

USEFUL INFO ON CAPACITORS & CAP BANKS.

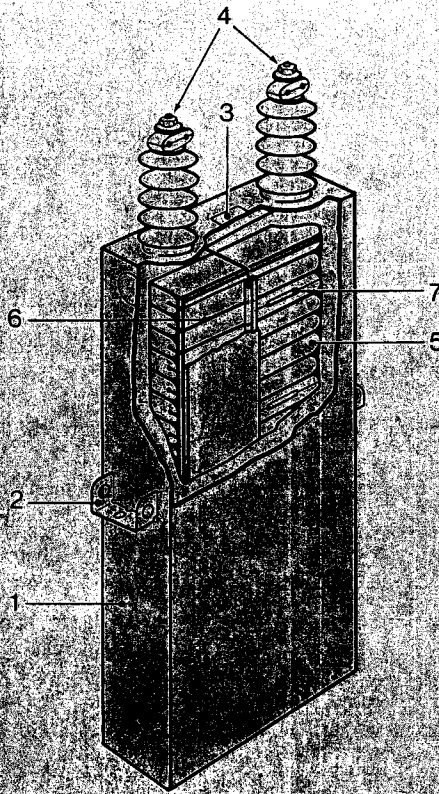


Fig. 1 1: Stainless steel tank
2: Mounting bracket
3: Nameplate
4: Bushings/Studs with paragroove terminals
5: Capacitor elements (packs)
6: Internal fuses (optional)
7: Built-in discharge resistor



Fig. 2 Dielectric pad design

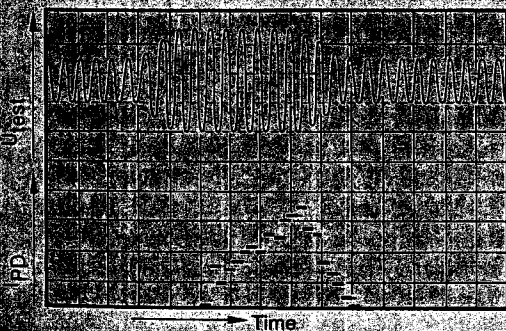


Fig. 3 Transient overvoltage test at -55°C

LOW-LOSS ALL-FILM DIELECTRIC DESIGN

The all-film dielectric of ASEA's latest generation of power capacitors offers the following distinct advantages over the mixed-dielectric design.

- The dielectric loss factor has been drastically reduced to about 0.10 W/kvar.
- The variation in capacitance with ambient temperature has decreased, thus giving more constant bank output. This is an important feature especially in filter applications.
- The capacitor performance at low ambient temperatures has been significantly improved.

The solid dielectric in ASEA's all-film capacitor utilizes the most advanced polypropylene films available having a textured surface on both sides (see Fig. 2). This design offers easy impregnation and superior dielectric performance. The standard element design with extended and folded foils offers the lowest possible resistive losses and excellent partial discharge properties. To assure high reliability, each element (pack) is individually tested before assembly into the capacitor unit.

The capacitor units meet or exceed the requirements in the most widely specified standards: ANSI C55.1, NEMA CP1, and IEC 70. The units are of single-phase design with one or two bushings. Unit ratings vary between 120 and 400 kvar at 60 Hz or 100 and 333 kvar at 50 Hz. The design is available for operation in all ambient temperatures specified by the standards.

FARADOL®: NON-PCB IMPREGNATION FLUID

In addition to its excellent electrical performance, FARADOL® is also characterized by its low toxicity, low bioaccumulation tendency, and rapid biodegradation in the environment. It is an OSHA IIIB combustible fluid. Burning of FARADOL® produces no poisonous gases, such as hydrochloric acid, so impregnated material can be disposed of in conventional incinerators.

The dielectric design of the capacitors is based on extensive tests performed in ASEA's own laboratories and also by independent test institutes. Some of the most rigid tests were conducted by EdF in France and KEMA in Holland, including transient overvoltage withstand ability at low temperatures and long term endurance at 1.4 times nominal voltage. The capacitors also pass the stringent new IEC endurance test.

A recording of the partial discharge intensity during a transient overvoltage is shown in Fig. 3. Measurements of this kind are extremely useful for establishing optimal dielectric design parameters.

CAPACITORS PROTECTED BY EXTERNAL FUSES

ASEA offers capacitors protected by external fuses where suitable. This may be the case in banks with small units and high unit voltages or for replacement of units in existing banks. In new installations ASEA recommends internal fuses for several reasons.

INTERNAL PROTECTION: HIGH RELIABILITY, NO CASE BURSTING

In the internally protected design each element (pack) is series connected with a built-in fuse. If a failure in one element should occur, it is instantly disconnected. The capacitor unit will remain in operation with only a slight reduction in its power output. By using a well proven design for the internal fuses, adjacent elements and fuses are not affected by the fuse operation. The lifetime of the unit is, therefore, hardly affected.

The capacitor design with internal fuses offers several advantages in

ABB

Construction

The capacitor units have a rectangular container, for outdoor use made of chromium stainless steel and thoroughly painted to resist severe conditions. The terminals are welded to the container.

The units are provided with either one bushing and the container live, or two bushings and the container insulated. Choice of capacitor type is determined as the alternative giving the most economic bank design for the voltage and power rating in question.

Each capacitor unit is built up of a great number of elements having a dielectric of plastic films between aluminium foils.

The capacitor elements are assembled to a stack closely fitting into the container in order to reduce the amount of free impregnation fluid. The container will easily accommodate changes in the fluid volume following variations in the temperature.

Impregnation fluids

All capacitors are impregnated with FARADOL, which is the name of ASEA's non-PCB impregnation fluids. All are biodegradable and environmentally accepted. FARADOL impregnated capacitors may be installed without any special ground protection. As the fluids are inflammable, capacitors can be scrapped by burning.

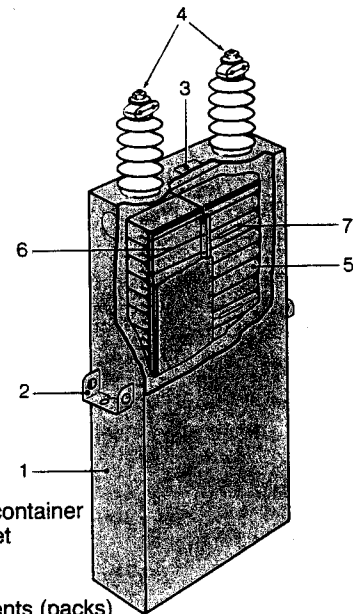
Protection

ASEA offers capacitors protected by external fuses or by internal element fuses. External fuses are suitable for banks with small units and high voltages, but for most installations ASEA recommends internal fuses. The main reason is that in the internally protected unit each element is series connected with a built-in fuse. If a failure should occur, the faulty element is instantly disconnected by its fuse. The capacitor will remain in operation with only a slight reduction in its output. A single failure does not affect the service of the bank and the remaining lifetime is barely affected.

Discharge

The capacitors are normally discharged through built-in discharge resistors. These resistors will discharge the bank from rated voltage to less than 50 V within five minutes. Quicker discharge can be obtained through parallel connection of the capacitor bank with a three-phase set of voltage transformers.

