal of the faulted unit is important for protection of the remaining undamaged capacitor units, and will allow the capacitor bank to remain in service. A proper fuse operation is desirable in order to minimize the chance of cascading failure of additional capacitor units that may, in turn, lead to a major bus fault within the capacitor bank.

Proper operation of an individual capacitor-unit fuse depends largely upon the bank configuration. In a large capacitor bank, the impedance of the other series groups of capacitor units in a particular phase leg will limit the current in a faulted capacitor unit. However, the energy stored in other capacitor units in the series group will discharge into the faulted capacitor unit; this discharge should be withstood by the faulted capacitor unit and its fuse. This limits the maximum number of capacitor units that may be placed in parallel in the same series group when expulsion fuses are used.

Table 3—Summary of Shunt Capacitor Protection Methods

Condition	Type of Protection and Preventive Measures	Remarks
Bus faults	(1) Supply breaker with overcurrent relays (2) Power fuses	Conventional methods apply.
System surge voltages	Surge arresters	Grounded capacitor banks partially reduce surge voltages. Check arrester rating.
Overcurrents due to individual capacitor unit failures	Individual capacitor unit fuses (expulsion or current limiting types)	Coordination normally provided by capacitor manufacturer.
Continuous capacitor unit overvoltages	(1) Unbalance sensing with current or voltage relays for Y or double Y banks (2) Periodic visual fuse inspection (3) Phase voltage relays	The various schemes used have some limitations and suitability depends on bank arrangement and rating. Not suitable for unmanned substations. For system overvoltage.
Discharge current from parallel capacitor units	(1) Individual capacitor unit fuses (current limiting type) (2) Proper bank design	Coordination normally by capacitor manufacturer. Limit number of parallel capacitors.
Inrush current	Switched or fixed impedance in series with capacitor bank	To reduce inrush current. May not be necessary if only a single bank.
Rack faults	(1) Unbalance relaying (2) Overcurrent relaying	Prompt relay action necessary to limit fault damage.

The capacitor-unit fuse should be selected to:

- 1) Accommodate the maximum anticipated continuous capacitor-unit current, allowing for system overvoltage, capacitor-unit tolerance, and harmonic currents.
- 2) Withstand the transient outrush current from a healthy capacitor unit that occurs when:
 - a) a nearby capacitor bank is energized (back-to-back switching); and
 - b) when an adjacent capacitor unit fails.
- 3) Operate as promptly as possible in sponse to an escalating capacitor-unit refailure, and in all cases respond to a completely shorted unit.
- 4) Protect the capacitor unit from case rupture in accordance with applicable case-rupture curves.

In some instances, it may be difficult to select a capacitor-unit fuse that will meet all of these objectives and, in such cases, trade-offs among the various criteria should be made. Refer to the fuse manufacturer or the capacitor manufacturer for specific fusing recommendations.

Expulsion fuses have provided excellent capacitor-unit protection for many years at relatively low costs. And when using such fuses, it is desirable that the fuse link operate with failure of the fewest number of series packs shorted before complete capacitor-unit failure occurs. The slower characteristics of the T-speed fuse link may permit use of a smaller ampere rating than that with the K-speed fuse link. Where fault currents are high, current-limiting fuses, with their higher interrupting ratings, can be used, but at a higher cost. The large ampere ratings required with current

limiting fuses, relative to the capacitor-unit current, may make it difficult to achieve protection against case rupture for low-magnitude faults. The combination of expulsion fuses and current-limiting fuses provides for both conditions. Where extremely large capacitor banks are required, it is recommended that double-Y construction be employed in order to retain the use of expulsion fuses. For additional information on capacitor-unit fusing, refer to the fuse manufacturer.

6.2 Bank Overcurrent Protection

Protecting against a major fault, such as a line-to-line fault or a line-to-ground fault will generally require some form of external protection for the capacitor bank, such as power fuses, circuit breakers, or circuit switchers with associated relay circuits (see Fig 4). For grounded-Y capacitor banks, the backup protection need only respond to high-magnitude faults. However, on an ungrounded Y bank, a line-to-neutral fault will cause an increase in the line current, in the faulted phase, of only 3 times the normal phase current. Since capacitor banks can operate indefinitely at current levels in excess of that based on rated kvar and voltage, the backup protection should allow 125% or 135% of rated current to be carried continuously. At the same time, the backup protection should isolate the bank in the event of the three-per-unit phase current. It may be difficult to accomplish this protection with power fuses.

