An American National Standard

IEEE Guide for 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. Bank design tradeoffs are also discussed since bank design influences protection. The guide does not include a discussion of pole mounted installations on distribution circuits or applications such as capacitors connected to motor terminals.

2. References

2.1 Standards References

ANSI/IEEE C37.04-1979, Rating Structure for ac High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

ANSI C37.06-1979, Preferred Ratings and Required Capabilities for ac High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis[1]

ANSI/IEEE C37.012-1979, Application Guide for Capacitance Current Switching of ac High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

ANSI/IEEE C37.90a-1974, Guide for Surge Withstand Capability (SWC) Tests

ANSI/IEEE Std 18-1980, IEEE Standard for Shunt Power Capacitors

IEEE Std 469-1977, Recommended Practice for Voice-Frequency Electrical-Noise Tests of Distribution Transformers

NEMA CP1-1976,[2] Shunt Capacitors

2.2 References

[1] HARNER, R.H. and OWEN, R.E. Neutral Displacement of Ungrounded Capacitor Banks During Switching. *IEEE Transactions on Power Apparatus and Systems*, paper no 71 TP67, Jul-Aug 1971, pp 1631-1638.

[2] SHEPPARD, N.R. and SCHULTZ, N.R. Some Considerations in the Protection of High-Voltage Capacitor Banks. *AIEE Transactions*, vol 75, part III, 1956, pp 686-694.

[3] COOPER, J.R. and ZULASKI, J.A. Improved Protection System Increases Capacitor Bank Utilization. Presented at the Pennsylvania Electric Association Relay Committee Meeting, Oct 27, 1972, Hagerstown, MD.

[4] TOM, M.O. A Static Voltage Differential Relay for Protection of Shunt Capacitors. *AIEE Transactions*, vol 80, part III, Feb 1962, pp 1086-1089.

[5] ABDULRAHIM, M.J., ANDERSON, P.M. and FOUAD, A.A. Inrush Currents in a Switched Parallel-Capacitor Bank. IEEE Conference Paper slCP 66-101, New York, NY.

[6] The Telephone Influence Factor of Supply System Voltages and Currents. Joint Subcommittee on Development and Research, EEI Pub 60-68. EEI and Bell Telephone System: New York, NY, 1960.

---

[1] ANSI documents are available from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

[2] NEMA documents are available from the National Electrical Manufacturers' Association, 155 East 45th Street, New York, NY 10017.

[7] ROGERS, E.J. and GILLIES, D.A. Shunt Capacitor Switching EMI Voltages, Their Reduction in Bonneville Power Administration Substations. IEEE Transactions on Power Apparatus and Systems, vol 93, 1974, pp 1849-1860.

[8] HARDER, J.E. Selection and Protection of Current Transformers for Use in Shunt Capacitor Banks. IEEE Power Engineering Society paper A 76 335-0.

[9] MILLER, D.F. Application Guide for Shunt Capacitors on Industrial Distribution Systems at Medium Voltage Levels. *IEEE Transactions on Industry Applications*, vol IA-12, no 5, Sept-Oct 1976, pp 444-459.

[10] STEEPES, D.E. and STRATFORD, R.P. Reactive Compensation and Harmonic Suppression for Industrial Power Systems Using Thyristor Converters. *IEEE Transactions on Industry Applications*, vol IA-12, no 3, May-Jun 1976, pp 232-254.

[11] PRATT, R.A., OLIVE, W.W., JR, WHITMAN, B.D. and BROWN, R.W. Two Fuse System Protects Capacitors, *Electrical World*, Jun 1977, pp 46-48.

[12] MOORE, A.H. Application of Power Capacitors to Electrochemical Rectifier Systems. *IEEE Transactions on Industry Applications*, vol IA-13, no 5, Sept-Oct 1977, pp 399-406.

3. Basic Considerations

Protection of switched shunt capacitors requires an understanding of the capabilities and limitations of both the capacitors and the associated switching devices. The basis for capacitor considerations, including definitions, is IEEE Std 18-1980. Applicable standards for the associated switching devices are referenced as discussed.

3.1 Capacitor Unit Ratings (ANSI/IEEE Std 18-1980). Capacitors shall be capable of continuous operation up to 110% of rated terminal rms voltage, including harmonics, and up to 180% of rated rms current, including fundamental and harmonic currents.

Capacitors shall 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.

Capacitors shall be suitable for continuous operation at 135% of rated reactive power caused by the combined effects of:

(1) Voltage in excess of nameplate rating of fundamental frequency but not over 110% of rms rated
(2) Harmonic voltages
(3) Manufacturing tolerance

3.2 Protection Considerations. Shunt capacitor bank design requirements necessitate an increase in minimum bank size with system voltage. The higher the system voltage the larger is the bank investment and risk of costly damage. Capacitors of larger kvar ratings reduce the cost but may also reduce the choice of different capacitor combinations. Protection begins with the bank design.

Availability of a capacitor bank for service requires reliable protection which will result in minimal damage to the bank. The bank should be removed from the system before it is exposed to severe damage or before a fault is established on the system. When a single capacitor unit fails within a bank, the capacitor unit should be disconnected without transferring problems to adjacent units.

Bank protective equipment must guard against 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
(7) Arc-over within the capacitor rack

Table 1 summarizes the type of protection and preventive measures. Bus fault and surge voltage protection are conventional in nature. Capacitor overcurrent protection is obtained through proper fuse coordination. Capacitor manufacturers usually assist in this task, but a thorough understanding of capacitor unit and bank fusing is recommended. Consideration of discharge current from parallel capacitor units influences selection of fuse type.

Capacitor unit voltage, current, kVA, and temperature are important considerations in

Table 1
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	(1) Surge arresters (2) Spark gaps	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	The various schemes used have some limitations and suitability depends on bank arrangement and rating.
	(2) Periodic visual fuse inspection	Not suitable for unmanned substations.
	(3) Phase voltage relays	For system overvoltage.
Discharge current from parallel capacitor units	(1) Individual capacitor unit fuses (current limiting type)	Coordination normally by capacitor manufacturer.
	(2) Proper bank design	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.

avoiding failure. Avoiding capacitor unit failure is the first step in minimizing the probability of capacitor case rupture. The maximum allowable capacitor temperature should not be exceeded.

Capacitor switching devices require special attention since more severe switching duties exist for the interruption of shunt capacitor banks than for other forms of switching.

4. Bank Arrangements and Connections

There are five common connections. The connection selected depends upon the best utilization of the standard voltage ratings of capacitor units, fusing, and protective relaying. Virtually all high voltage banks are connected in wye (Y) while low voltage banks may be connected in Y or delta (Δ).

The various types of connections illustrated in Fig 1 are:

(1) Δ
(2) Grounded Y
(3) Ungrounded Y
(4) Ungrounded double Y
(5) Grounded double Y

Δ and Y are the basic connections while the double Y is used for larger kvar bank ratings. The neutral point can be grounded or ungrounded. The Y-connected bank, having only a single group of parallel connected capacitors per phase, is usually not grounded.

4.1 Δ-Connected Banks. Δ-connected banks are generally used only at low voltages with one series group of capacitors rated for line-to-line voltage since Y-connected banks are less complicated and more economical. Δ-connected banks require either two-bushing capacitors with a grounded rack or single-bushing units with an insulated rack. The greatest use is at 2400 V since this is the lowest standard capacitor rating. A Y-connected rating for 2400 V is not available.

With one series group, no overvoltage of capacitor units occurs from unbalance so that no voltage unbalance protection is required. Third harmonic voltages are in phase in the three phases. Therefore, no third harmonic currents can flow in a Δ-connected capacitor bank.

On banks where one series group per phase is used, the individual capacitor fuses must be

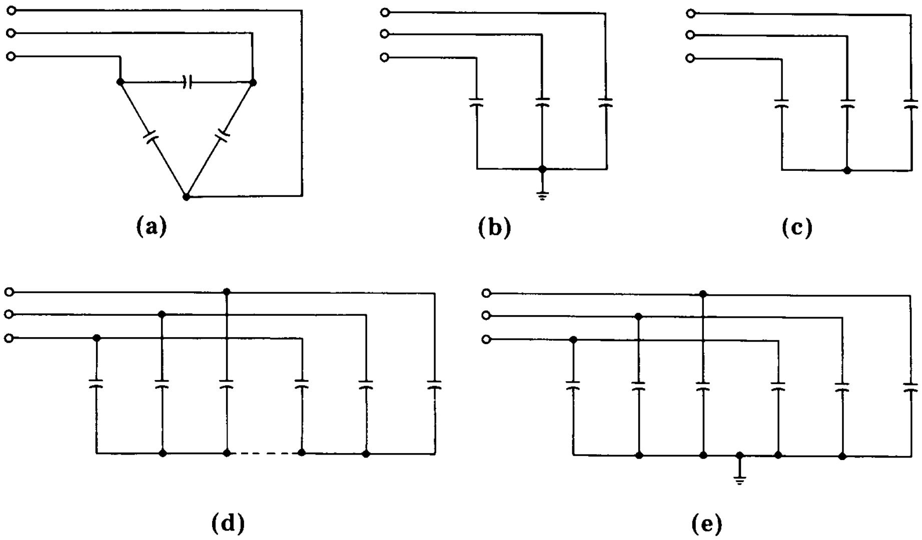


Fig 1
Basic Capacitor Bank Connections
(a) Delta. (b) Grounded Wye. (c) Ungrounded Wye
(d) Ungrounded Double Wye-Neutrals (may or may not be tied)
(e) Grounded, Double Wye

capable of interrupting the system short-circuit phase-to-phase fault current. This nearly always necessitates a current limiting fuse. Such fuses are about five times the cost of the expulsion fuse.

4.2 Y-Connected Banks, One Group per Phase. For systems with line-to-neutral voltages corresponding to standard capacitor ratings, Y-connected capacitor banks with a single group per phase may be used. The capacitor bank neutral is usually not grounded in order to avoid the need for current limiting fuses to interrupt system short-circuit fault current. See 6.1. This requires that the capacitor units be mounted on an insulated rack. Either single- or two-bushing capacitor units may be used.

Ungrounded Y capacitor banks usually do not require current limiting fuses in that current through a faulted capacitor unit is limited to three times normal phase current. However, caution needs to be exercised when refusing a bank of this type, in that faulted capacitors in different phases could result in a phase-to-phase system fault. With two-bushing capacitor units mounted on a grounded rack, the fuses should be capable of interrupting the system phase-to-ground fault current. Expulsion fuses may be used in those cases of very limited short circuit capability. Current limiting fuses are required if the parallel kvar exceeds 3100 kvar.

Ungrounded Y banks do not permit third harmonic currents or large capacitor discharge currents during system ground faults. The neutral, however, must be insulated for full line voltage since it is momentarily at phase potential when the bank is switched or when one capacitor unit fails.

4.3 Grounded Y Banks, Multiple Series Groups. 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 2 shows a typical bank arrangement. A number of series group combinations are given in Table 2.

The multiple series groups limit the maximum fault current so that high capacity or current limiting individual capacitor fuses are usually not required unless the parallel kvar exceeds 3100 kvar.

Table 2
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 wye connected bank which operates near rated capacitor unit voltage.

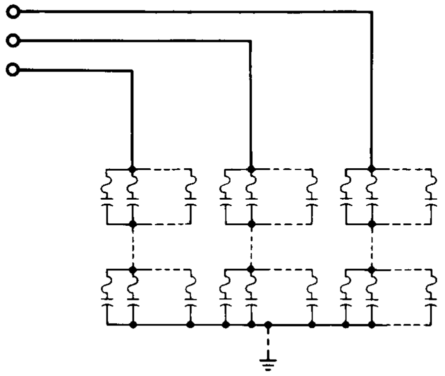
Grounded capacitor banks provide a low impedance path to ground for lightning surge currents and give some protection from surge voltages. Sometimes the bank may be operated without surge arresters, taking advantage of this self-protective feature.

Grounded neutral capacitor banks provide a low impedance path to ground for harmonic currents. The resulting harmonic currents may cause communication facility interference if such circuits parallel power lines. An open phase produces zero sequence currents which may cause ground relay operation. Third harmonic resonance could be a problem.

Since the neutral is grounded, recovery voltages are usually reduced and the capacitor bank is switched as three single-phase sections.

4.4 Ungrounded Y Banks, Multiple Series Groups. Y banks with multiple series groups, Fig 2, may also be ungrounded. Such a bank cannot 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 voltage.

Fig 2
Y-Connected Capacitor Bank Showing Arrangement of Capacitor Units, Fuses, and Series Groups



If a voltage transformer (VT) or potential device connected from neutral to ground is used for unbalance detection, it should be capable of withstanding neutral displacement voltages of 0.5 to 2.4 times system phase-to-neutral voltage [1].[3] At the higher system voltages, requiring larger voltage transformer ratios, the neutral voltage unbalance detection becomes very insensitive. Special relaying techniques are required. See 7.6.

4.5 Double Y Banks, Multiple Series Groups. When a capacitor bank becomes too large for the 3100 kvar per group maximum for expulsion fuses or is large enough to meet the minimum units per group requirement as outlined in 4.6, the bank may be split into two Y sections. The two neutrals are usually ungrounded, and therefore, the bank has some of the characteristics of the ungrounded single bank. A current transformer is connected between the two neutrals to detect an unbalance and neutral shift of one Y section with respect to the other Y section. A voltage transformer may also be used but sensitivity is reduced. See Fig 10. As for any ungrounded Y bank, the neutral should be insulated from ground for the full line voltage. The neutral current transformer, or VT, should be rated for the line voltage [8].

When ungrounded, the unbalance detection circuit is not sensitive to system unbalances, including an open-phase condition.

Double Y banks may also be grounded, in which case they will pass third harmonic currents and the unbalance detection equipment will receive full line current during an open phase. The two neutrals should be directly connected, with a single connection to ground.

The two Y sections are generally made equal or nearly equal in rating (kvar). Sometimes a single Y ungrounded bank with auxiliary bank composed of one unfused capacitor unit per series group, similar to Fig 10(a), is used. Neutrals of the main and auxiliary bank are interconnected through a current transformer as in the double Y bank connection. The auxiliary bank provides balanced impedances as comparison for the main bank. Unbalance in the main bank will cause neutral current to flow. A current detector adjusted for the double Y bank is used and provides protection for main and auxiliary bank. One advantage of this connection not listed above for double Y banks is the increased number of units in parallel per series group in the main bank in comparison to the balanced double Y. A disadvantage is that the high impedance of the auxiliary bank decreases currents to be detected.

4.6 Capacitor Group Ratings and Limitations. Capacitors are available in the voltage ratings shown in Table 2 and in ratings of 50, 100, 150, 200, and 300 kVA at most of the voltage ratings. A bank of a given size and voltage rating may be made up of a number of combinations of individual capacitor size, number of series groups as indicated in Table 2, and number of parallel capacitors in a group.

In general, use of the largest capacitor units results in the minimum number of units, the smaller rack structure, and the most economical bank. However, there are other restrictions that may apply.