Fig 3



1. Stainless steel container
2. Mounting bracket
3. Nameplate
4. Bushings
5. Capacitor elements (packs)
6. Internal fuses (optional)
7. Built-in discharge resistor

Fig 4 Capacitor element

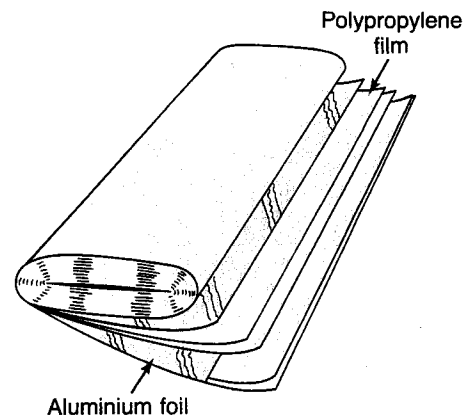
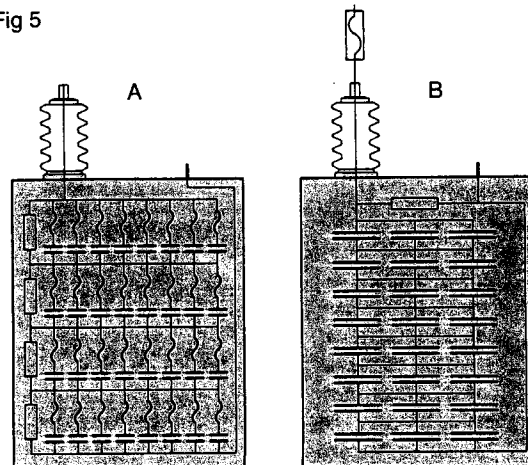


Fig 5



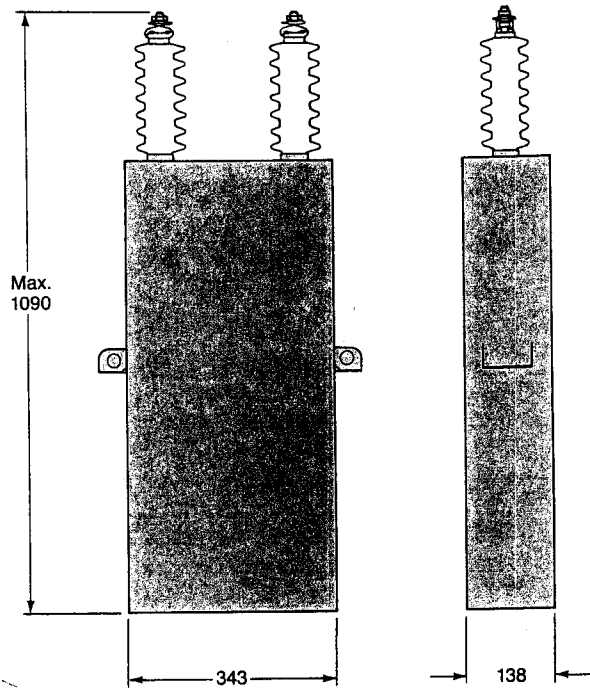
- A Capacitor with internal element fuses
B Capacitor with external fuse

Fig 6

CAPACITOR RATINGS

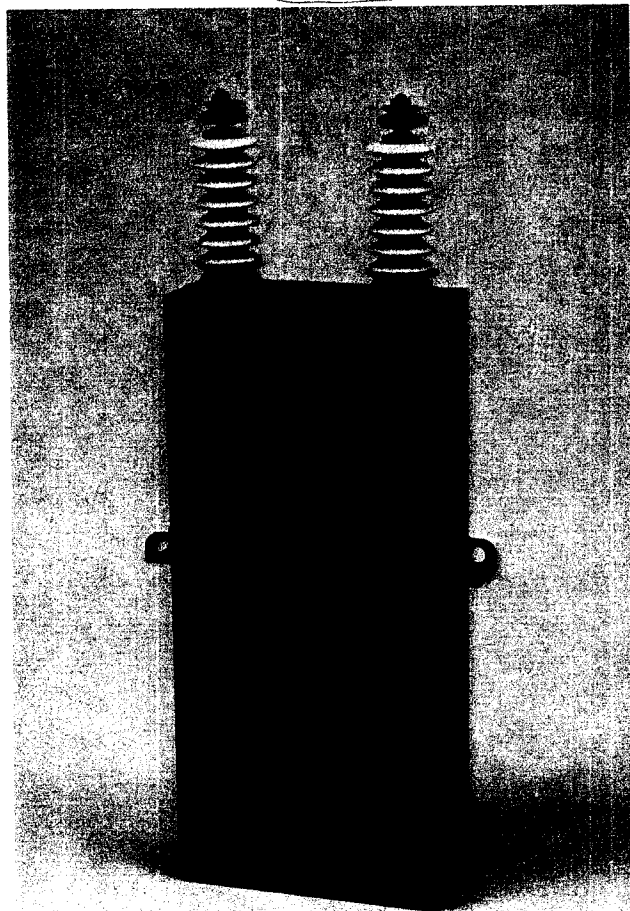
Capacitor ratings normally lie within the ranges presented below. The extreme values of the various variables can usually not be obtained simultaneously. That means for example, that the highest power output cannot be combined with the lowest unit voltage.

Voltage, internal fuses	1.5-8.7 kV ✓
external fuses	1.5-13.8 kV
Output 50 Hz	250-333 kvar
60 Hz	300-400 kvar ✓
Temperature range	-40/+40°C
Losses, including fuses and discharge resistors	< 0.2 W/kvar
Connection	Clamps for max. 2x70 mm ² Cu conductor

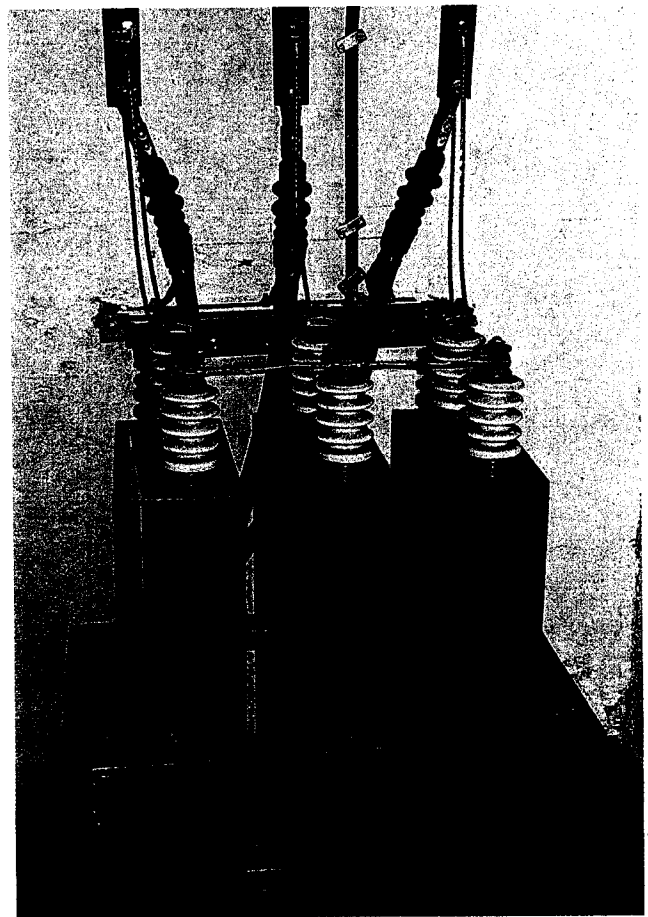


$\frac{10}{6} = 1.67 \text{ MVAR}$
series
 6-12.3 kV A ASSI/5/phase
 5 caps/ASSI (333 KVAR each)
 30 caps/phase
 EXTERNAL

High voltage capacitor



Capacitor bank, 750 kvar, 11 kV, internal fuses



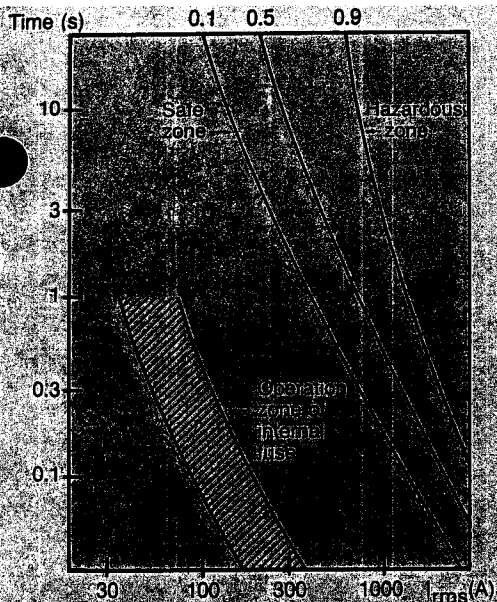


Fig. 4 NEMA's case rupture curve

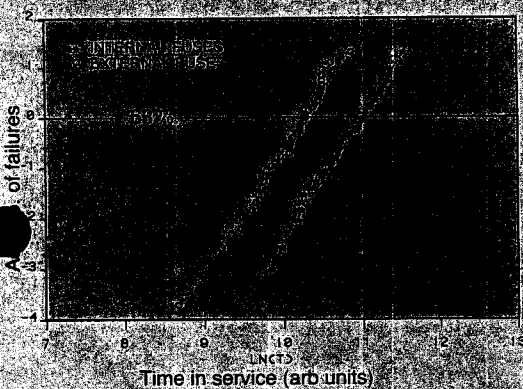


Fig. 5 Weibull probability diagram
Computer simulation of bank life shows advantage of internal fuses