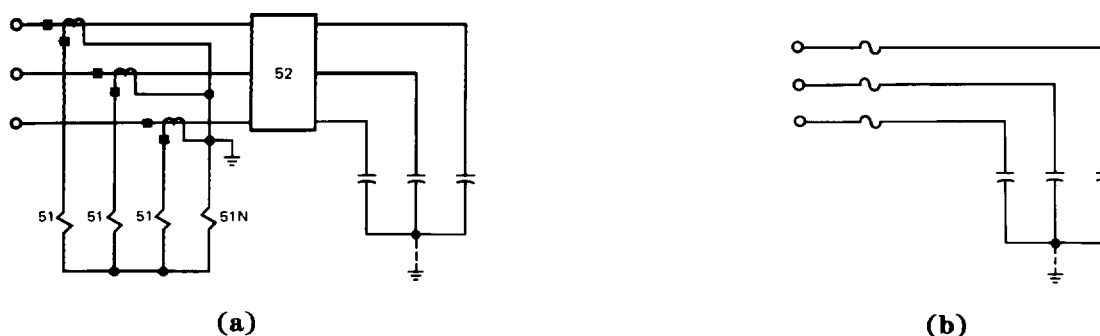


Figure 4—Capacitor Bank Protection
(a) Using Phase Overcurrent Relays
(b) Using Bank Fuses

If step switching is used with ungrounded Y banks, external protection can be even more difficult to accomplish. The most economical protection is usually provided by a power fuse, circuit breaker, or circuit switcher in the line supplying all steps, rather than protection in the lines of each step. This is especially true if the switching devices for the individual steps do not have sufficient interrupting capacity to protect the bank for line-to-line or line-to-ground faults.

Consider an ungrounded-Y connected bank having only two steps. If the backup protection is in the line supplying both steps, it should carry 270% of the rated current of one step when both steps are in service. At the same time, it should remove both banks in the event of 300% of the rated current of one step. This would be a relatively difficult task for relays, and would be virtually impossible for power fuses. When three steps are considered, the situation becomes impossible for relays as well. If, on the other hand, each capacitor bank step has its own unbalance relay protection, to detect the line-to-neutral fault, then the backup protection in the line supplying the entire installation need only detect and respond to high magnitude faults.

Time-overcurrent relays can be applied with normal settings without encountering false operations due to inrush currents. Instantaneous relays, however, should be set high to override these transients, or have tuned circuits so that pickup increases with frequency. Successful operation has been obtained by setting instantaneous relays at 3 times the capacitor rated current. Where capacitor banks are switched back-to-back (that is, in parallel with other capacitor

banks on the same bus) a setting of 4 times the rated capacitor bank current is commonly used for the instantaneous setting. This setting is used regardless of the capacitor bank connection [20].

6.3 Protection for Rack Faults (Arc-Over Within the Capacitor Rack)

With a capacitor bank of the usual construction, where the individual phases are well separated, an arc-over within the capacitor bank will begin as an arc-over of a single series section. Such a fault produces very little phase overcurrent and, if an unbalance relay protection scheme is not provided, more and more series groups of the same phase can become involved until the instantaneous relay trips the bank or fuses clear. The total arcing time can be on the order of a few seconds. This is accompanied by heavy damage to the bank, including many blown fuses and a few ruptured capacitor units. The nature of a capacitor unit rupture, without the appearance of very much case swelling, is more typical of a high-energy type rupture than that due to merely 60 Hz fault current. This stored energy comes from the other units in the same parallel groups that have been subjected to a high overvoltage as a result of other groups being shorted. Instantaneous overcurrent relays are not effective for rack faults.

The main protection for an arc-over within the capacitor bank is provided by fast timing of the unbalance relay. An unbalance time delay of 0.3 to 0.5 second will provide good protection for rack faults and has had considerable use on power systems that are effectively grounded. The unbalance time delay, however, should never be less than the maximum clearing time of the capacitor-unit fuse for a completely shorted capacitor unit.

On resistance-grounded and ungrounded power systems, an unusually long unbalance time delay is required to coordinate with the line relays, unless the unbalance relay scheme is of the type that does not respond to system voltage unbalance. As noted in 5.2, resistance grounded and ungrounded power systems would utilize ungrounded capacitor banks. Some of the types of unbalance relays for ungrounded capacitor banks that do not respond to system voltage unbalance are shown in Figs 5a), 6(a), 6(b), 6(d), 7, and 8. The unbalance relays shown in Figs 9(a) and 9(b) also do not respond to system voltage unbalance, but they are used only for grounded capacitor banks.

The sensitivity of the unbalance-trip relay is determined on the basis of protecting the capacitor units from continuous overvoltages, as a result of individual failure and resultant fuse operation (see Section 7). When set on this basis, the resultant sensitivity is adequate to relay for the initial rack fault, assuming the initial fault is across one series section of one phase.

If the timing relay does not have a definite time characteristic, the 0.3 to 0.5 second time delay setting is made at the multiple of pickup corresponding to the initial rack fault. For a single ungrounded-Y bank with an unbalance relay of the type that detects neutral-to-ground voltage, the per-unit neutral-to-ground voltage, when one complete series section is shorted, is given by:

$$V_{NS} = \frac{1}{3S-2}$$

where

$$\begin{aligned} S &= \text{number of series sections per phase} \\ V_{NS} &= \text{neutral-to-ground voltage in per-unit of the applied line-to-neutral volts} \end{aligned}$$

For a neutral current type of unbalance relay on a single-Y bank with the neutral grounded through a current transformer, the initial rack fault, assuming one series section is shorted, is:

$$I_N = \frac{1}{S-1}$$

where I_N = neutral current expressed in per-unit of normal phase current.