The overvoltage caused by failure of an individual capacitor unit is reduced as the number of capacitor units per series group is increased. Use of larger individual unit capacitor kvar ratings increases the overvoltage change due to a single capacitor failure for a given bank size.

Capacitors with the highest voltage rating, requiring the minimum number of series groups, permit the simplest and most economical rack structure. They also provide the greatest sensitivity of the unbalance detection scheme for a given overvoltage of the remaining units of a group. The available unbalance signal level decreases significantly as the number of series groups is increased and as the number of units per group is increased.

The number of capacitor units per 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 failure of one capacitor unit in that 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.

---

[3] Numbers in brackets correspond to those in the References, Section 2 of this guide.

The minimum recommended number of capacitor units in parallel per series group is listed in Table 3. This requirement may limit the maximum size capacitor unit that can be used for relatively small banks. It emphasizes the desirability of using the highest voltage rating and minimum number of series groups in order to obtain an adequate number in each group.

The maximum number of capacitor units which may be placed in parallel is governed by a different consideration. When a capacitor unit fails, the other capacitors in the same series group will probably contain some amount of charge. This charge will then drain off as a high frequency transient current through the faulted unit and its fuse. The fuse holder and the failed capacitor unit must withstand this discharge transient. If the fuse link does not blow during the transient, it will certainly blow when the first peak of the 60 Hz fault current occurs.

The discharge transient from a large number of paralleled capacitors can be severe enough to cause rupture of the failed capacitor unit or of the expulsion fuse assembly before the arc has been successfully cleared. Rupture of the capacitor unit may result in damage to adjacent units and rupture of the fuse can cause a major bus fault within the bank.

To minimize the probability of failure of the expulsion fuse or rupture of the capacitor case, or both, the total energy stored in a parallel connected group of capacitors should not exceed 10 000 Ws at a maximum peak voltage (rated voltage $\times$ 1.1 $\times$ $\sqrt{2}$). For 60 Hz applications, 3100 kvar at rated voltage is recommended as the maximum limit for parallel connected kvar. See NEMA CP1-1976.

If a bank having the minimum number of series groups requires more than 3100 kvar per group, capacitors of a lower voltage rating requiring more series groups and fewer units per group may be a suitable solution. However, this will reduce the sensitivity of the unbalance detection scheme. 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.

The above shows that a minimum number of parallel capacitors is required to prevent dangerous overvoltages after single capacitor failure but that a further increase in the number of parallel capacitors will reduce the failure sensing signal and make fuse coordination more difficult or costly by requiring current limiting fuses. However, twice as many parallel capacitors are needed before a second capacitor loss may occur safely within a series group (see Eqs 6, 15, and 19, Appendix B).

Table 3
Minimum Recommended Number of Units in Parallel per Series Group to Limit Voltage on Remaining Units to 110% with One Unit Out

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

Failure of additional capacitors is most likely to occur in the same series group as the first failure since these units have the highest voltage stress. However, when two capacitors fail within the same phase but not in the same series group, overvoltages occur in the two series groups with missing capacitors but the percentage overvoltage is less than that of a single series group in which two capacitors would fail. The second failing capacitor in a second series group has a compensating effect on the overvoltage seen in the series group with the capacitor which failed first. The overvoltage for a given neutral unbalance signal is much less than for the case of two units isolated in the same group. The failing of two capacitors in the same series group results in the highest percentage overvoltage.

The conditions described above can be calculated for various bank configurations with the equations in Appendix B or determined from the curves of Figs 14, 16, and 18.

4.7 Grounding

4.7.1 General. Generally, 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. A rule of thumb continues to be one of considering grounding the neutral of capacitor banks only on systems which are effectively grounded. Thus, during a switching operation, portions of the system with capacitor banks connected remain effectively grounded with no backfeed through Δ-connected transformers.

One of the main advantages of grounding concerns the severity of the recovery voltage across the first pole to clear in a switch interruption of the charging current on 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 2 to 2.5 times normal peak voltage when the bank is grounded. On an ungrounded bank, the recovery voltage can be slightly more than 3 times the peak 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 is desirable, in terms of switch rating and cost, to ground the neutral of large shunt banks rated above 100 kV. ANSI/IEEE C37.04-1979 and ANSI C37.06-1979 require both the shunt capacitor bank and the system to be grounded at voltage levels of 121 kV and above. It is also stated that the circuit breaker manufacturers should be consulted for application of a breaker if the neutrals of the system and the capacitor bank are both ungrounded.

While many shunt capacitor banks are directly connected to a high voltage substation bus, switched capacitor banks may be applied to tertiaries of power transformers which are connected to the line or possibly to the bus. Grounding the neutral of the Y-connected capacitor bank would violate the rule of thumb mentioned previously. Since the Δ tertiary of the autotransformer represents an isolated source, grounding the capacitor bank neutral would make this side of the transformer capacitive grounded, yielding negative ratios of $XO/X1$. Excessively high overvoltages may be experienced during line-to-ground faults for certain ratios of $XO/X1$ depending on system, transformer, and capacitor bank parameters. Thus individual applications should be specifically analyzed so that high overvoltages can be determined for proper application of surge arresters, bank configuration, and bank switching device.

4.7.2 Grounding of Multiple 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.

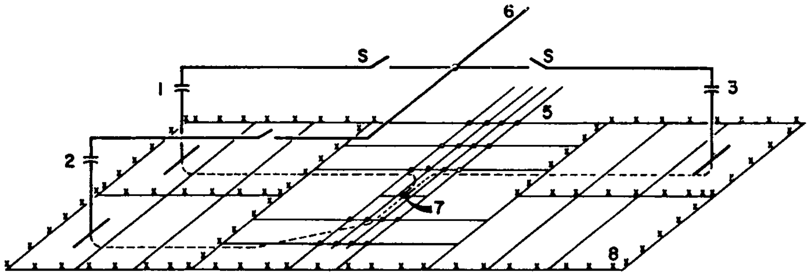
The design of the substation ground grid and the connections of the respective bank neutrals to the substation grid is of prime importance.

Improper grounding can result in neutral current transformer, VT or control cable failures. Two methods of neutral grounding have been successfully used: single point grounding and peninsula type grounding. With single point grounding, all neutrals of all capacitor groups of a given voltage are connected together with insulated cable and tied to the ground grid at only one point. All equipment grounds are connected to the regular ground grid. This arrangement prevents the high frequency currents which flow between banks during back-to-back switching from flowing in the ground grid. Unfortunately, it 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 ground connections are made to this isolated peninsula ground grid conductor(s) only [7]. This arrangement allows the capacitor neutral potential (and associated current transformers and VTs) to rise during capacitor bank switching, but provides the lowest possible impedance between capacitor groups. See Fig 3.

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

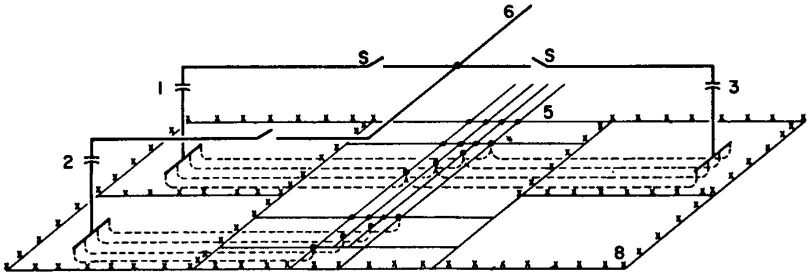
The routing of control cables from neutral current transformers or VTs should be kept at right angles with respect to the common neutral bus to minimize induction. These induced voltages can be minimized by shielding the cables and using a radial configuration for circuits (circuits completely contained within one cable so that inductive loops are not



------------------	Insulated Capacitor Neutrals
1, 2, 3	3 Phase Capacitor Groups
5.	Substation Ground Grid
6.	H.V. Bus
7.	Single Point Capacitor Neutral Ground
8.	Capacitor Group Fence

Capacitor bank neutral cables insulated, tied together and connected to station ground grid at one point; all equipment grounds connected to station ground grid.

(a)



------------------	Capacitor Grounding Conductors (Bare)
1, 2, 3	3 Phase Capacitor Groups
5.	Substation Ground Grid
6.	H. V. Bus
8.	Capacitor Group Fence

Capacitor bank neutrals and all equipment grounds tied together and connected to station ground grid at one point; neutral leads routed beneath phase conductors.

(b)

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

formed).

Control cables entering the capacitor bank area must be kept as close as possible to the ground grid conductors (4/0 copper minimum) in the cable trench or on top of the duct run, or in contact with the ground grid conductor if direct buried. This is mandatory if peninsula grounding is used. A minimum of four control cable shield grounds is recommended: the first, at the cable termination in the capacitor area; the second, where the cable enters the main cable trench or duct run; the third, where the cable enters the control house; and the fourth, at final termination. The VT secondary should be grounded at the switchboard.

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

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 must use the same grounding scheme in the same substation.

5. Ratings and Requirements of Capacitor Switching Devices

The various devices which may be used for capacitor switching include the following.

Circuit Breakers	Interrupter Switches
Air	Oil
Air-magnetic	SF_6
Oil	Vacuum
SF_6	
Vacuum	

Reference should be made to ANSI/IEEE C37.04-1979, ANSI C37.06-1979, and ANSI/IEEE C37.012-1979.

All capacitor switching devices should be applied within their maximum voltage, frequency, and current ratings, including transient inrush current and frequency. Since capacitors can be operated continuously up to 10% above the capacitor rated voltage, the switching device should have at least this voltage rating.

The current rating of the switching device should include the effects of overvoltage (1.1), capacitor tolerance (1.05 to 1.15), and harmonic component (1.05 for ungrounded capacitor bank, 1.1 for grounded capacitor bank). It is usually considered adequate to use a total multiplier of 1.25 for ungrounded operation and 1.35 for grounded operation.

Most switching devices are derated for capacitor switching to a value well below their continuous current rating.

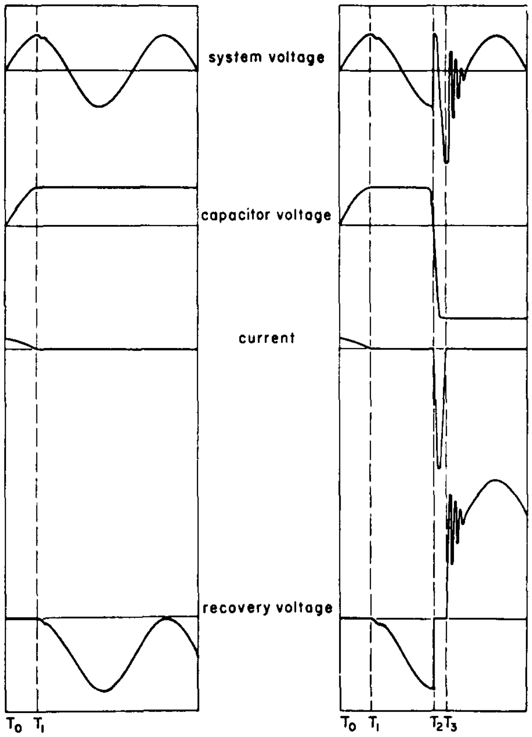
5.1 Inrush Currents. The energizing of a capacitor bank will result in a transient inrush current. The magnitude and frequency of this inrush current is a function of the applied voltage (point on the voltage wave at closing), the capacitance of the circuit, the inductance in the circuit, any charge on the capacitor bank at the instant of closing, and any damping of the circuit due to closing resistors or other resistance in the circuit. See Appendix C for inrush current calculations.

The transient inrush current to a single isolated bank is less than the available short circuit current at the capacitor location. Since a circuit breaker must meet the momentary current requirement of the system, transient inrush current is not a limiting factor in the isolated capacitor bank-breaker application. However, the momentary rating of other switching devices not intended for fault current interruption should be checked.

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

The magnitude and consequent effects of inrush current to a switched capacitor bank may be greatly reduced by use of series reactors or a capacitor switching device furnished with preinsertion resistors. When used for daily switching of back-to-back capacitor banks, the life of the switching device contacts can be extended by increasing the inductance between banks to lower the inrush current below the maximum allowable to reduce contact erosion. However, for a given reduction in transient current, the resistor is more effective in reducing the transient overvoltage.

5.2 Transient Overvoltage. An important consideration for application of circuit breakers for capacitor switching is the transient overvoltage which may be generated by restrikes during the opening operation. At current zero, the capacitor is left charged to nearly full peak line voltage. Very little recovery voltage appears across the circuit breaker contacts at this instant and the capacitance current arc is usually interrupted at the first current zero after the circuit breaker contacts open. After interruption, the normal frequency alternation of the voltage on the source side of the breaker results in a recovery voltage across the breaker contacts, ½ cycle later, approaching twice the peak line voltage. If a breakdown were to occur at T_2 in Fig 4 (b), the capacitor voltage immediately attempts to equalize with the system voltage, but the circuit is oscillatory and at the first peak of the transient the capacitor voltage has overshot by an amount nearly equal to the difference between the two voltages immediately prior to the restrike. If the current is interrupted at its first high frequency current



(a) (b)

Opening the circuit to a single phase capacitor in one step. On the left an opening without restrike. On the right, the maximum effect possible with one restrike.

Fig 4
Opening the Circuit to a Single-Phase Capacitor in One Step (a) No Restrike (b) One Restrike

zero (T_3), the transient voltage peak is trapped on the capacitor bank.

The recovery voltage reaches a value greater than that following the first interruption, but the contacts have moved farther apart and the buildup of dielectric strength may prevent additional restrikes.

If the gap breaks down less than ¼ cycle after a current zero, the amplitude of the voltage oscillation will not exceed the crest voltage, and no overvoltage is caused. This is defined as a reignition rather than a restrike.

In Fig 4(b) the restrike is shown to occur a full ½ c after current interruption. This is the worst possible condition for the first restrike because the recovery voltage has reached its maximum and the resultant surge voltage can theoretically reach 3 times normal line-to-ground crest voltage. In actual practice it seldom exceeds 2½ times normal. This should not be damaging to the system; however, additional restrikes can produce higher crest voltages and the sudden voltage changes and high frequency oscillations may produce other relatively higher voltages elsewhere on the system. Therefore, it is desirable to limit restrikes or the voltage phenomenon resulting from them to protect the entire system.

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

5.3 Parallel Banks. When deenergizing 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 breaker 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 which 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 usual circuit between the banks, it can be reduced by the addition of inductance to the circuit. An inductance with a 60 Hz reactance as little as ½ to 1% of the 60 Hz capacitive reactance of the banks, and placed in a series with them, will greatly reduce both the rate of rise and the peak value of the inrush current which, in turn, greatly reduces the severity of the breaker 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 on the capacitor switching device will also effectively limit the inrush current.

6. Capacitor Bank Protection

Several types of faults or abnormalities must be considered when the protection for a shunt capacitor bank is evaluated.