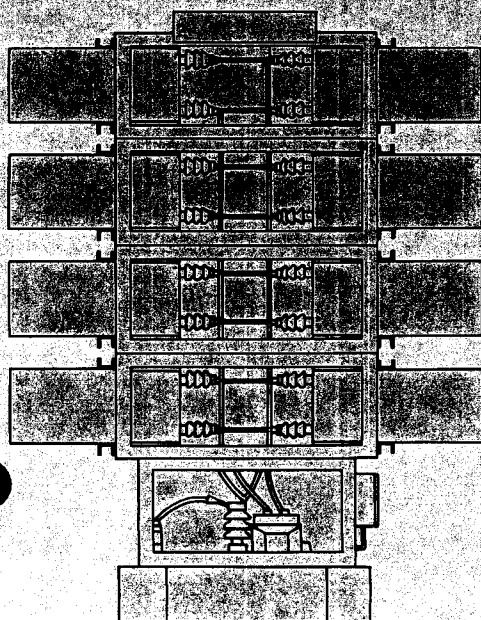


Fig. 6 Enclosed capacitor bank, type SIKAP

The routine testing of the internally fused capacitor units also checks the performance of the fuses. A direct discharge test determines their mechanical withstand capability.

Capacitor banks equipped with internally fused units generally show superior availability. This is due to the excellent possibilities of obtaining direct coordination between the bank unbalance current and the protection level settings for alarm and trip.

QUALITY FROM START TO FINISH

The production of ASEA's capacitors follows a rigorous quality assurance program starting with careful selection and control of all materials and components, including continuous recording of process parameters, and ending with a comprehensive test of electrical and mechanical parameters of the finished products.

All designs are based on extensive development, type and batch tests.

By using an advanced computer simulation method, the reliability of the combined dielectric and protection system of the capacitors can be checked (see Fig. 5). It is now routinely used for optimizing both unit and bank design.

GREAT FLEXIBILITY IN BANK DESIGN

The capacitor units can be used in all medium and high voltage applications and in banks with all voltage and power ratings. Units with internal fuses, particularly, offer great flexibility in the bank design since there is no minimum requirement on the number of units connected in parallel in each phase. This means that the inherent disadvantages of high unit voltages can be avoided and also that large – and therefore economical – units can be used in most applications.

Internally fused units simplify bank layout. The absence of fuse-holders and extra busbars makes for more compact designs with fewer components. No extra strike clearance is needed for the fuse operation.

ASEA can also offer factory assembled, completely enclosed capacitor banks for system voltages up to 24 kV. In these banks the internally fused units are used to full advantage by mounting them into their racks with the bushings pointing inwards (see Fig. 6). Enclosed banks are available in two designs each requiring only a minimum of space and no fencing-in:

- Type SIKAP includes capacitors and unbalance protection current transformer.
- Type EMPAC is a complete, modular capacitor system. The modules include capacitors, high voltage switch, damping reactors, busbars, and current transformers.

EXPERIENCE AND INNOVATION

ASEA's Power Capacitor Division is one of the world's leading manufacturers with over fifty years of experience in this field.

Some of the high technology capacitor applications which ASEA has pioneered, and taken a leading position in, are

- Series capacitors with associated protection equipment.
- SVS (Static Var Systems) for reactive power control in transmission, distribution, and industrial systems.
- Tuned AC filters, DC filters and compensation for HVDC converter stations.

All of these applications demand in-depth knowledge of both system and component technology as well as exceptionally high reliability of the capacitors.

The product and systems know-how is backed by extensive and qualified research into dielectric phenomena. ASEA's new line of FARADOL® (non-PCB) impregnated capacitors (including also DC capacitors, capacitor voltage transformers, low voltage power capacitors) are all based on research, development and testing within the Division.

Westinghouse



Dated, but still valid.

Stack Type Capacitor Equipments

2.4-500 Kv, 300 Kvac and Above

Using 50, 100, 150 or 200 Kvac Capacitor Units

Step 8 – Select Insulation Between Individual Stacking Units (NEMA Ref. CPI-1973 Part 6)

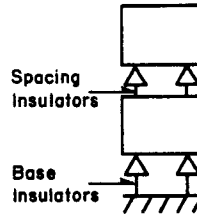
General

Insulators between stacking units may be required because the stacking unit frame is usually energized. Insulation between physical ground and the vertical stack of stacking units may also be required. Listed below is a simple method of determining when insulators are required.

Definitions of Terms

Spacing Insulators – Insulator mounted between stacking units.

Base Insulators – Insulator mounted between the bottom stack and the base support.

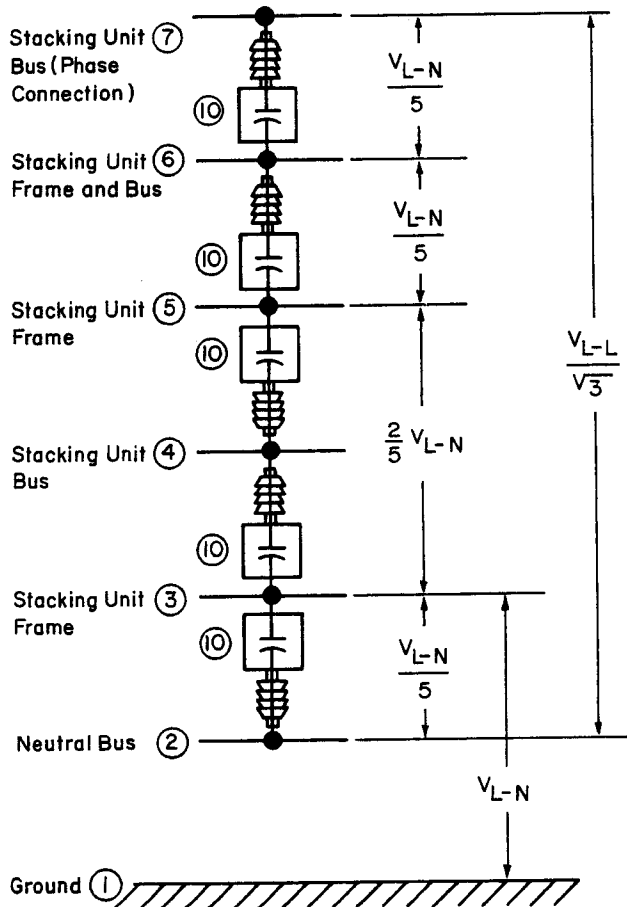


To determine insulators required, draw a schematic of the stacking arrangement showing the capacitor, stacking unit frame and stacking unit bus.

Rule: The neutral and phase connection should terminate on insulated bus.

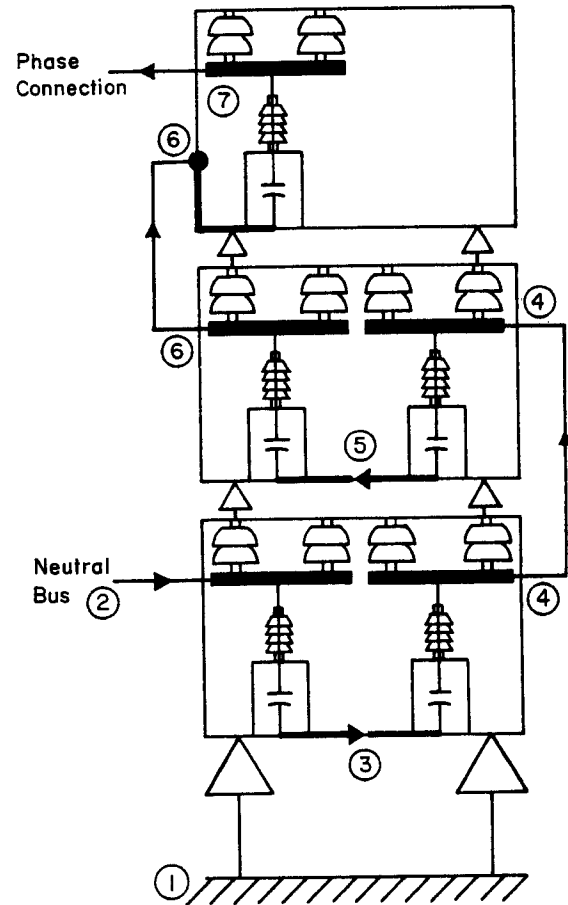
Example

SUMMARY: 115 KV Line-Line
13280 V capacitor unit
Equal split bus stacking unit
10 capacitors per series group
5 series groups per phase



Phase A (Typical)

Fig. 13 Voltage Division Between Stacking Unit Frames



Equal Split Bus Stacking Arrangement Phase A (Typical)

Stack Type Capacitor Equipments

2.4-500 Kv, 300 Kvac and Above

Using 50, 100, 150 or 200 Kvac Capacitor Units

Example

Base Insulation:

For ungrounded wye base insulation would be full line-to-line insulation or 115.0 KV. For grounded wye insulation would be equal the insulation of the last capacitor unit. (For the above example 15 KV).