An effective setting for the time-overcurrent (TOC) relay is 1.35 times the rated capacitor current. This setting has had considerable use and does not false-trip for ungrounded-Y banks; an occasional operation on grounded Y banks may

give a warning of excessive harmonic currents. Time-overcurrent relays of the short-time characteristic have ample time adjustment to ride through transients, while being capable of the faster timing to minimize damage from rack faults.

To analyze the performance of overcurrent relays on rack faults that involve only one phase, the following formulas are useful:

$$\text{Single-grounded Y, } I = \frac{S}{S-F}$$

$$\text{Single-ungrounded Y, } I = \frac{1.5S}{1.5S-F}$$

$$\text{Double-ungrounded Y, } I = \frac{6S}{6S-5F}$$

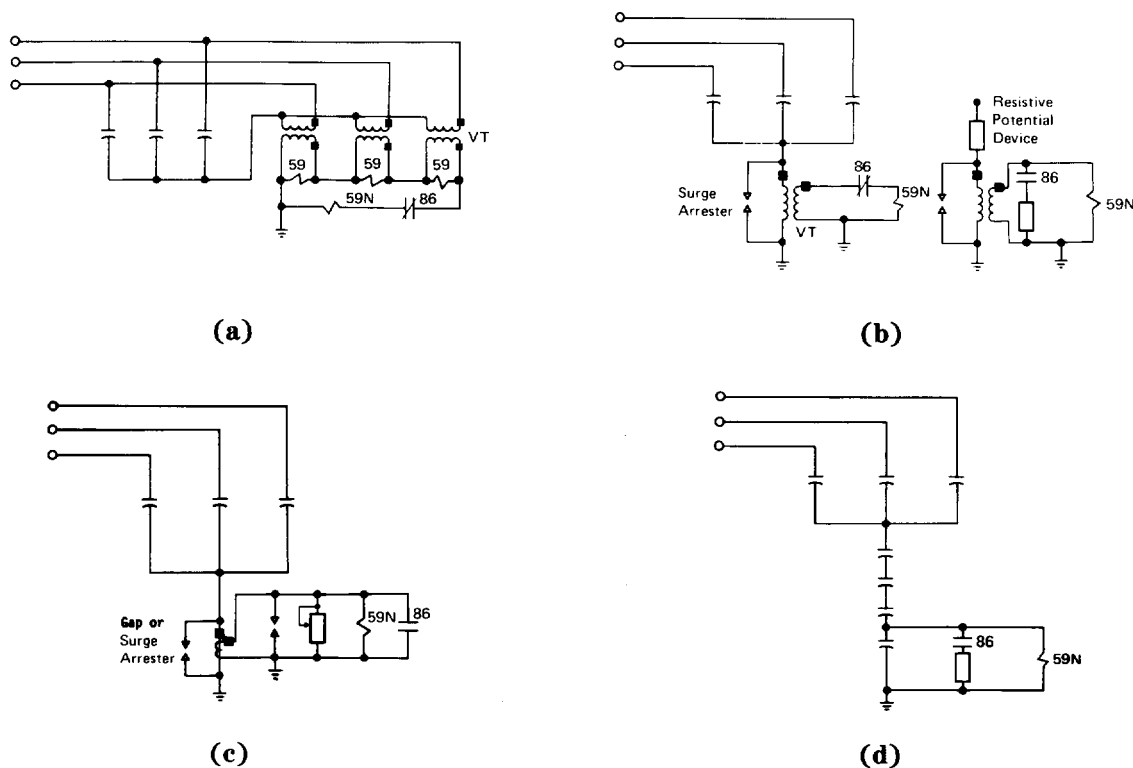


Figure 5—Shunt Capacitor Bank Protection Methods, Single Y-Connected Banks
(a) Summation of Line-to-Neutral Voltage Protection Method with Optional Line-to-Neutral Overvoltage Protection, Ungrounded Y-Connected Capacitor Bank
(b) Neutral Voltage Unbalance Protection Method, Ungrounded Y-Connected Capacitor Bank
(c) Neutral Current Unbalance Protection Method, Grounded Y-Connected Capacitor Bank
(d) Neutral Voltage Unbalance Protection Method, Ungrounded Y-Connected Capacitor Bank Using Capacitor Voltage Divider

where

S = number of series groups per phase
 F = number of series groups flashed over
 I = per unit of normal capacitor phase current

NOTE — On a grounded-Y bank, where $F = S$, the current is the system line-to-ground fault duty.