6.1 Individual Unit Overcurrent Protection. The first line of protection for a capacitor bank is the individual capacitor fuse. The job of the fuse is to sense and indicate 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 the protection of the remaining good ones and to allow the capacitor bank to remain in service. A nonviolent fuse blowing is desirable so as to minimize the chance of starting a major bus fault.

Proper clearing of an individual capacitor unit fuse depends largely upon the selection of the bank configuration. In a large capacitor bank, the impedance of the other series groups in a particular phase leg will limit the current in a faulted capacitor unit. However, the energy stored in the other capacitor units in the group is discharged into the faulted capacitor unit; this discharge must be withstood by the fuse and faulted capacitor. This limits the number of capacitor units that may be placed in the same parallel group with expulsion fuses.

There is also a minimum number of capacitors that can be connected safely in parallel in a group. Below this critical number, individual capacitor fuses are rated at such a large percentage of the total phase current that in the event of failure in that unit the magnitude of the phase current is insufficient to produce rapid fuse clearing.

After considering the size of fuses that must be used to avoid operation on switching transients, and taking into account the arc energy required to rupture the capacitor case, the current through the fuse when a unit becomes shorted should not be less than 10 times the normal capacitor unit current through the fuse. The amount of current that flows through a fuse when a unit is shorted is also affected by the number of series groups and whether or not the neutral is grounded. This requirement will be met by the minimum number of capacitors per group given in Table 3. See Appendix B for fault current calculations.

The fuse link should be capable of continuously carrying 125% or 135% of the rated capacitor current. (See Section 5.) The time-current clearing characteristics of the fuse link should coordinate with the case rupture curves of the capacitor.

The pressure buildup due to low level internal capacitor faults require fusing which will operate at the lowest possible current without blowing on combined inrush current and load current. It is desirable to blow the fuse with failure of several series packs before complete failure occurs. These considerations with K or T links would indicate a fusing ratio of 1.25 or less. The slower characteristics of the T link may permit a lower fusing ratio with the T link than with the K link. Expulsion fuses have given good protection for many years at relatively low cost. Where fault currents are large, current limiting fuses can be used which go beyond the interrupting rating of expulsion fuses, but at a higher cost. The high fusing ratios required with current limiting fuses may make it difficult to prevent case rupture on low magnitude faults. The combination of expulsion and current limiting fuses provides for both conditions. See ANSI/IEEE C37.012-1979. The manufacturer should be consulted for probability of case rupture data.

Where a larger capacitor bank is desired, it may be better to go to a double Y construction so as to retain the use of expulsion fuses. Selection of the individual capacitor fuse is usually up to the capacitor manufacturer and may be on the basis of a fusing ratio greater than 1.25.

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 backup protection, such as power fuses or circuit breakers with associated relay circuits. See Fig 6. 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 current. Capacitor banks may operate indefinitely at 135% of rated kvar or 135% of rated current. The backup protection, therefore, must allow 125% or 135% of rated current to be carried continuously, but at the same time, remove the bank in the event of 3 times line current. It may be found difficult to accomplish this with power fuses.

If step switching is used, this consideration must be included in backup protection. The most economical backup protection is usually provided by a circuit breaker or power fuse 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 interrupting capacity sufficient to serve as protection against line-to-line or line-to-ground faults.

Consider a bank having only two steps. If the backup protection is in the main line supplying both steps, this device must carry 270% of the rated current of one step, but at the same time must remove the banks in the event of 300% of the rated current of one step. It can be seen that this would be a relatively difficult adjustment for relays and would be virtually impossible for fuses. When three steps are considered, the situation becomes impossible for relays no matter how sensitive they may be.

If, on the other hand, each of the steps has some form of unbalance detection associated with it, the circuit may be used to detect the line-to-neutral fault and trip the bank having the fault. This allows the backup protection in the line supplying the entire installation to protect only against high magnitude faults, such as line-to-line or line-to-ground.

Time-overcurrent relays may be given normal settings without experiencing false operations on switching surges or inrush currents. Instantaneous relays, however, must 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 capacitor rated current when no parallel banks are present and at 4 times capacitor rated current when parallel banks are present [2].

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

6.3.1 General. 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 allowed to burn, involving more and more series groups of the same phase until the instantaneous relay trips the bank or fuses clear, the total arcing time will be 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 the capacitor unit rupture, without the appearance of very much case swelling, is more typical of a high-speed energy type of rupture than that due to merely 60 Hz fault current. This stored energy comes from the other units in the same parallel groups which have been subjected to a high overvoltage as a result of other groups being shorted. Instantaneous overcurrent relays are not effective for rack faults.

6.3.2 Unbalance Relaying. The main protection for arc-over within the capacitor bank is fast timing of the unbalance relay. An unbalance time delay of 0.3 to 0.5 s will provide good protection against rack faults and has had considerable use without misoperation on power systems that are effectively grounded. On resistance-grounded and ungrounded power systems, an unusually long time delay is required to coordinate with the line relays unless the unbalance relay is of the type that does not respond to system voltage unbalance. Using the rule of thumb in 4.7, resistance grounded and ungrounded power systems would use 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 7(c), 10(a), 10(b), 11, and 12. The unbalance relay shown in Fig 9 does not respond to system voltage unbalance, but is 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 0.5 s time 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

S = number of series sections per phase

V_{NS} = neutral-to-ground voltage in per unit of the applied line-to-neutral volts

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 shorted, is

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

where

I_N = neutral current expressed in per unit of normal phase current

6.3.3 Overcurrent Relaying. 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 rated capacitor bank current is commonly used for the instantaneous setting. This setting is used regardless of the capacitor bank connection.

An effective setting for the time-overcurrent (TOC) relay is 1.35 times 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 gives 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 which involve only one phase, the following formulas are useful:

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

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

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

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.

It can be noted from the formulas that a TOC relay cannot reach the initial rack fault ($F=1$) on a single ungrounded Y bank that has more than two series sections per phase, nor on a single grounded Y bank that has more than three sections per phase. Also, on a single ungrounded Y bank where $S=2$, and on a single grounded Y bank where $S=3$, the current, I, is 1.5 for the initial rack fault, which is 1.11 times pickup with a setting of 1.35 times rated capacitor bank current. This performance is marginal, and becomes useful only by using a short-time characteristic, and a low time-lever setting.

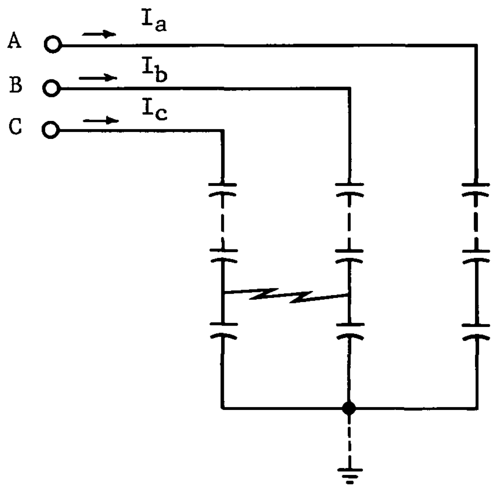


Fig 5
Midrack Phase-to-Phase
Arcing Fault

6.3.4 Fault Involving Two Phases. Although the unbalance-trip relay is the most effective protection for arc-over of a series section, the neutral voltage type of unbalance relay (Fig 7(b) should not be relied upon for rack fault protection on capacitor banks where the phases are not well separated. For example, consider an ungrounded Y capacitor bank with two series groups per phase. The individual phases are stacked over each other so that the initial fault may occur as a midrack phase-to-phase fault, as shown in Fig 5. This fault does not affect the unbalance relay of the neutral voltage type (or neutral current type if grounded).

The initial fault may spread until it becomes severe enough to operate the time or instantaneous overcurrent relays up to 5 s later. There may be considerable damage involving all three phases.

The currents and neutral shift voltage can easily be computed for the initial rack fault. First, the impedance of each phase to the new neutral point, which is the point of fault, is obtained. This results in a set of impedances, Y-connected, which are unequal. Using a

Y-Δ transformation, the equivalent Δ impedances can be found. The Δ currents are the line-to-line voltages divided by the Δ impedances. The line currents can be computed from the phasor addition of two Δ currents. In this manner, the per unit currents (of normal phase current) in Fig 5 with two series groups per phase are:

$I_a = 1.0$
$I_b = 1.8$
$I_c = 1.8$

The voltage drop from phase A to the former neutral, where the primary of the potential device is connected, is $I_a Z_a$, which is the same as before the fault. Therefore, there is no neutral shift. The IZ drops can be added from one phase to another and compared to the applied line-to-line voltage as a check on the accuracy of the calculations.

Protection for rack faults on banks of this construction with two series groups per phase can be obtained by using TOC relays of a short-time characteristic, a setting of 1.35 times rated current, and a timing of 0.2 s at 150% of tap value current.

6.4 Bank Overvoltage Protection. Lightning and switching transient overvoltages must be curtailed with standard overvoltages protection equipment, such as surge arresters or similar spark gaps. A capacitor generally absorbs overvoltages since it acts temporarily as a short circuit for step voltage changes. Overvoltages around capacitor banks are greatly reduced, but complete protection is not assured. The overvoltage on a bank depends upon the length of line between the shunt capacitor bank and the point at which the transient voltage is generated as well as on the surge duration.

The capacitor bank may also be subjected to overvoltages resulting from abnormal system operating conditions. If it is felt that the overvoltage can be sufficient to damage the bank, overvoltage relays should be considered. Table 4 lists recommended short-term overvoltage limits.

Table 4
Limits of Short Time Power Frequency Overvoltage at Subzero Temperatures

Duration	Multiplying Factor Times Rated rms Voltage
0.5 c	3.0
1.0 c	2.7
6.0 c	2.2
15.0 c	2.0
1.0 s	1.7
15.0 s	1.4
1.0 min	1.3
5.0 min	1.2
30.0 min	1.15

NOTE: The short time power frequency overvoltage should be limited to the values listed here at subzero temperatures. Higher limits may be permissible with less severe conditions.

*These limits are for emergency or infrequent conditions. See IEEE Std 18-1980.

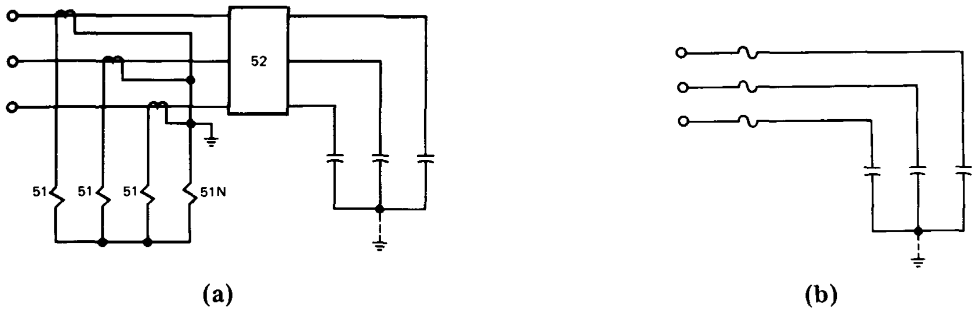
7. Unbalance Relay Protection

7.1 Introduction. Removal of a failed capacitor unit by its fuse results in an increase in voltage across the remaining units within the group. A continuous excessive overvoltage should be prevented by means of protective relays which trip the bank switching device to remove the bank from service. Failure to provide protection may lead to one or more of the following situations:

(1) Excessive damage to the capacitor bank
(2) Adverse system effects
(3) Spread of damage to adjacent equipment
(4) Excessive period of unavailability of the damaged equipment
(5) Possible undesirable discharge of dielectric liquid

Most installations will require an individual engineering analysis to determine the best and most economical scheme. The engineer will want to take a systems approach since bank design, fuse coordination, and selection of a sensing device will directly affect sensitivity and timing requirements of the protection scheme. Selection of the bank configuration and the bank design should include an analysis of the amount of inherent unbalance that can be expected.

7.2 Inherent Unbalance and Other Errors. In practice, the unbalance seen by the unbalance relay due to loss of individual capacitor units is somewhat different than the calculated value because of inherent unbalance. This inherent unbalance, which exists on all capacitor bank installations, is primarily due to system voltage



(a)

(b)

Fig 6
Bank Overcurrent Protection
(a) Using Phase Overcurrent Relays. (b) Using Bank Fuses.

unbalance or capacitor manufacturing tolerance unbalance, or both. The inherent unbalance may be in a direction such as to prevent protective relay operation, as well as to cause false operation. The inherent unbalance for various configurations resulting from system voltage unbalance or capacitor manufacturing tolerance unbalance, or both, may be estimated using equations in Appendix D. A worst case estimate can be made by assuming the unbalance errors to be additive.

Figures 20, 21, and 22 indicate the allowable neutral unbalance for positive detection of the first blown fuse. The curves are based on the relay being set to operate at a point half-way between the critical step and the next lowest step. The critical step is the step for which the voltage applied to surviving capacitor units equals or exceeds 110% of rated voltage. If the estimated inherent unbalance, as determined from equations of Appendix D, exceeds the allowable neutral unbalance as determined from curves or equations of Figs 20, 21, and 22, steps should be taken to compensate for the inherent unbalance error.

Harmonic voltages can also influence the operation of the unbalance relay unless proper filtering is provided. The third harmonic predominates, although special applications such as arc furnaces can produce a wide variety of harmonic frequencies.

In addition, secondary errors may be introduced by sensing device tolerances, temperature differences between capacitor units within the bank, and partially deteriorated capacitor units which have not yet blown their fuses.

7.3 General Unbalance Relay Considerations

7.3.1 The unbalance relay should coordinate with fuses, such that fuses operate to isolate a defective capacitor unit before the bank is switched out of service and thus provide a convenient visual means of locating the defective capacitor unit.

7.3.2 The unbalance relay should be sensitive enough to alarm on 5% or less overvoltage and trip and lockout on loss of individual capacitor units that will cause a group overvoltage condition in excess of 110% of rated voltage.

7.3.3 The unbalance relay should have time delay short enough to minimize damage due to an arcing type fault within the bank structure and to prevent exposure of the remaining capacitor units to overvoltage conditions beyond their permissible limits. The time delay should also be short enough to avoid damage to the current transformer or VT and relay system for a single-phase or an open-phase condition.

7.3.4 The unbalance relay should have time delay adequate to avoid false operations due to inrush, ground faults on the line, lightning, switching of nearby equipment, and nonsimultaneous pole operation of the energizing switch. 0.5 s should be adequate for most applications.

7.3.5 The unbalance relay should be protected against transient voltages appearing on control wiring. (See ANSI/IEEE C37.90a-1974.)

7.3.6 The unbalance relay may require a filter to minimize the effect of harmonic voltages. It should be recognized that the relay may not operate for excessive harmonic (resonant) currents.

7.3.7 The unbalance relay scheme should have a lockout feature to prevent automatic closing of the capacitor bank switching device in the event an overvoltage trip has occurred. The unbalance relay trip circuit components should be coordinated. For example, the .2A target and seal-in coil of the voltage relay has about 50 Ω impedance at 60 Hz. The armature-closed current of a 120 V ac lockout relay may not hold the seal-in unit operated.