Spacing Insulation:

From bottom stacking unit to middle stacking unit.

$$\text{Insulation Required} = \frac{2}{5} V_{L-N} = \frac{2}{5} (66.4) = 26.4 \text{ KV}$$

Next standard insulator is 34 KV.

From middle stacking unit to top stacking unit.

$$\text{Insulation Required} = \frac{1}{5} V_{L-N} = \frac{1}{5} (66.4) = 13.2 \text{ KV}$$

Next standard size is 15 KV.

Bill-Of-Material Per Phase

- 4 ea. - 115 KV Base Insulators
- 4 ea. - 34 KV Spacing Insulators
- 4 ea. - 15 KV Spacing Insulators

Insulation Diagrams For Other Numbers of Series Groups Per Phase

The following figures are shown to illustrate the various insulations required.

1 SERIES GROUP PER PHASE

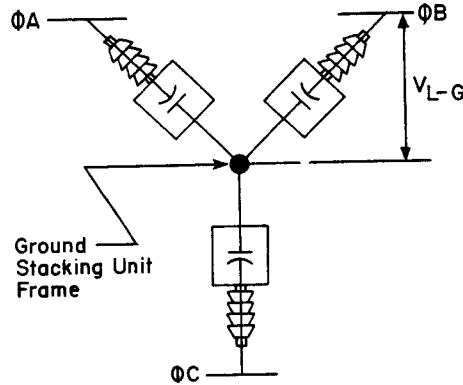


Fig. 14 Grounded Wye Connection Using 3 Phase Stacking Unit

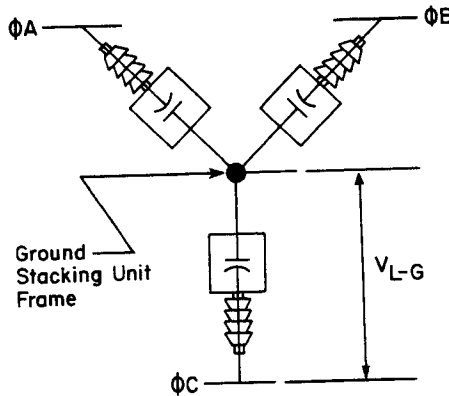


Fig. 15 Grounded Wye Connection Using 1 Series Group Per Stacking Unit

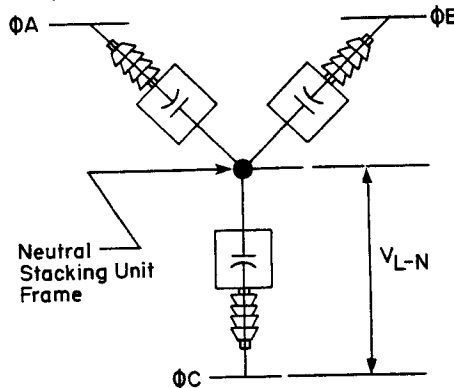
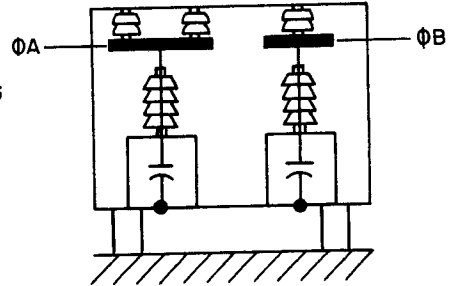
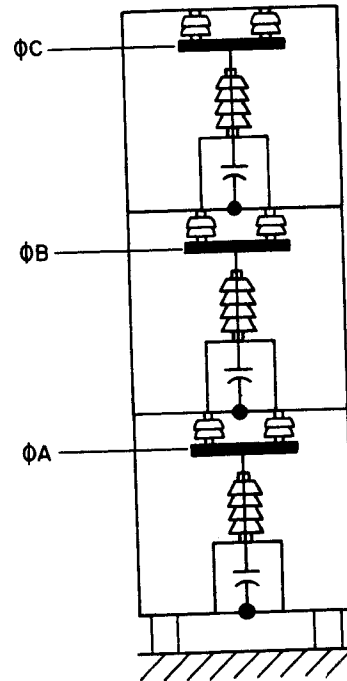


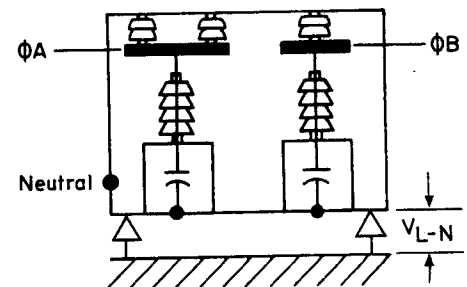
Figure 16 Ungrounded Wye Using 3 Phase Stacking Unit



Note: Phase C capacitors cannot be seen, no base insulation required.



Note: No Base Insulators or Spacing Insulators are Required



Note: Phase C capacitors cannot be seen



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2.4-500 Kv, 300 Kvac and Above
 Using 50, 100, 150 or 200 Kvac
 Capacitor Units

Stack Type Capacitor Equipments

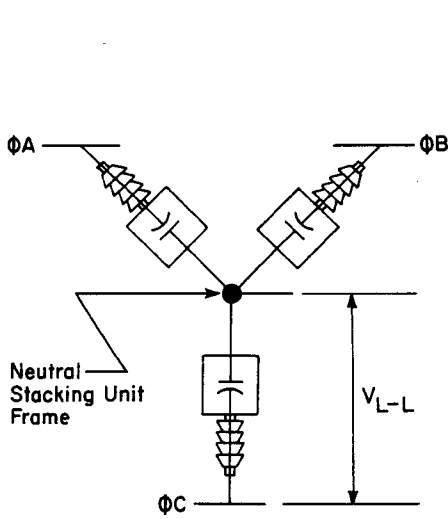


Fig. 17 Ungrounded Wye Using 1 Series Group Per Stacking Unit

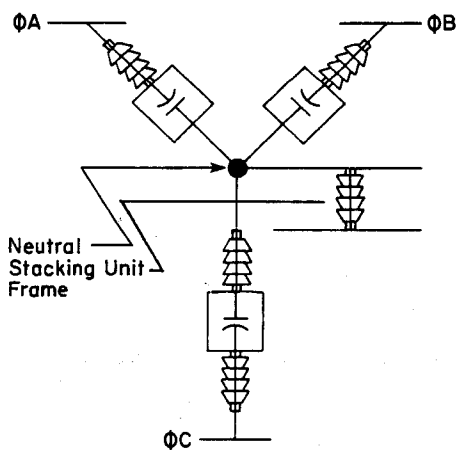
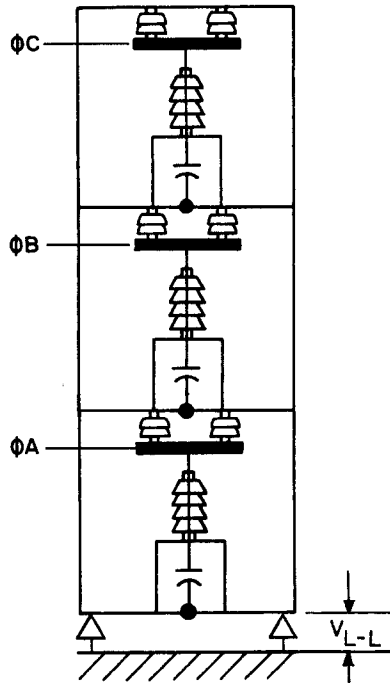
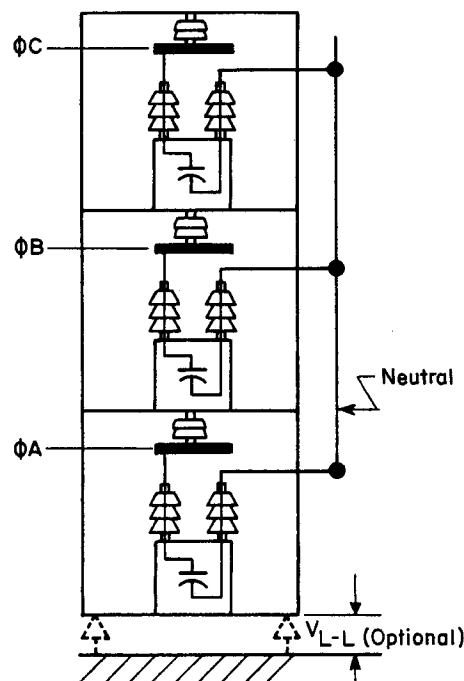