7.3.8 Where neutral unbalance due to system variations or capacitor manufacturing tolerances is not negligible, a compensating means should be provided to negate the effect of this unbalance. Careful consideration of bank design may also remedy the problem. Before making changes, the load current of each phase and the capacitance or load current of each capacitor should be checked for indication of failure of a single capacitor pack within the can. The unbalance relay should be set taking this unbalance into account. See 7.8.

7.3.9 Since most unbalance detection schemes do not measure overvoltage due to balanced high system voltage, the unbalance relay should be set on the basis of maximum continuous system operating voltage.

7.3.10 To allow for the effects of inherent unbalance, the unbalance relay alarm should be set to operate at one-half the level of neutral displacement, or neutral current, determined for the desired alarm condition. The alarm should have sufficient time delay to override external disturbances.

7.3.11 To allow for the effects of inherent unbalance, the unbalance relay trip should be set to operate at a level of neutral displacement, or neutral current, half-way between the critical step and the next lowest step. The critical step is the number of removed capacitor units that will cause a group overvoltage in excess of the manufacturer's recommended maximum continuous operating voltage.

7.3.12 All neutral unbalance schemes detect an unbalance in the three phases. Overvoltage caused by loss of an equal number of capacitor units in one or more groups in each phase can not be detected. In practice, this is not a significant limitation.

7.3.13 With grounded capacitor banks, failure of one pole of the switching device or single phasing from a blown bank fuse will produce zero sequence currents in the system ground relays. Capacitor bank relaying, including the operating time of the switching device, should be coordinated with the operation of the system ground relays. This may be several seconds for some devices.

7.4 Neutral Current Unbalance Protection Method, Grounded Y Bank. Fig 7(b) shows a neutral unbalance relay protection scheme for a grounded Y capacitor bank. An unbalance in the capacitor bank will cause current to flow in the neutral. The amount of neutral current due to loss of individual capacitor units can be determined from Fig 13 or equation (5) of Appendix B. The voltage on the remaining capacitor units can be determined from Fig 14 or equation (1) of Appendix B.

The unbalance protective scheme consists of a current transformer with rated 5 A secondary connected from the capacitor neutral to ground. The current transformer secondary is loaded with an adjustable resistor, usually 10 to 25 Ω maximum, and connected to a time delay voltage relay having a third harmonic filter for reduced sensitivity at frequencies other than 60 Hz. A typical relay has 60 Hz pickup taps of 5.4, 7.5, 12.5, and 20 V. The voltage relay operates a latching relay through an *a* contact of the capacitor switch to initiate opening the capacitor switch and blocking its closing. Other schemes may combine the current transformer loading resistor, relay with continuously adjustable pickup, and control relays in a single package.

Each time the capacitor bank is energized, momentary capacitor charging currents in one phase and the neutral current transformer will approach the available ground fault value. Where a parallel bank is already energized, currents can be on the order of thousands of amperes [5]. Various undesirable effects have been recorded, such as spurious relay operations, relay failures, current transformer failures, charged substation fences, and ground mat problems. (The neutral connection between banks should not be through the ground mat.) However, for small to medium-sized single bank installations, this approach works quite well and is economical. If instantaneous overcurrent relays are used they must not operate on the initial inrush current.

A reasonably conservative voltage rating for the neutral current transformer to withstand the surge voltages is 0.2 of the system voltage

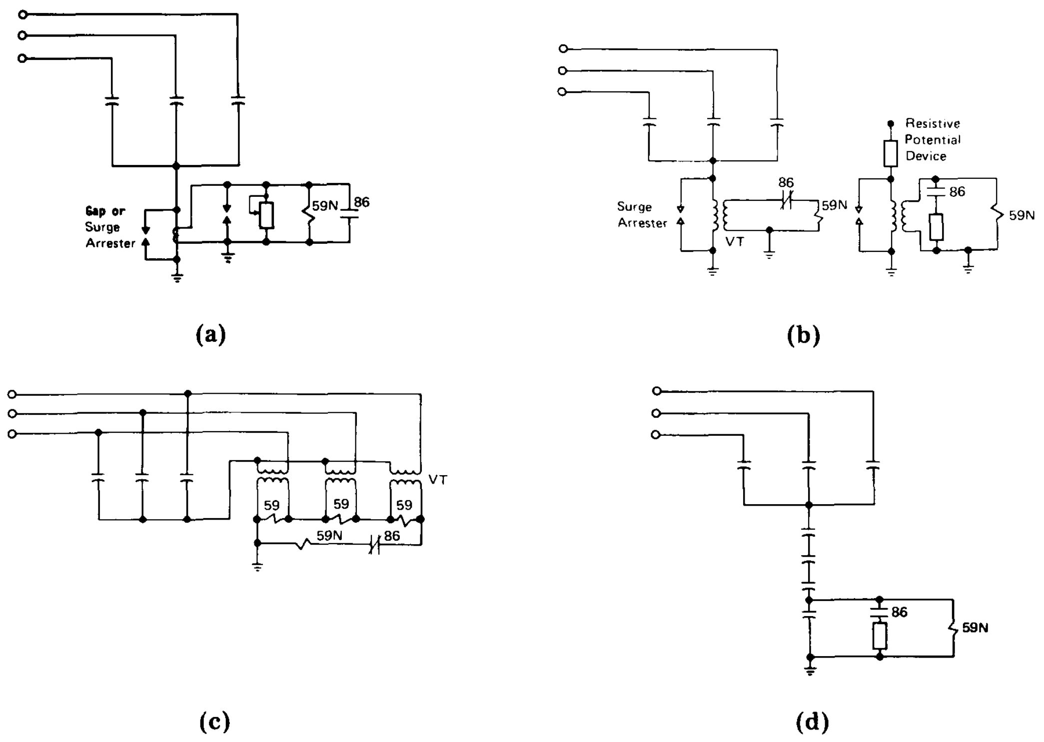


Fig 7
Shunt Capacitor Bank Protection Methods Single Y Banks
(a) Neutral Current Unbalance Protection Method, Grounded Y-Connected Capacitor Bank.
(b) Neutral Voltage Unbalance Protection Method, Ungrounded Y-Connected Capacitor Bank.
(c) Summation of Line-to-Neutral Voltage Protection Method with Optional Line-to-Neutral Overvoltage Protection, Ungrounded Y-Connected Capacitor Bank.
(d) Neutral Voltage Unbalance Protection Method, Ungrounded Y-Connected Capacitor Bank Using Capacitor Voltage Divider.

[8]. However, many have been applied at 0.1 of system voltage without trouble. To protect the neutral current transformer, a rod gap of 3/64 to 1/16 in must be directly connected across the primary terminals and a low voltage surge arrester must be connected across the secondary terminals. A low voltage surge arrester across the primary may be suitable only on relatively small capacitor banks where the surge current is within the arrester capability. If one side of the surge arrester is grounded by its mounting, one primary and one secondary terminal must be grounded at the current transformer terminals instead of at the relay location.

Nonsimultaneous making and breaking times of the three poles of the capacitor switch or circuit breaker may allow full phase current to flow in the neutral current transformer and relay during the time of unbalance. This current can flow for an indefinitely long time if one or two poles fail to open mechanically, if one or two poles fail to interrupt, if the linkage between the three poles is improperly adjusted or fails, or if an operator fails where three electrically ganged single pole switches must be used. For these reasons, it is important to select the neutral current transformer ratio for a secondary current of not more than 10 A with full capacitor line current in the primary.

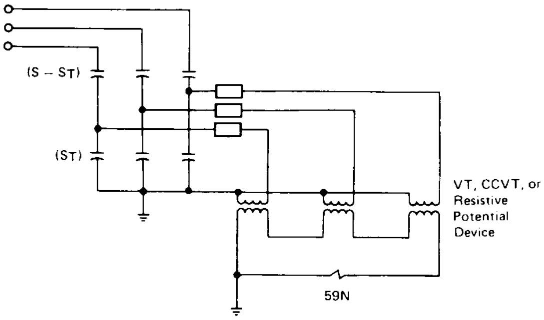
The current transformer loading resistor should have a 200 W or higher rating, preferably an edge wound resistor on a porcelain form without a porcelain glaze covering. This is necessary to avoid fracturing the porcelain and *hot spot* melting of the resistance wire due to very rapid heating with one or two phases open from switch failure or misoperation.

To prevent protective equipment damage due to failure of the switching device, the latching or lockout relay should have contacts wired to the current transformer cable terminals to short out the current transformer secondary after it has operated. The current transformer loading resistor should be able to stand the rapid heating in the case of single phasing without damage until the unbalance protection voltage relay and lockout relay operate.

The voltage relay and current transformer loading resistor settings should be made to operate when the voltage across any capacitor exceeds 110% of rated voltage. Note that the relay detects only the unbalance in the capacitor bank (and in supply voltage), but capacitor overvoltage may also be due to above rated balanced system voltage. The maximum normal system voltage with capacitor bank energized should be considered. The relay should normally be set on its lowest tap (5.4 V).

7.5 Summation of Intermediate Tap Point Voltages Method, Grounded Y Bank. Fig 8 shows an unbalance voltage protection scheme for a grounded Y capacitor bank using capacitor tap point voltages. An unbalance in the capacitor bank will cause an unbalance in the voltages at the tap point of the three phases. The tap voltage percent unbalance due to the loss of individual capacitor units can be determined from Fig 13 or Eq 5 of Appendix B by considering the vertical scale as *Tap Voltage Percent Unbalance*. The voltage of the remaining capacitor units can be determined from Fig 14 or Eq 1 of Appendix B.

The unbalance protective scheme consists of three potential devices connected between the capacitor intermediate point of each phase and ground and a time delay voltage relay with the third harmonic filter connected to the series-connected (broken Δ) secondaries of the potential devices. For an even number of series groups, a midpoint tap is used. For an odd number of series groups, the number of series groups between the tap point and ground should be one less than the number of series groups between the tap point and the line. The potential devices may be transformers, capacitor devices, or resistance devices. The relay may include provisions to compensate for the tap point error voltages caused by inherent capacitor bank unbalance, fixed system voltage unbalance, and potential device ratio errors.



If S is an even number, then

$S - ST = ST = S/2$

If S is an odd number then

$ST = \frac{S - 1}{2}$ and $S - ST = \frac{S + 1}{2}$

NOTE: Summation may also be obtained by use of a summing amplifier.

Fig 8
Summation of Intermediate Tap-Point Voltage Protection Method

The tap voltage percent unbalance can be determined from Fig 13 for isolation of capacitor units in any series group of a capacitor bank having an even number of series groups per phase. The values are also valid for isolation of capacitor units in series groups located between the tap point and the line of a capacitor bank having an odd number of series groups per phase. However, for isolation of capacitor units in series groups between the tap point and ground of banks with an odd number of series groups per phase, the values from Fig 13 must be multiplied by the following factors.

Total No of Series Groups Per Phase	Adjustment Factor for % Tap Unbalance Voltage
3	2.0
5	1.5
7	1.33
9	1.25
11	1.2
13	1.16
15	1.14

For banks having only three or five series groups per phase, this may affect the coordination of alarm and trip level settings. Loss of a second capacitor unit in the same phase but in a second series group on the opposite side of the potential device tap has a compensating effect on the overvoltage and may reduce the unbalance signal to zero.

7.6 Neutral Voltage Unbalance Protection Method, Ungrounded Y Bank. Figure 7(b) shows a neutral unbalance relay protection scheme for an ungrounded Y capacitor bank. Unbalance sensing is accomplished by means of a potential sensing device connected between the bank neutral and ground. An unbalance in the capacitor bank will cause voltage to appear at the bank neutral with respect to ground. The amount of neutral voltage due to loss of individual capacitor units is determined by Fig 15 or Eq 14 of Appendix B. The voltage on the remaining capacitor units can be determined from Fig 16 or Eq 10 of Appendix B.

The unbalance protective scheme consists of a time delay voltage relay with the third harmonic filter connected across the potential device secondary. The potential sensing device may be a voltage transformer, capacitive potential device, or resistive potential device. However, a voltage transformer used in this application should be rated for full system voltage because the neutral voltage can be expected to rise to as high as 2.5 per unit during switching and a derated potential transformer will be driven into deep saturation [1]. The potential sensing device should be selected for the lowest voltage ratio attainable while still being able to withstand transient and continuous overvoltage conditions in order to obtain the maximum unbalance detection sensitivity.

With three or more series groups, the neutral shift voltage obtained from the secondary of a VT of system voltage rating is very small. A VT of lower voltage rating and ratio can be used to obtain a usable relay voltage if the primary is gapped. Flashover of the primary gap will ground the capacitor bank neutral, short out the VT and prevent operation of the overvoltage relay. Therefore, the unbalance relay will not operate for an open phase causing continuous flashover of the neutral VT primary gap. Protection for this condition can be obtained by a residual current relay connected to line current transformers or to a neutral current transformer of the same ratio in series with the neutral VT and VT gap.

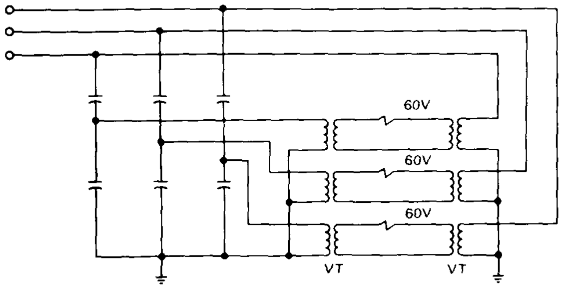


Fig 9
Voltage Difference Protection Method
Grounded Y-Connected Capacitor Bank

The use of an underrated resistance potential device, with secondary voltage limiter, will permit relay operation with an open phase to the capacitor bank. The potential device resistor must be suitable for the short time overvoltage condition.

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

Another scheme, shown in Fig 7(d), consists of standard capacitor units connected in series to form a voltage divider. A conventional inverse time voltage relay is connected across the grounded end capacitor. This grounded end capacitor is a low voltage unit, 2400 V or less, and sized to provide the desired unbalance voltage to the relay. If single phasing of the capacitor bank is a possibility (blown primary fuse) and the voltage of the neutral relay exceeds its short time rating, some means of limiting this voltage must be provided. If the voltage exceeds the continuous rating of the relay, a lockout relay contact should short out the relay through a resistor to limit capacitor discharge current. Without a transformer for isolation, the relay is connected directly to the capacitor bank ground.

A capacitor voltage divider may also use a carrier coupling type of capacitor with a low energy static relay.

Figure 7(c) shows a neutral unbalance relay

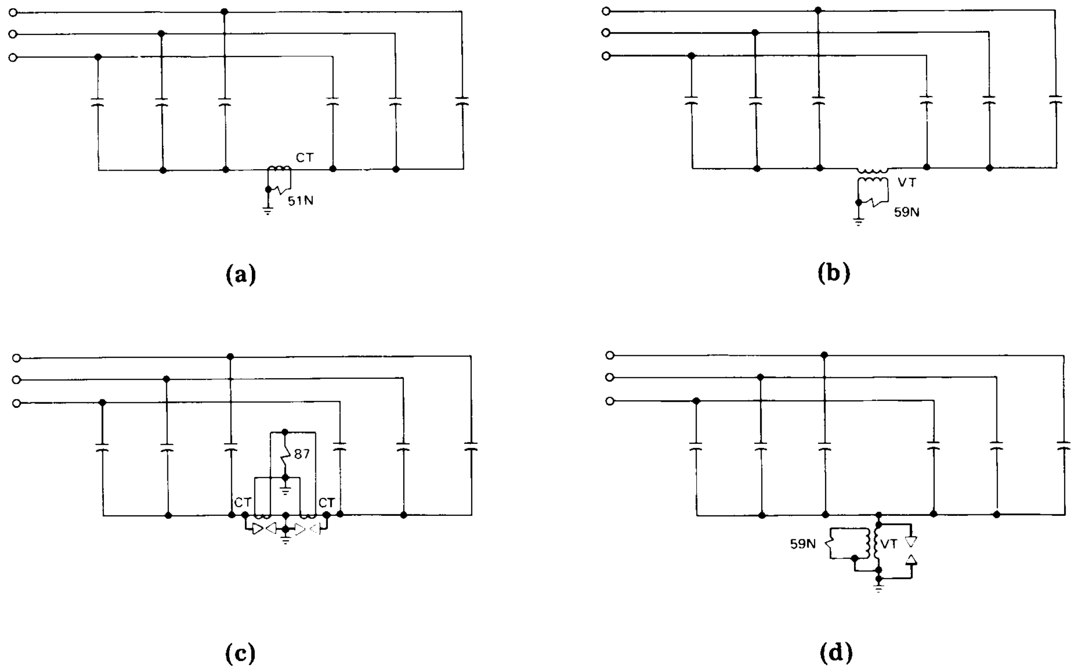


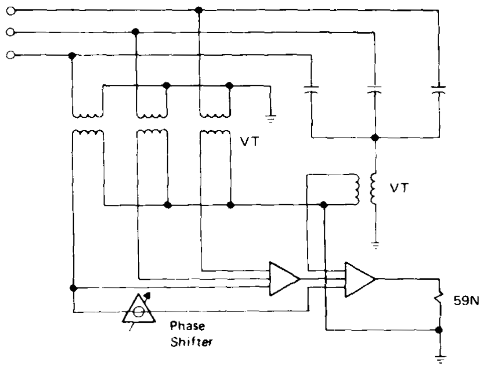
Fig 10
Shunt Capacitor Bank Protection Methods Double Y-Connected Banks
(a) Neutral Current Unbalance Detection Method Ungrounded Double Y-Connected Capacitor Bank. (b) Neutral Voltage Unbalance Protection Method, Ungrounded Double Y-Connected Capacitor Bank (Neutrals Isolated). (c) Neutral Current Differential Protection Method, Grounded Double Y-Connected Capacitor Bank. (d) Neutral Voltage Unbalance Protection Method, Ungrounded Double Y-Connected Capacitor Bank (Neutrals Tied Together)

protection scheme using three line-to-neutral VTs with their secondaries connected in broken Δ to an overvoltage relay. This scheme is not sensitive to system voltage unbalance.

The VTs must be rated for line-to-line voltage. The unbalance voltage to the overvoltage relay is 3 times the neutral shift voltage as obtained from Fig 15. With the same VT ratio as for the neutral-to-ground VT, there is a gain of three in sensitivity over the single neutral-to-ground VT scheme.

7.7 Double Y Unbalance Protection. Figure 10 shows four methods of providing unbalance protection for double Y banks. Schemes (a) and (b) are ungrounded and use either a current transformer and overcurrent relay or VT and overvoltage relay connected between the two neutrals. The effects of system voltage unbalances are avoided by both schemes and both are unaffected by third harmonic currents or voltages. The two sections may be of equal size or one section may consist of only a single unfused capacitor unit per series group. The current transformer or VT must be rated for system voltage.

The amount of neutral current due to the loss of individual capacitor units in a bank of two equal sections can be determined from Fig 17. The current is one-half that of a grounded bank of the same size as each section. However, the current transformer ratio and relay rating may be selected for the desired sensitivity. The current transformer and relay are not subjected



NOTE: Compensating voltage is system zero sequence voltage and a phase shifted voltage of one phase.

Fig 11
Neutral Voltage Unbalance Protection Method
Ungrounded Y-Connected Capacitor Bank
With Compensation for Inherent Unbalance

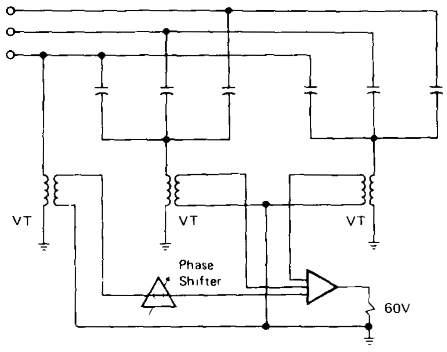


Fig 12
Neutral Voltage Unbalance Protection Method
Ungrounded Double Y-Connected
Capacitor Bank (Neutrals Isolated)
With Compensation for Inherent Unbalance

to switching surge currents or single phase load currents as with the grounded neutral scheme.

The neutral voltage shift can be determined from Fig 15 in the same manner as for a single Y bank of the same rating as one section of the double Y bank. Although a low ratio VT would be desired, a VT rated for system voltage is required for the ungrounded neutral and, therefore, a high turns ratio must be accepted. The resulting unbalance signal voltage is very small.

In Figure 10(c) the neutrals of the two sections are grounded through separate current transformers to a common ground. The current transformer secondaries are cross-connected to an overcurrent relay so that the relay is insensitive to any outside situation which affects both sections of the capacitor bank in the same manner. The current transformers are subjected to switching transient currents and require surge protection. They should be sized for single phase load currents if this is a possibility. The relay does not require a harmonic filter. The unbalance current can be determined from Fig 13 and the overvoltage on remaining capacitor units can be determined from Fig 14.

In Figure 10(d) a neutral of the two capacitor sections are ungrounded but tied together. A VT or potential device is used to measure the voltage between the capacitor bank neutral and ground. The relay should have a harmonic filter. The amount of neutral-to-ground voltage derived due to the loss of individual capacitor units can be determined from a curve of Fig 19 or from the equations in Appendix B. The voltage on remaining capacitor units can be determined from the curves of Fig 18 or from the equations in Appendix B.

7.8 Neutral Unbalance Protection with Compensation for Inherent Unbalance. The trend in recent years has been toward larger and larger capacitor banks at transmission voltage levels. The neutral unbalance signal due to the loss of one or two individual capacitor units for these very large banks is such that the inherent unbalance can no longer be considered negligible.

Ungrounded banks can be split into two equal banks as illustrated in Fig 12. This bank configuration inherently compensates for system voltage unbalances because the neutral current or voltages are sensed differentially. However, the effects of manufacturer's capacitor tolerance will affect relay operation unless steps are taken to compensate for this error. The equations in Appendix D may be used to estimate the possible effect of the inherent capacitor bank unbalance.

To compensate for this fixed unbalance it is necessary to generate an equal and opposite phasor to be summed with the fixed inherent capacitor tolerance unbalance phasor to yield a null or zero signal output. The inherent unbalance at the neutral of the capacitor bank still exists, but the relay is no longer responsive to this fixed unbalance component.

A phase shifting network with amplitude and phase adjustment is used to generate the compensating phasor. The input for the phase shifter should be bus derived to reduce the effect of nominal system voltage changes. The output of the phase shifter along with the inherent unbalance signal are summed by means of transformers or a summing amplifier.

It may not be possible or desirable to go to a split bank arrangement, depending on the individual circumstances of the application. For compensation of system voltage unbalance on single ungrounded banks, use is made of the fact that the voltage appearing at the capacitor bank neutral due to system unbalance is the zero sequence component. A zero sequence component can be derived utilizing three potential sensing devices with their high side connected from line-to-ground and the secondaries connected in a broken Δ. See Fig 11. Very often bus VTs are already available for station relaying and all that is needed are isolation transformers to derive the broken Δ. This difference voltage between the neutral unbalance signal due to system unbalance and the broken Δ output of the bus VTs is then adjusted to zero by means of an amplitude control. Once this adjustment is made, the effect of system voltage unbalance will be compensated for all conditions of system unbalance. The error appearing at the neutral due to manufacturer's capacitor tolerance can be compensated for by means of the phase shifter circuit previously described.

7.9 Voltage Differential Protection Method, Grounded Y Bank. A means of compensation for inherent unbalance of a grounded Y capacitor bank is illustrated in Fig 9. This approach is really three single phase relay schemes.

A signal responsive to the loss of individual capacitor units is derived by comparing capacitor bank tap voltage with the bus voltage. The capacitor bank tap voltage is obtained by connecting a potential sensing device between the lowest parallel group or groups of capacitors and ground. The bus potential is usually available. Initially, the voltage levels are adjusted to be equal, assuming that all capacitors are good and no fuses have operated. The initial difference signal between capacitor bank tap voltage and bus voltage signals is zero. Capacitor tolerance and system unbalance variation is compensated. If the system voltage should vary, the relay system is still compensated since a given percent change in bus voltage results in the same percent change on the capacitor bank tap. Any subsequent voltage difference between capacitor tap voltage and bus voltage will be due to unbalances caused by loss of capacitor units within that particular phase. See Fig. 9. Loss of capacitor units in each phase is detected independently [3], [4].

The sensitivity of this method is high and serves in particularly high voltage banks or banks which consist of a large number of individual capacitors.

Transient voltage disturbances are overriden by an adjustable time delay. Independent unbalance level detection is provided with separate adjustments for an alarm signal when the first capacitor fails and a tripping signal when dangerous overvoltages occur.

8. System Considerations

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

The capacitor bank may resonate with harmonics produced elsewhere, such as at remote loads. There is extensive and growing use of thyristors in industry to derive dc variable potential from an ac source. Such phase controlled thyristors generate harmonics, particularly 3rd, 5th, 7th, and 11th. More instances of parallel resonance are occurring due to this cause, and even some examples of harmonic series resonance with utilities due to adjacent utility loads. This also includes utility distribution circuits which have capacitors that supply medium industrial and commercial loads. In most of these instances some form of harmonic filtering may be involved to control the harmonic voltage and high capacitor harmonic currents. Higher voltage rated capacitors may be used [9], [10], [11], [12].

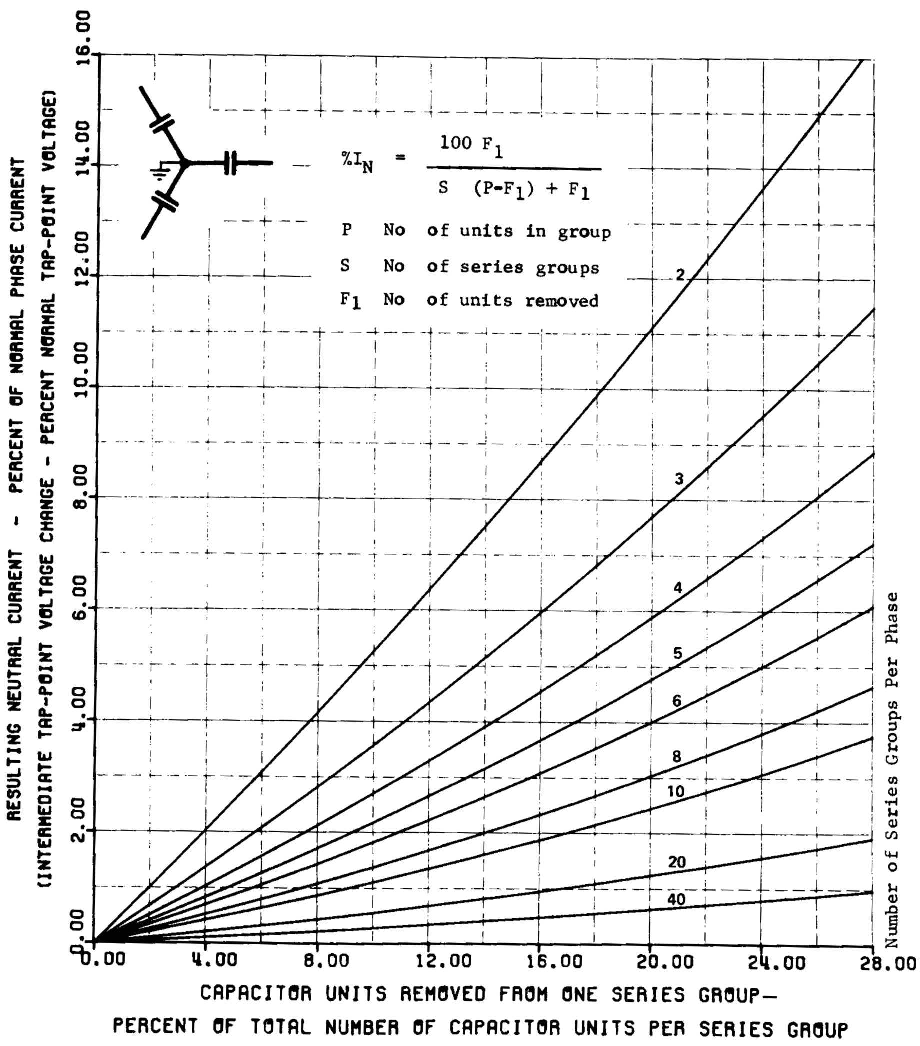


Fig 13
Grounded Y-Connected or Grounded Double Y-Connected Capacitor Bank: Neutral Current (also change in intermediate tap-point voltage) Versus Percentage of Capacitor Units Removed from Series Group

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

Problems associated with resonance may usually be resolved by the application of the proper capacitor switching device, the addition of appropriately rated reactors (or reactors and resistors in parallel) in series with the switched capacitor bank, or the relocation or change in size of the switched capacitor bank.