Fig. 18 Ungrounded Wye Using 1 Series Group Per Stacking Unit 2 Bushing Capacitors



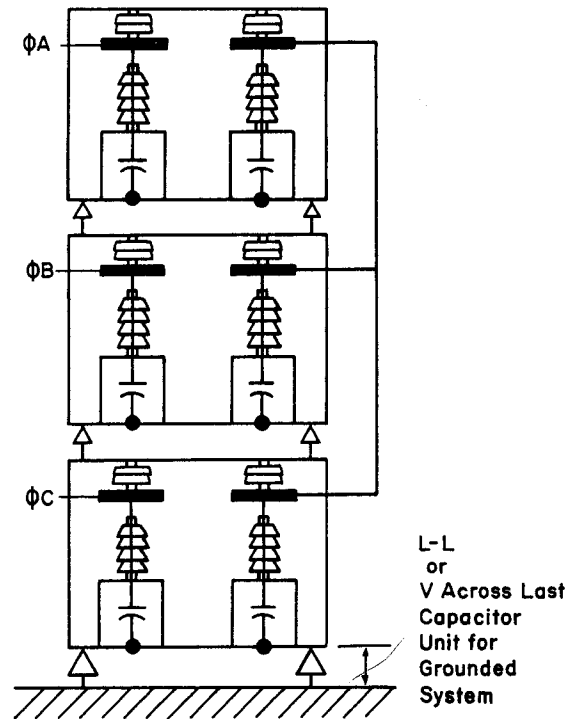
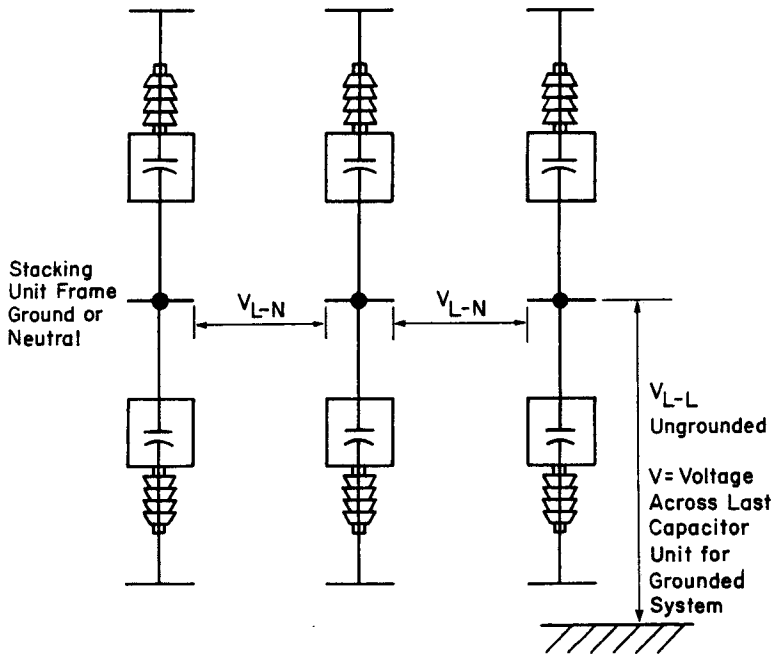


Fig. 19 2 Series Groups Per Phase Using Double Bus Stacking Units

Rule: Spacing insulators must be applied between every second group of series groups in the same phase.

Spacing insulator must be applied between stacking units of different phases in the same vertical stack.

Note: Users should specify all types and ratings of both base and spacing insulators. If user does not specify, Westinghouse will quote insulator per the above method.

Step 9 – Select Proper Capacitor Unit Fuse (NEMA Ref. CPI-1976 Para. 6.07)

General
The stacking units have individual fuses mounted on the horizontal bus above the

capacitor units. The fuse pig tail lead passes through the coil spring ejector and is clamped to the capacitor terminal which also firmly supports the coil spring. This places the fuse pig tail under tension. If the fuse blows, the spring ejects the pig tail and part of the fuse element.

Types of Fuses

- 8 KV type CXP expulsion fuse (for capacitors rated 2400 through 7960 volts). Interrupting rating of 10000 amperes asymmetrical.
- 20 KV type CXP expulsion fuse (for capacitors rated 7961 through 14400 volts). Interrupting rating of 4000 amperes asymmetrical.
- 20 KV type CXP expulsion fuse (for capacitors rated 14401 through 19900 volts). Interrupting rating of 3000 amperes asymmetrical.

The 8 and 20 KV CXP fuses have an energy rating of 30,000 watt-seconds and will accept fuse links up to 100 amperes.

The CXP fuse is normally adequate when the neutral is ungrounded (fault current is equal to three times normal line current) or where there are two or more series groups if the neutral is grounded and where the energy from adjacent parallel units discharging through a faulted unit does not exceed 10,000 watt seconds. (3100 KVAC in paral-

lel per NEMA CPI-1976 Para. 6.07). This fuse uses standard type K fuse links and is refusable. (Selection of fuse link size by Westinghouse and user).

Where the above fuse is not adequate a combination current limiting-expulsion fuse is available.

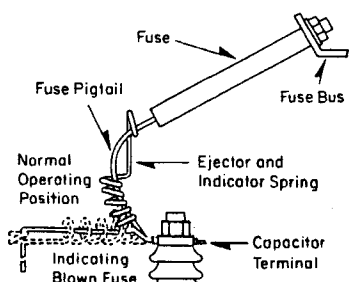
- 2.8 KV type COL for use with capacitors rated 2400 volts.
- 5.5 KV type COL for use with capacitors rated 4160 through 4800 volts.
- 8.3 KV type COL for use with capacitors rated 6640 through 8320 volts.
- 15.5 KV type COL for use with capacitors rated 9540 through 14400 volts.
- 23.0 KV type COL for use with capacitors rated 19920 through 22800 volts.

To calculate stored energy in a single group:

The stored energy at peak rated voltage is 2.64 watt-seconds per KVAC. Stored energy of a capacitor is expressed as:

$$E = \frac{1}{2} CV^2$$

The possibility exists that the fuse may be required to operate during a 10% over-voltage condition.



Typical fuse assembly drawing.



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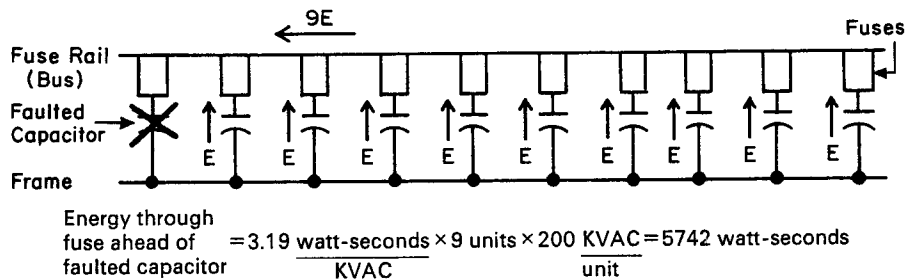
2.4-500 Kv, 300 Kvac and Above
Using 50, 100, 150 or 200 Kvac
Capacitor Units

Stack Type Capacitor Equipments

$E = 2.64 (1.10)^2$ watt-seconds per KVAC
 $E = 3.19$ watt-seconds per KVAC for 10%
overvoltage condition
 $E = 3.80$ watt-seconds per KVAC for 20%
overvoltage condition

Rule: The size and number of capacitors
connected in parallel in any one series group
should not result in more than 10,000 watt-
seconds being liberated into a faulted capa-
citor unit when using an 8 or 20 KV type CXP
expulsion fuse.