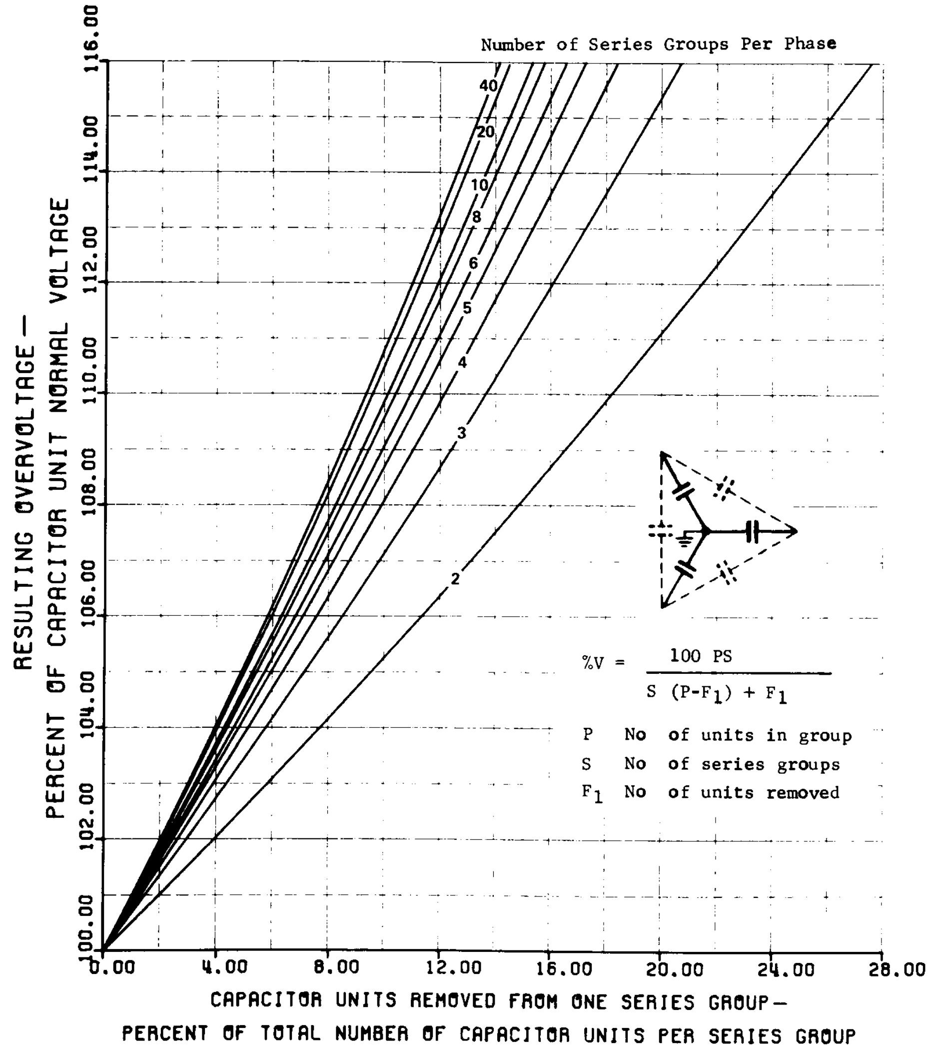


Fig 14
Grounded Y-Connected, Δ, or Grounded Double Y-Connected Capacitor Bank: Voltage on Remaining Capacitor Units in Series Group Versus Percentage of Capacitor Units Removed from Series Group

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

The measure of the capability of a power circuit to act as a noise source is the telephone influence factor (TIF). This is a dimensionless quantity indicative of wave form [6]. See IEEE Std 469-1977.

Before attempting to apply corrective measures to a capacitor bank that caused interference, it would be well to locate the source of the noise. The best corrective measures are usually applied at the source. If corrections

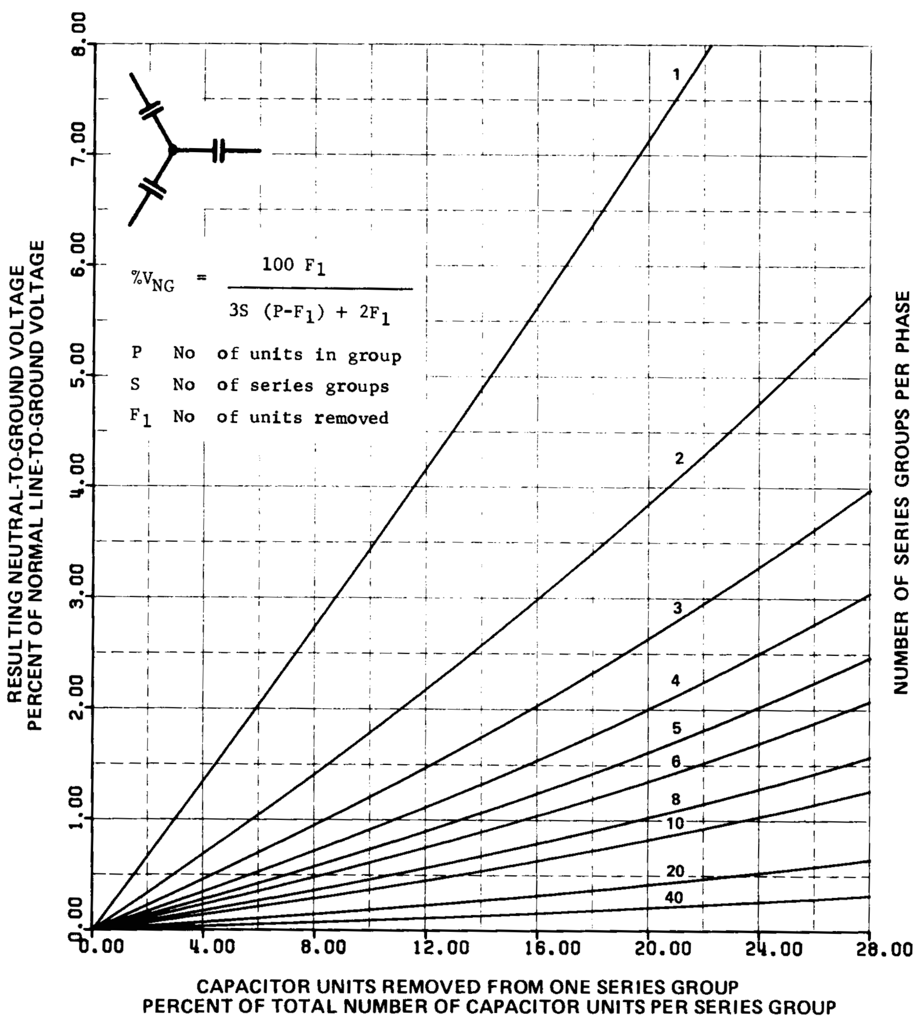


Fig 15
Ungrounded Y-Connected or Ungrounded Double Y-Connected (Neutrals Isolated) Capacitor Bank: Voltage Between Capacitor Bank Neutral and Ground Versus Percentage of Capacitor Units Removed from Series Group

must be made at the capacitor bank, modifications to change the resonant frequency can be made.

8.3 Inrush (Parallel Banks). The phenomenon of inrush to a single isolated switched shunt capacitor bank and to a bank switched back-to-back with a parallel energized bank or banks has been discussed in 5.1. In a given application, the currents and voltages associated with inrush to a capacitor bank may precipitate undesirable resonant effects with other parts of the system, induce hazardous surges in station control cable, and cause interference with communication facilities in the area.

Closing resistors on the switching device and current limiting reactors installed in series with a switched capacitor bank will serve to alter the

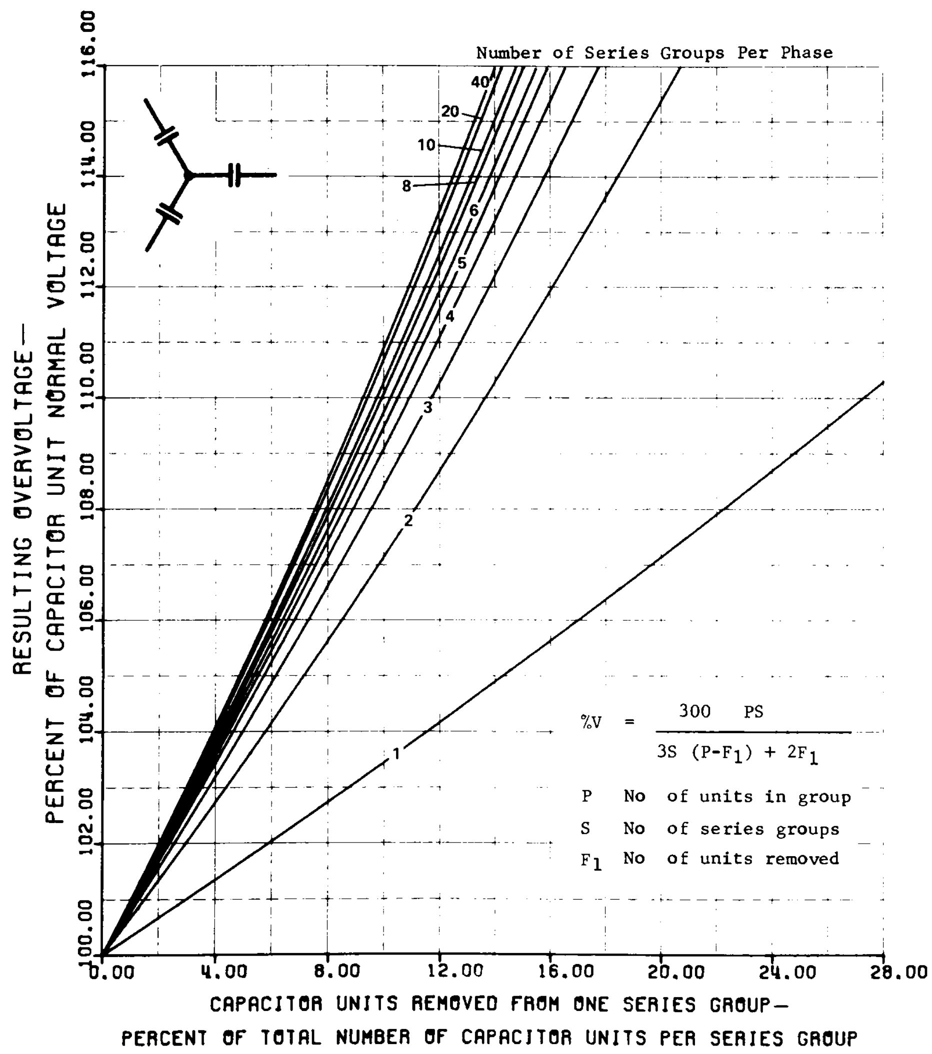


Fig 16
Ungrounded Y-Connected or Ungrounded Double Y-Connected (Neutrals Isolated) Capacitor Bank: Voltage on Remaining Capacitor Units in Series Group Versus Percentage of Capacitor Units Removed from Series Group

frequency of the inrush transients and to reduce the magnitude of the transients. The reactors applied must have a sufficiently high basic impulse isolation level (BIL) rating that gaps or surge arresters required for reactor protection will not short out the reactors during energization of the capacitor bank.

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

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

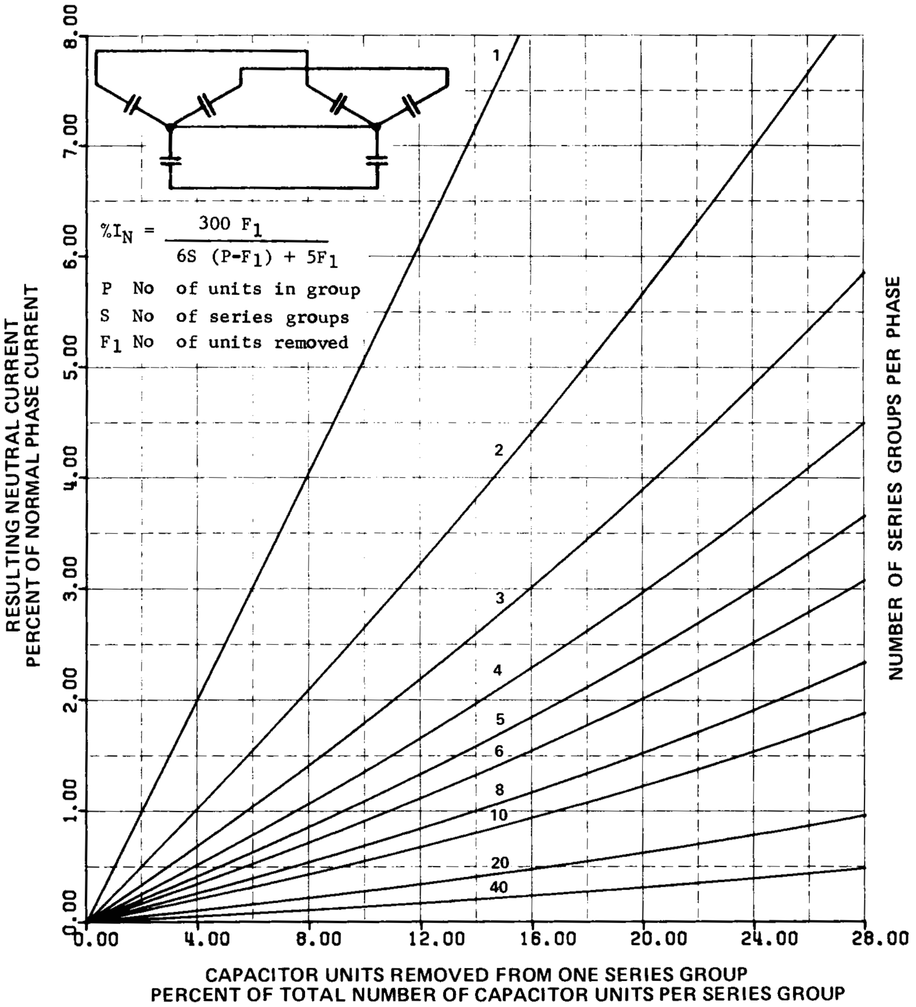


Fig 17
Ungrounded Double Y-Connected (Neutrals Tied Together) Capacitor Bank: Neutral Current Versus Percentage of Capacitor Units Removed from Series Group

Instantaneous phase and ground overcurrent relays applied for capacitor bank protection must be set high enough not to trip undesirably on inrush current.

In a station where large capacitor banks are connected to a common bus, it may be necessary to check the transient capacitor discharge current to a fault to determine that the breaker capability is not exceeded. The peak discharge current of the individual capacitor bank is:

$$I_{\mathrm{pk}} = \sqrt{2}\, V_{\mathrm{LG}} \sqrt{\frac{C}{L}}$$

$$= 1.33 \sqrt{\frac{\mathrm{kvar}\,(3\phi)}{L}} \text{ A}$$

C = farads
L = henrys (total inductance, capacitor to fault)

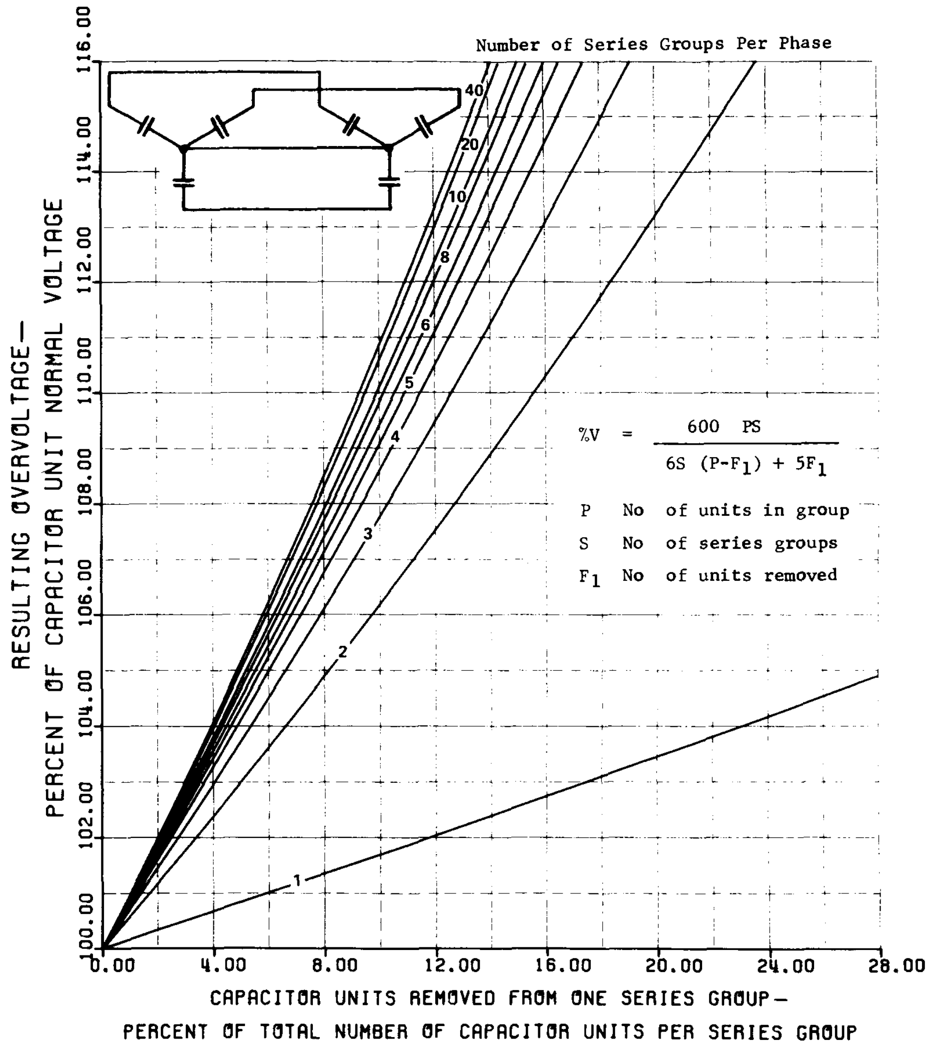


Fig 18
Ungrounded Double Y-Connected (Neutrals Tied Together) Capacitor Bank: Voltage on Remaining Capacitor Units in Series Group Versus Percentage of Capacitor Units Removed from Series Group

Transient inrush currents through a circuit breaker, in addition to involving the contact capability, may also cause secondary flashover of bushing current transformers (BCT). The voltage developed in the secondary circuit is proportional to the frequency and magnitude of the transient inrush current.

$$\text{BCT secondary voltage (crest)} = \frac{\text{transient current}}{\text{BCT ratio}} \times \text{current transformer burden reactance } (\Omega) \times \frac{\text{transient frequency}}{\text{system frequency}}$$

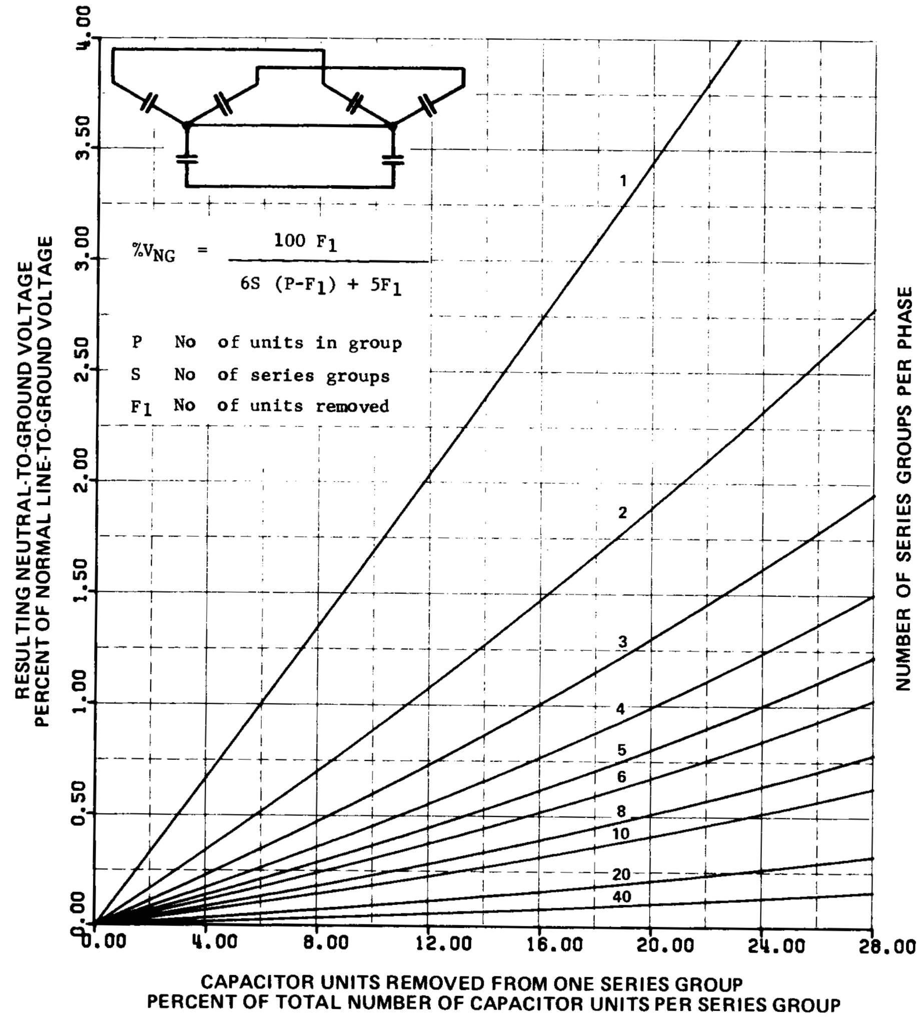


Fig 19
Ungrounded Double Y-Connected (Neutrals Tied Together) Capacitor Bank: Voltage Between Capacitor Bank Neutral and Ground Versus Percentage of Capacitor Units Removed from Series Group

9. Bibliography

KEEZER, D.C. and DOWNING, W.C., JR. Relay Protects Floating Neutral Capacitors. *Electrical World*, Mar 11, 1963, p 86.

RANSOM, J.C.W. and MOULTON, C.H. Relay for Shunt Capacitor Bank Protection. *Allis-Chalmers Engineering Review*, vol 31, no 1, 1966.

SCHULTZ, N.R. and SHEPPARD, R.S. Protection of High Voltage Capacitor Banks. *Electric Light and Power*, Aug 15, 1958, pp 51-55.

MINDER, P.M. New Relay Scheme Protects Floating-Wye Capacitor Bank. *Electrical World*, May 16, 1955, p 122.

CLARK, N.R. and FARAHAM, S.B. Connection Arrangements and Protective Practices for

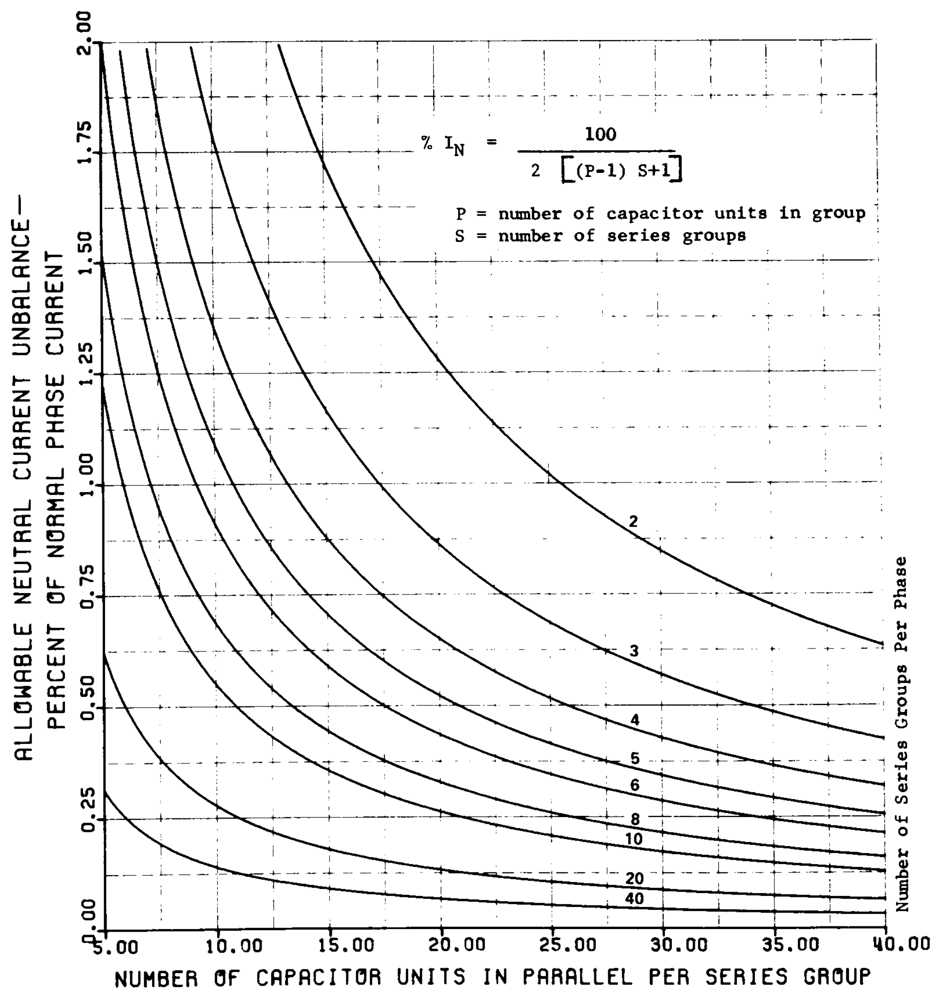


Fig 20
Grounded Y-Connected Capacitor Bank: Percentage of Allowable Inherent Neutral Current Unbalance for Positive Detection of First Blown Fuse Versus Number of Capacitor Units in Parallel per Group and Number of Series Groups

Shunt Capacitor Banks. *AIEE Transactions*, 1949, vol 68, part II, pp 1226-1231.

COMPTION, O.R. Balancing Double-Wye High Voltage Capacitor Banks. *AIEE Transactions*, 1955, vol 74, part III, pp 573-579.

BOSKAMP, J.B. Protection of Bulk Capacitor Banks. *Electrical South*, Dec 1963/Jan 1964, parts I and II, p 41.

SAINE, J.A. Shunt Capacitor Bank Connections. *Distribution*, Jan 1969, pp 22-24.

PFLANZ, H.M. and LESTER, G.N. Control of Overvoltages on Energized Capacitor Banks. *IEEE Transactions on Power Apparatus and Systems*, May/Jun 1973, IEEE T72 541-1, pp 907-914.

STONE, H.C. Unbalance Protection of Large

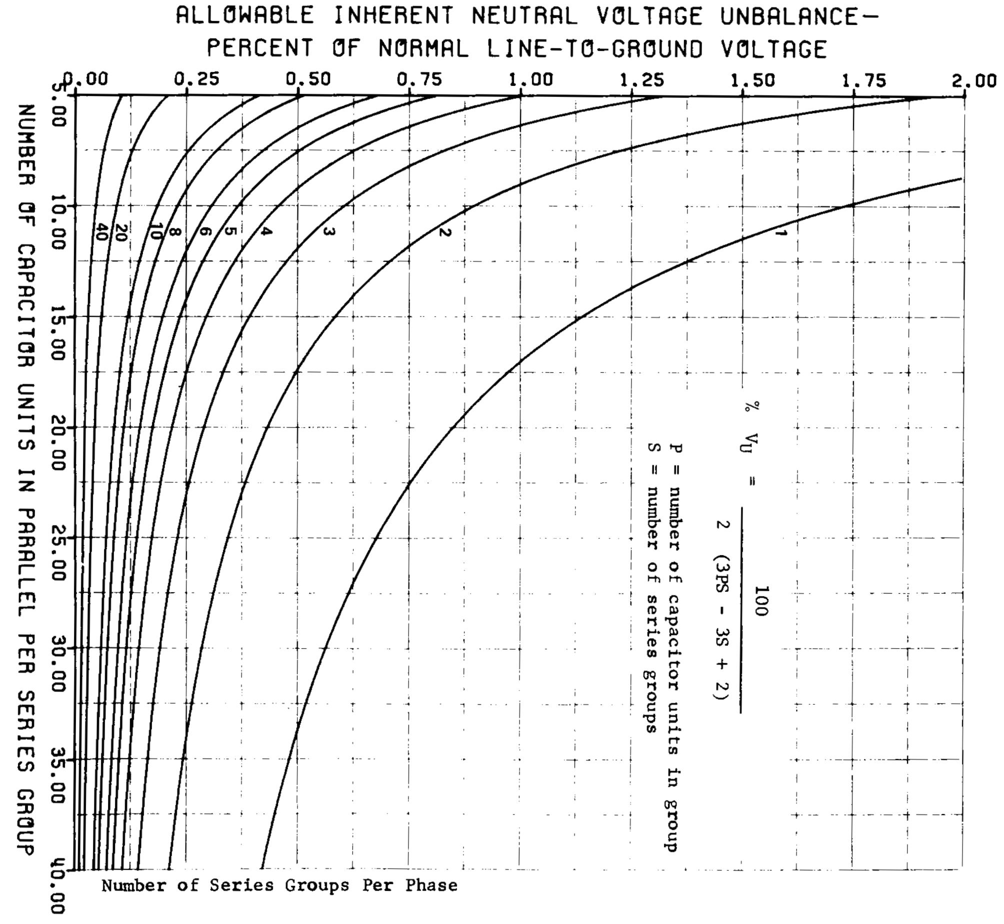


Fig 21
Ungrounded Y-Connected Capacitor Bank: Percentage of Allowable Neutral Voltage Unbalance for Positive Detection of First Blown Fuse Versus Number of Capacitor Units in Parallel per Group and Number of Series Groups

Capacitor Banks. *The Line*, The Line Material Company: Milwaukee, WIS, Oct 1956.

KELLY, W.L. Switching Shunt Capacitors. General Electric Company, Jun 1954.

Application of Capacitors to Power Systems, 4th edition, Westinghouse T & D, pp 233-264.

BUTLER, J.W. Shunt Capacitor Application Problems. *General Electric Review*, vol 43, May 1940, pp 206-212.

BEEHLER, J.E. Capacitance Switching with Power Circuit Breakers. IEEE Conference Paper 68-CP-161-PWR, 1968.

STONE, H.C. High-Voltage Capacitor Bank Design Factors. McGraw Edison Co Technical Bulletin no 104, 2-61.

Capacitors, No 9, Engineering and Technical Data. Allis-Chalmers Corp, Jan 1960.