Example: 5 series groups, 10 ea. 200 KVAC, 13280 V capacitor units per series group.



Select a 15 Kv type CXP expulsion fuse

Rule: Current limiting type COL fuses should be used when the maximum parallel KVAC exceeds 3100 KVAC.

Step 10 – Accessory Selection (NEMA Ref. CPI-1976)

Elevating Structures

Since most stack type capacitor banks utilize the structural frame of the stacking units as part of the electrical circuit, some precautions are necessary to prevent personnel from accidentally coming into contact with the frame while the bank is energized. One solution is to surround the bank with a fence, the gate of which is interlocked with the bank disconnect means.

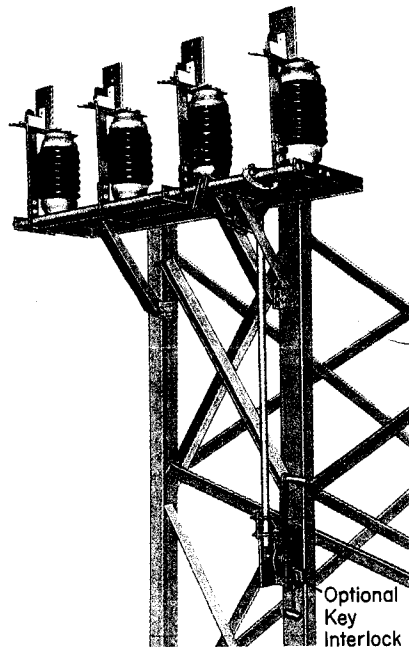
Another solution is to purchase 8 foot elevating substructures. When the base insulation and stacking units are mounted on top of these substructures, all energized parts are raised above the accidental reach of personnel.

Sometimes, both solutions are applied to the same bank particularly when other apparatus besides the capacitor bank may be included within the fenced area.

Elevating structures are supplied to mount directly under the stacking units. The elevating structures must be sized to fit the type of stacking unit design – conventional or edge-mounted.

Grounding Switches For Banks Rated 2.4 Through 34.5 Kv

For capacitor banks up through 34.5 Kv, a 400 ampere, 4 pole, gang-operated switch including operating mechanism can be supplied to short and ground the capacitor line terminals and neutral. The capacitor bank must



include 8-foot elevating substructure or substructures since this device mounts on the substructure. When desired, this shorting and grounding switch can be equipped with a Kirk-Key interlock for interlocking with the capacitor bank's main switch or breaker.

Shorting Switches For Banks Rated 2.4 Through 500 Kv

As a safety measure, before maintenance is attempted, the capacitor bank should be dis-

connected from the line, preferably by means of a visibly open disconnect mounted separate from the capacitor bank. After waiting 5 minutes for the capacitors to drain their charge to a safe value, all buses and the neutral should be shorted to a common point and this point grounded.

Normal procedure may be to use grounding chains or other similar methods to accomplish the shorting and grounding. As an optional item, Westinghouse can provide a simple single pole hookstick operated, knife blade switch (1 for each bus) mounted on stacking unit frame to short the bus to the frame. One single pole grounding switch with appropriate insulation can also be supplied to connect the stacking unit frames to ground.

To restore the capacitor bank to normal service, all shorting and grounding switches must be opened before the main disconnect switch is closed.

Automatic Switching Devices: (NEMA Ref CPI-1976 Para 4.09) Bank Voltages 2.4 Through 34.5 Kv

The following 15 Kv, 23 Kv or 34.5 Kv electrically operated devices may be supplied within their capability for mounting on an 8 foot elevating substructure.

Westinghouse

- 3 ea. – Single phase, 200 amp Westinghouse type CSL oil switches.
- 1 ea. – Three phase, 400 amp Westinghouse type ESC oil switch.
- 1 ea. – Three phase, 600 amp Westinghouse type ESC oil switch.



McGraw-Edison

- 3 ea. – Single phase, 200 amp type NR, 14.4 Kv.
- 3 ea. – Single phase, 200 amp type NRV, 20 Kv.
- 1 ea. – Three phase, 400 amp type VCR, 14.4 Kv.
- 1 ea. – Three phase, 400 amp type VRV, 34.5 Kv.

Joslyn

- 1 ea. – Three phase, 400 amp type VBM, 15 Kv.
- 1 ea. – Three phase, 600 amp type VBM, 15 Kv.
- 1 ea. – Three phase, 300 amp type VBM, 34.5 Kv.
- 1 ea. – Three phase, 400 amp type VBM, 34.5 Kv.
- 1 ea. – Three phase, 600 amp type VBM, 34.5 Kv.

Allis-Chalmers

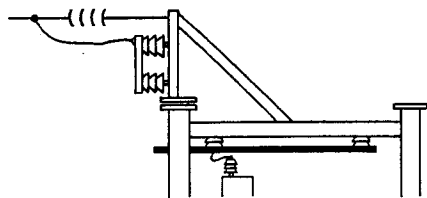
- 1 ea. – Three phase, 300 amp, type VSC-15, or VSC 1-15.
- 1 ea. – Three phase, 300 amp, type VSC-34.

Bank Voltages Above 34.5 Kv

Automatic capacitor switches above 34.5 Kv are not available as part of the capacitor bank.

Bank Isolating Switches And Power Fuses (NEMA Ref. CPI-1976 Para 4.09) General

Power fuses and disconnect switches are normally mounted remotely to the stack type capacitor bank. Upon special request these devices may be mounted above the top stacking unit on an A-Frame.

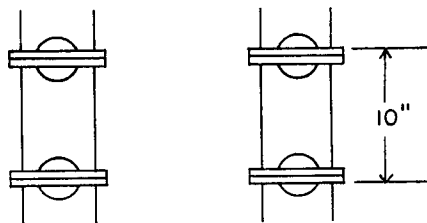


General arrangement of the A-Frame and devices.

Spacers General

On occasion, the user may desire to have the stacking units in one vertical stack further apart than standard. A spacer 10" in height, aluminum or galvanized is available.

10" spacers are required for edge mounted stacking units using 1 series group per stacking unit when arranged 3 stacking units in one vertical stack.



Spacer arrangement

Terminals General

Terminals to connect line leads to individual bus within the stacking unit are not manufactured by Westinghouse. Each user connecting location (bus) is provided with a flat NEMA – 2 hole terminal surface (2 ea. 5/16 inch holes on 1 1/4 inch centers).

Westinghouse will, if requested by user, order terminals from specified manufacturers and have terminals shipped direct from terminal manufacturer to user.

Controls For Capacitor Bank Protection (NEMA Ref CPI-1976 Para 4.10) Relaying Schemes for Detecting Capacitance Unbalance

1. Single Wye bank neutral ungrounded with three potential transformers and voltage relay detecting voltage unbalance. Refer to Figure 20.
2. Single Wye bank neutral ungrounded with three capacitor potential devices and insulating transformer to energize relay for detecting voltage unbalances. The potential devices can be adjusted initially to compensate for slight unbalance in phase capacitances permitting minimum setting of relay. Refer to Fig. 20.
3. Single Wye bank with current transformers and relay between neutral and ground detecting neutral current. Refer to Fig. 21.
4. Single Wye bank with voltage transformer and relay between neutral and ground detecting neutral voltage. Refer to Fig. 22.
5. Double Wye with current transformer and current relay between ungrounded neutrals detecting unbalance current. Refer to Fig. 23. Two relays may be used one to sound an alarm

for fuse operation and other to trip breaker for greater unbalance.

6. Double Wye with current transformer between each neutral and ground with current relay detecting differential neutral current. Two relays may be used: one to sound an alarm for fuse operation, and one to trip breaker for greater unbalance.

7. Double Wye with voltage transformer and voltage relay between ungrounded neutrals detecting unbalance voltage. Refer to Figures 23 and 24.

8. Divided delta bank two current transformers per phase with secondaries connected to a single current relay to detect differential phase current. Refer to Fig. 25.

9. Grounded single Wye bank with three potential transformers, one per phase across series group of capacitors nearest neutral. See Fig. 26.