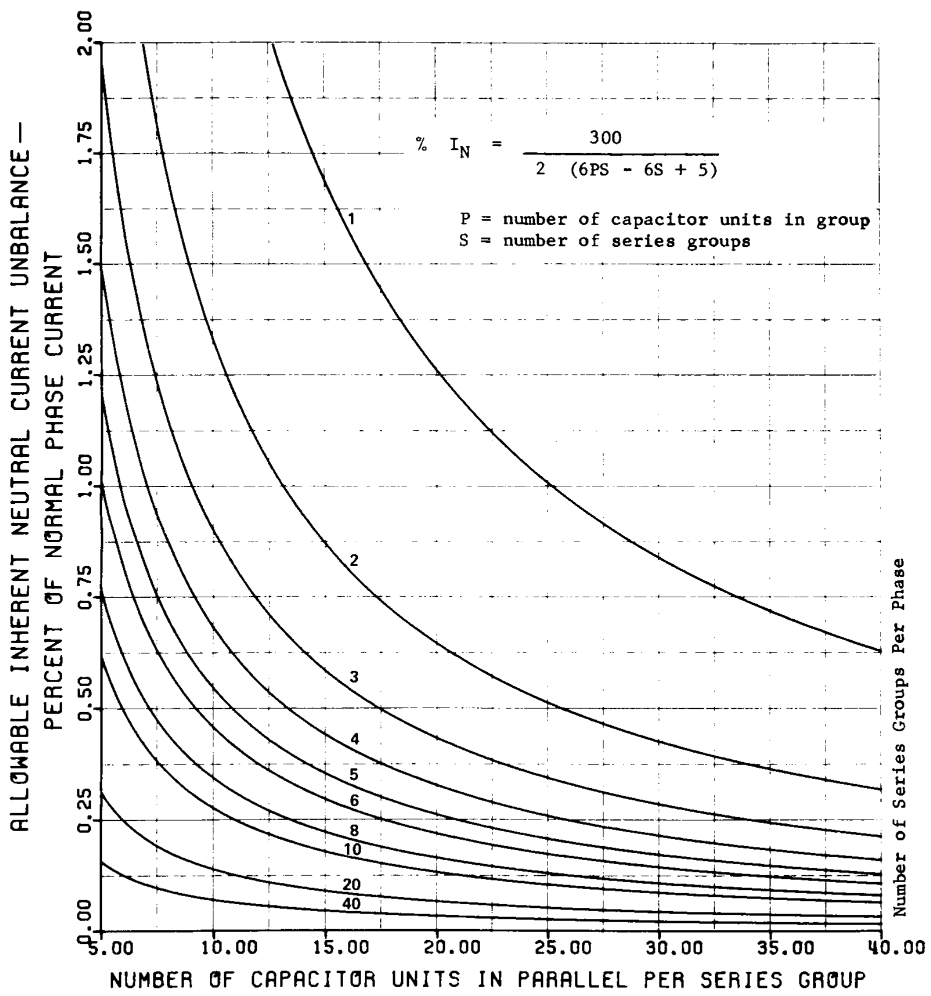


Fig 22
Ungrounded Double Y-Connected Capacitor Bank: Percentage of Allowable Inherent Neutral Current Unbalance for Positive Detection of First Blown Fuse Versus Number of Capacitor Units in Parallel per Group and Number of Groups in Series

Unbalance Protection of Large Capacitor Banks. *Design Principles and Methods,* McGraw Edison Co, Feb 1962.

NEUMANN, M.E. Philosophy of Shunt Capacitor Bank Protection. Presented at the 1973 Conference for Protection Relay Engineers, Allis-Chalmers Corp, Apr 16-18, 1973.

ELLIOTT, L.C., BUETTNER, D.E., and ANDERL, H.W. Capacitance Switching. Westinghouse Transmission Report no 72-066.

WALSH, G.W. Power System Considerations Relating to Thyristor dc Drive Applications. *Industrial Power Systems,* vol 2, no 2, Jun 1968.

Appendixes

(These Appendixes are not a part of ANSI/IEEE C37.99-1980. IEEE Guide for Protection of Shunt Capacitor Banks.)

These Appendixes contain tables, formulas and equations which will be a source of information to the protective engineer in determining voltages, inrush current and frequency for switching capacitor banks, in addition to useful data for evaluation of the protection of a shunt capacitor bank.

Appendix A
Symbol Definitions

V_{LL} = line-to-line voltage, V

V_{LG} = line-to-ground voltage, V (use maximum value where appropriate)

ΔV_{LG} = variation of V_{LG} between phases, per unit

$S = \frac{V_{LG}}{V_C}$ = number of series groups

S_T = number of series groups, sensing tap to ground

P = number of parallel capacitors per series group

F_1 = number of eliminated capacitors within the same series groups within one phase

F_2 = number of series groups within one phase which each have a single capacitor eliminated

V_C = rated capacitor voltage, V

V_{C1} = voltage across the series group with removed capacitors, V

ΔV_{C1} = voltage change across the series group with removed capacitors, V

V_{C2} = voltage across the series group with the correct number of capacitors, V

ΔV_{C2} = voltage change across series group with the correct number of capacitors, V

I_C = capacitor current at rated voltage, A

I_ϕ = normal phase current, A

ΔI_ϕ = change in phase current, A

I_N = neutral current, A

$X_C = \frac{{V_C}^2 \cdot 10^{-3}}{\text{kvar}_U} = \frac{V_C}{I_C}$ = capacitor impedance

P_{min} = required minimum parallel capacitors per series group to limit overvoltage to 10%

P_{min1} = for F_1 type capacitor elimination

P_{min2} = for F_2 type capacitor elimination

ϕ = variance of phase angle between two phases from 120°

ΔC = per unit variation of capacitance between phases

V_{TG} = voltage between intermediate tap point and ground, V

V_{NG} = neutral to ground voltage, V

V_{NN} = voltage between neutrals, V

kvar_U = individual capacitor reactive power rating, kVA

kvar_B = capacitor bank reactive power rating, kVA

Appendix B
Equations

The following equations have been derived for the evaluation of shunt capacitor bank protection.

The change of phase impedance of a bank with series and parallel groupings is determined by the location as well as the number of isolated capacitors.

$$I_\phi = \frac{\text{var}_B}{3\,V_{LG}} = \frac{V_{LG}\,P}{X_C\,S} = \frac{V_{LG}\,I_C\,P}{V_C\,S}$$

B1. Equations for Grounded Y Banks (Also Δ Banks with V_{LL} substituted for V_{LG})

$$V_{C1} = V_{LG}\,\frac{P}{S\,(P-F_1)+F_1} \qquad \text{(Eq 1)}$$

$$\Delta V_{C1} = V_{LG}\,\frac{S-1}{S}\cdot\frac{F_1}{S\,(P-F_1)+F_1} \qquad \text{(Eq 2)}$$

$$V_{C2} = V_{LG}\,\frac{P-F_1}{S\,(P-F_1)+F_1} \qquad \text{(Eq 3)}$$

$$\Delta V_{C2} = \frac{V_{LG}}{S}\cdot\frac{F_1}{S\,(P-F_1)+F_1} \qquad \text{(Eq 4)}$$

$$I_N = \Delta I_\phi = I_\phi\cdot\frac{F_1}{S\,(P-F_1)+F_1} \qquad \text{(Eq 5)}$$

Minimum parallel capacitors per series group are required to limit the capacitor overvoltage to 10%.

For (F_1) failures only in one series group:

$$P_{\min 1} = F_1\,\frac{11\,(S-1)}{S} \qquad \text{(Eq 6)}$$

For single capacitor failures in (F_2) different series groups:

$$P_{\min 2} = \frac{11\,(S-F_2)}{S} \qquad \text{(Eq 7)}$$

Current and voltage change for F_1 capacitor failures in the same series group relative to normal values:

$$\frac{\Delta I_\phi}{I_\phi} = \frac{\Delta V_C}{V_C} = \frac{F_1}{S\,(P-F_1)+F_1} \approx \frac{1}{SP} \qquad \text{(Eq 8)}$$

(for $F_1 = 1$ and $P >> F_1$)

Approximation of Eq 5 yields for $F_1 = 1$ and and $P >> F_1$

$$\Delta I_\phi \approx \frac{\text{kvar}_U \cdot 10^3}{V_{LG}} \qquad \text{(Eq 9)}$$

B2. Equations for Ungrounded Y Banks

$$V_{C1} = \frac{3\,V_{LG}P}{3S\,(P-F_1)+2F_1} \qquad \text{(Eq 10)}$$

$$\Delta V_{C1} = V_{C1} - \frac{V_{LG}}{S} = \frac{V_{LG}\,F_1\,(3S-2)}{S\,[3S\,(P-F_1)+2F_1]} \qquad \text{(Eq 11)}$$

$$V_{C2} = \frac{3V_{LG}\,(P-F_1)}{3S\,(P-F_1)+2F_1} \qquad \text{(Eq 12)}$$

$$\Delta V_{C2} = \frac{V_{LG}}{S} - V_{C2} = \frac{2\,V_{LG}\,F_1}{S\,[3S\,(P-F_1)+2F_1]} \qquad \text{(Eq 13)}$$

$$V_{NG} = \frac{V_{LG}\,F_1}{3S\,(P-F_1)+2F_1} \qquad \text{(Eq 14)}$$

$$P_{\min 1} = F_1\,\frac{11\,(3S-2)}{3S} \qquad \text{(Eq 15)}$$

B3. Equations for Ungrounded Double Y Bank with Neutrals Tied Together

$$V_{C1} = \frac{6\,V_{LG}\,P}{6S\,(P-F_1)+5F_1} \qquad \text{(Eq 16)}$$

$$I_N = I_\phi\cdot\frac{3F_1}{6S\,(P-F_1)+5F_1} \qquad \text{(Eq 17)}$$

$$V_{NG} = \frac{V_{LG}\ F_1}{6S\,(P-F_1) + 5F_1} \qquad \text{(Eq 18)}$$

$$P_{\min 1} = F_1\ \frac{11\,(6S-5)}{6S} \qquad \text{(Eq 19)}$$

Table B4
60 Hz Fault Current and Voltage with One Unit Shorted

Y Bank Configuration	Fault Current		Voltage on Each Remaining Group in Series With Faulted Group	
Grounded	$\frac{S}{S-1}\ I\phi$*	(Eq 20)	$\frac{V_{LG}}{S-1}$	(Eq 21)
Single Ungrounded	$\frac{3S}{3S-2}\ I\phi$	(Eq 22)	$\frac{3\ V_{LG}}{3S-2}$	(Eq 23)
Double Ungrounded	$\frac{6S}{6S-5}\ I\phi$	(Eq 24)	$\frac{6\ V_{LG}}{6S-5}$	(Eq 25)

***For S=1, the current is the system line-to-ground fault current.**

B5. Stored Energy

Energy $= CV^2 = 2.65 \times$ kvar J (W•s)

$= 2.65 \times$ kvar J (W•s) (Eq 26)

$$C = \frac{\text{kvar} \cdot 10^3}{377 \cdot \text{V}^2} = \frac{2.65\ \text{kvar}}{V^2}\ \text{F}$$

V = rms V (Eq 27)

Appendix C
Inrush Current and Frequency for Switching Capacitor Banks

C1. Energizing an Isolated Bank

$$i_{\max}\ (\mathrm{A}) = 1.41\sqrt{I_{SC} \times I_1}\ \text{or}$$

$$1.41\ V_{LG}\sqrt{\frac{C_B}{L_S}} = 1330\sqrt{\frac{\mathrm{kvar}}{L_S}}$$

$$\mathrm{f\ (Hz)} = \mathrm{f}_s\sqrt{\frac{I_{SC}}{I_1}}\ \text{or}$$

$$\frac{10^6}{2\pi\sqrt{L_S\,C_B}}$$

C2. Energizing a Bank with Another on the Same Bus

$$i_{\max}\ (\mathrm{A}) = 55.2\sqrt{\frac{V_{LL}\ (I_1 \times I_2)}{L_{eq}\ (I_1 + I_2)}}$$

$$= 1330\sqrt{\frac{\mathrm{kvar}_1 \times \mathrm{kvar}_2}{L_{eq}\ \mathrm{kvar}_T}}$$

$$\mathrm{f\ (kHz)} = 0.3\sqrt{\frac{\mathrm{f}_s\ V_{LL}\ (I_1 + I_2)}{L_{eq}\ (I_1 \times I_2)}}$$

C_B	bank capacitance (μF)
L_S	system inductance (μH)
f_s	system frequency
L_{eq}	total equivalent inductance per phase between capacitor banks (μH)
I_1	load current of capacitor bank being switched
kvar_1	3ϕ kVA of capacitor bank being switched
I_2	load current of capacitor bank already energized
kvar_2	3ϕ kVA of capacitor bank already energized
$i_{\max}$	peak current without damping (actual value about 90%)
kvar_T	$\mathrm{kvar}_1 + \mathrm{kvar}_2$
I_{SC}	symmetrical rms short circuit current (A)

C3. Typical Values of Inductance Between Capacitor Banks (ANSI/IEEE C37.012-1979)

Rated Maximum Voltage (kV)	Inductance per Phase of Bus (μH/ft)	Typical Capacitor Bank Inductance (μH)
15.5 and below	0.214	5
38.0	0.238	5
48.3	0.256	10
72.5	0.256	10
121.0	0.261	10
145.0	0.261	10
169.0	0.268	10
242.0	0.285	10

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

Appendix D
Equations for Effect of Inherent Unbalances

Table D1 is intended as a *rule of thumb* for determining the effect of inherent unbalances on the displacement signal of various bank protection schemes.

Table D1
Effect of Inherent Unbalance on Displacement Signal

Shunt Capacitor Bank Configuration	Effect of Capacitor Manufacturing Tolerances	Effect of System Voltage Magnitude Changes	Effect of System Voltage Phase Angle Change
Grounded Y with Neutral Current Sensing	$I_N = \frac{\Delta C \text{ var}_B}{3\, V_{LG}}$	$I_N = \frac{(\Delta V_{LG})P \text{ var}_U}{S\,(V_C)^2}$	$I_N = \frac{2PV_{LG}\,(\sin\frac{\phi}{2}) \text{ var}_U}{S\,V_C{}^2}$
Ungrounded Y with Neutral Potential Sensing	$V_{NG} = \frac{\Delta C\, V_{LG}}{3}$	$V_{NG} = \frac{\Delta\, V_{LG}}{3}$	$V_{NG} = \frac{2}{3}(\sin\frac{\phi}{2})\, V_{LG}$
Ungrounded Double Y with Neutral Differential Potential Sensing	$I_N = \frac{\Delta C \text{ var}_B}{6\, V_{LG}}$	$I_N = 0$	$I_N = 0$
Ungrounded Double Y with Neutral Differential Potential Sensing	$\Delta V_{NN} = \frac{\Delta C\, V_{LG}}{3}$	$\Delta V_{NN} = 0$	$\Delta V_{NN} = 0$
Grounded Y with Differential Potential Sensing	$\Delta V_{TG} = \Delta C\, V_{LG} \frac{S_T}{S^2}(S-S_T)$	$\Delta V_{TG} = 0$	$\Delta V_{TG} = 0$