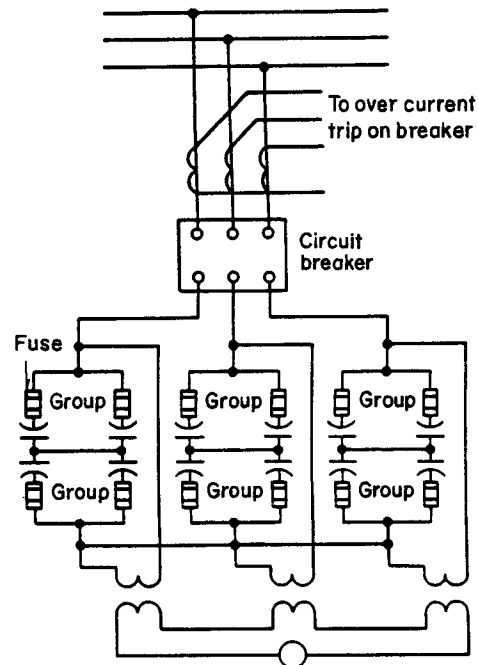


Fig. 20 Capacitor Protection by Voltage Unbalance Between Phases.

The single Wye bank permits minimum size capacitor banks or the maximum number of capacitors in parallel for a given number of series groups. When compared to double Wye or divided Wye of equal size there will be twice the number of capacitors in parallel in each series group of the single Wye bank, consequently less overvoltage is placed on the remaining units when a fuse blows. Grounding the capacitor neutral increases the lightning protection on the bus due to surge absorbing ability of the capacitors.

Westinghouse



Stack Type Capacitor Equipments

2.4-500 Kv, 300 Kvac and Above

Using 50, 100, 150 or 200 Kvac Capacitor Units

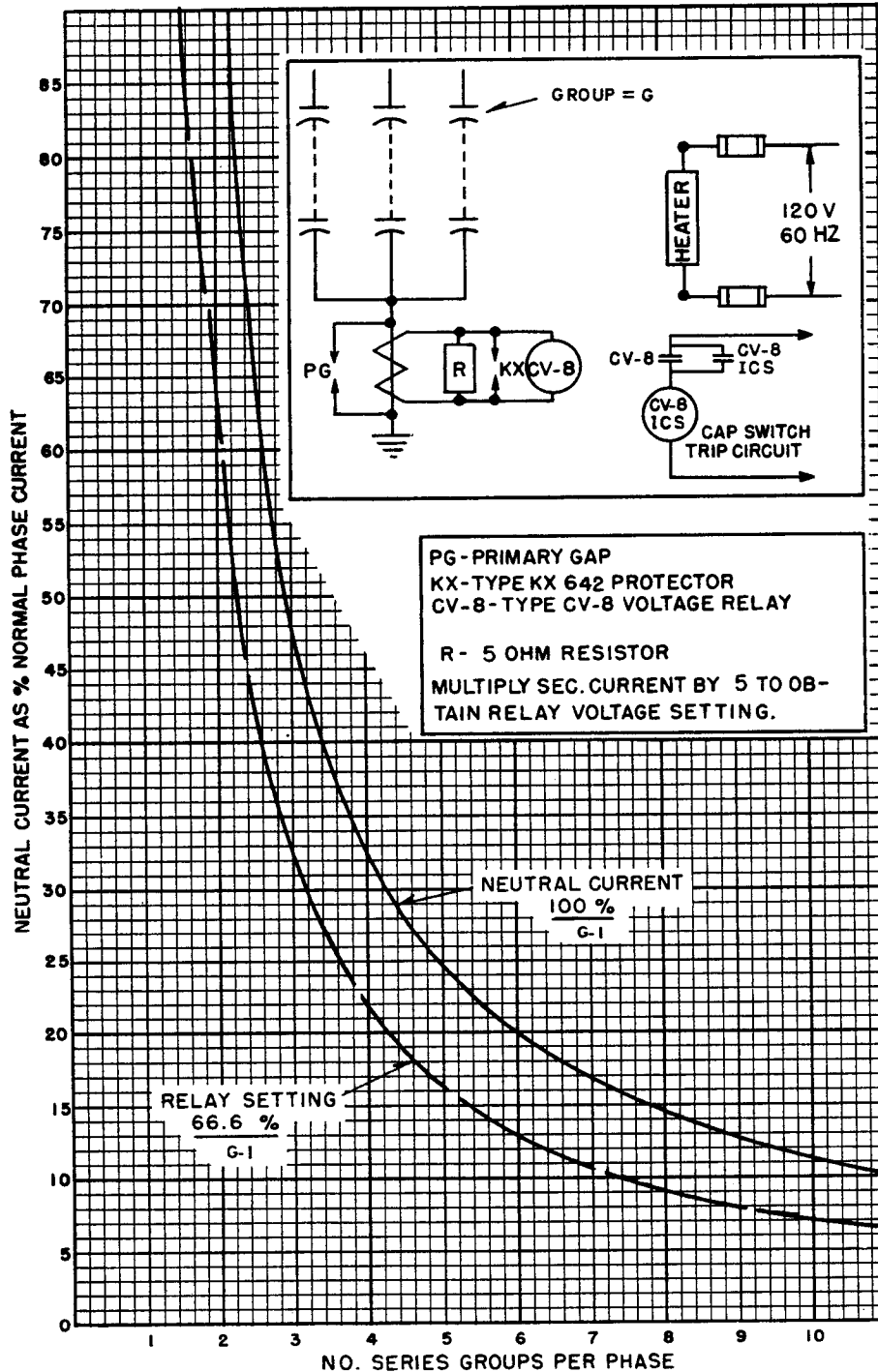


Fig. 21 Capacitor Protection by Neutral Current Detecting Arc-Over or Shorting of One Series Group, Proposed Relay Setting vs Number of Series Groups.

Prices effective November 1, 1973; subject to change without notice.
Selling Policy 39-000

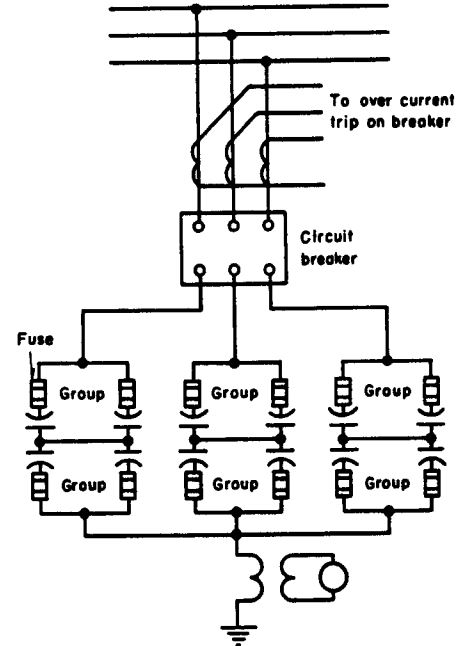


Fig. 22 Capacitor Protection by Voltage Unbalance Between Neutral and Ground.

It is usually not practical to obtain sensitive relay protection by measuring neutral ground current or voltage on a single Wye grounded bank because of the possibility of harmonic currents, variations in phase voltages and system capacitance unbalance that may be expected. This scheme can be used, however, for detecting an arc-over or short in a series group. Its use is based upon the low failure rate of capacitors and maintaining an inspection schedule for blown individual fuses to minimize the possibility of operating capacitors at excessive over voltages.

When the size of the high voltage capacitor bank is not large enough to economically permit dividing into two wye-wye sections then a single wye section with a current transformer and relay in the neutral is often used for detecting an arc-over or short of a series group. When this scheme is used it is necessary to take the calculated risk that an unexpected number of fuse operations will not occur between inspection periods resulting in damage to units from excessive overvoltage. This risk has been judged by some to be economically justified.

November 1, 1973
New Information
E, D, C/2001, 2002/PL

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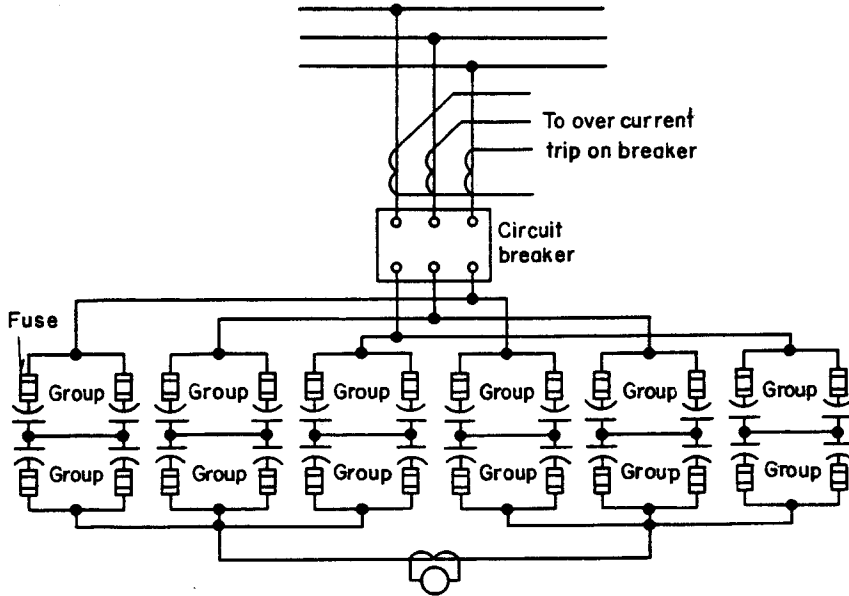


Fig. 23 Capacitor Protection by Unbalance Between Neutrals.

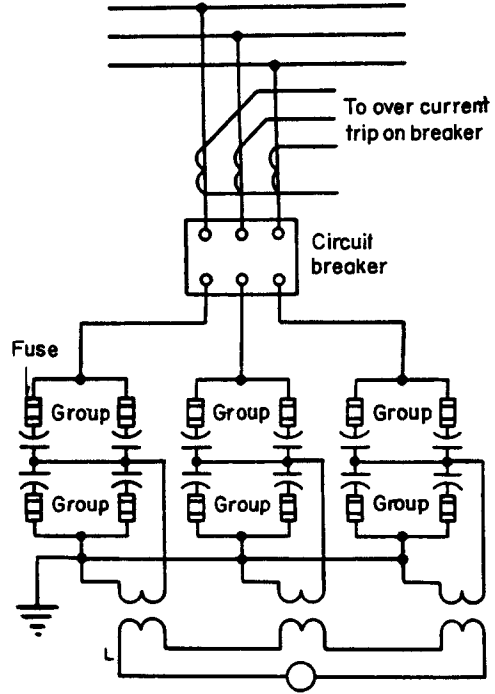


Fig. 26 Capacitor Protection by Voltage Unbalance Between Last Series Group to Neutral and Ground.

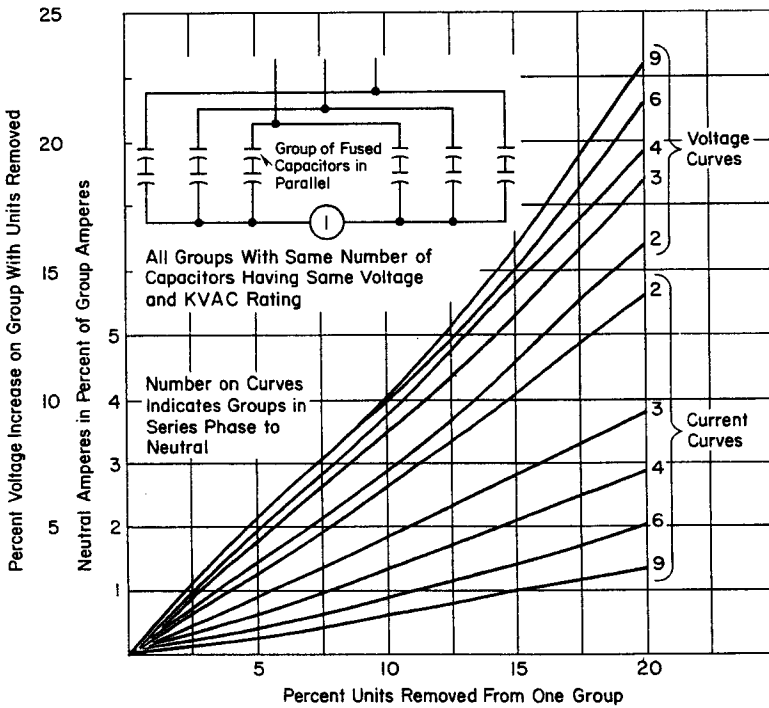


Fig. 24 Ungrounded Wye Bank with Two Equal Wye-Wye Sections - Overvoltages and Neutral Currents with Fuse Operations.

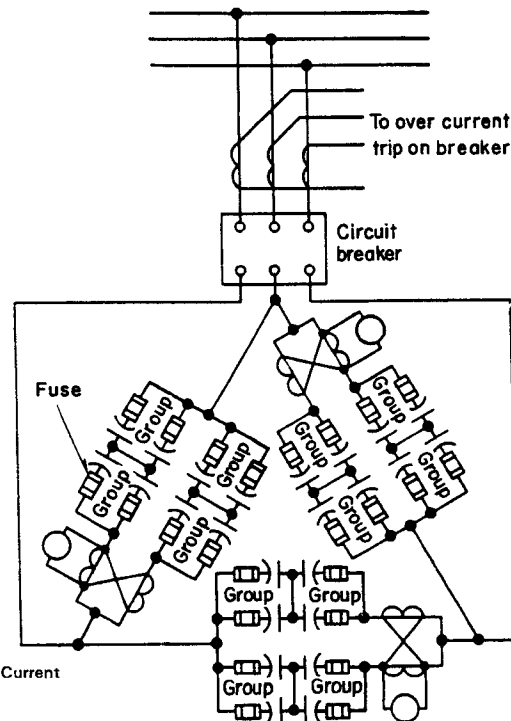


Fig. 25 Capacitor Protection by Differential Current Transformers in Parallel.

IMPROVED PROTECTION SYSTEM INCREASES CAPACITOR-BANK UTILIZATION

On paper, the application of station capacitor banks is a great idea. Capacitor banks maintain voltage, reduce losses, reduce operating costs, and delay the need for building additional transmission lines. Station banks have low switching costs per kvac and they concentrate large numbers of capacitor units where they can be easily inspected.

Unfortunately, a "paper" analysis of station capacitor banks may not make allowances for operating problems. A number of unusual problems have developed as the use of large switched banks has proliferated over the last 15 years. Surge arresters have exploded, insulators have flashed over, and oil circuit breakers have experienced rapid deterioration — to name a few. These problems have been alleviated by the use of switching devices tailored to the application and by developing ways to cope with the voltage and current surges resulting from switching.

The Cascading Failure Problem

A remaining problem in the application of capacitor banks is that of detecting the loss of individual capacitor units so that appropriate action can be taken before remaining capacitor units are subjected to conditions that will lead to a shortened service life. Figure 1 shows the configuration of a simple ungrounded-*Wye* bank consisting of two series groups per phase, each with three capacitor units per series group. Each capacitor unit is individually fused. Loss of a unit with its attendant fuse blowing at (X) increases the impedance of its series group, thereby increasing the voltage

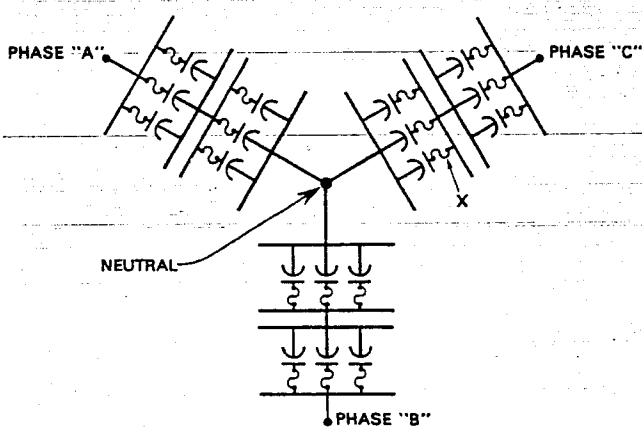


Figure 1. Configuration of simple capacitor bank. Loss of a unit at X causes overvoltage on remaining units in its group.

across the group, and increasing the possibility of failure of the remaining units. It is this increased voltage which has led, in some cases, to a complete failure of all units in one group when the voltage across individual units builds up, as more and more units fail.

The sensitivity of capacitor units to overvoltage is well known, as shown in Figure 2. The life would appear to be indefinite with just under 1.1 per-unit voltage applied. But, since voltage and heat are a capacitor unit's worst enemies, *any* overvoltage may cause a decrease in the life of a unit, and any marginal unit may be pushed beyond the failure point by prolonged exposure to overvoltage. The situation is compounded by the fact that most capacitor banks are not monitored and loss of several units in an unattended station may go unnoticed.

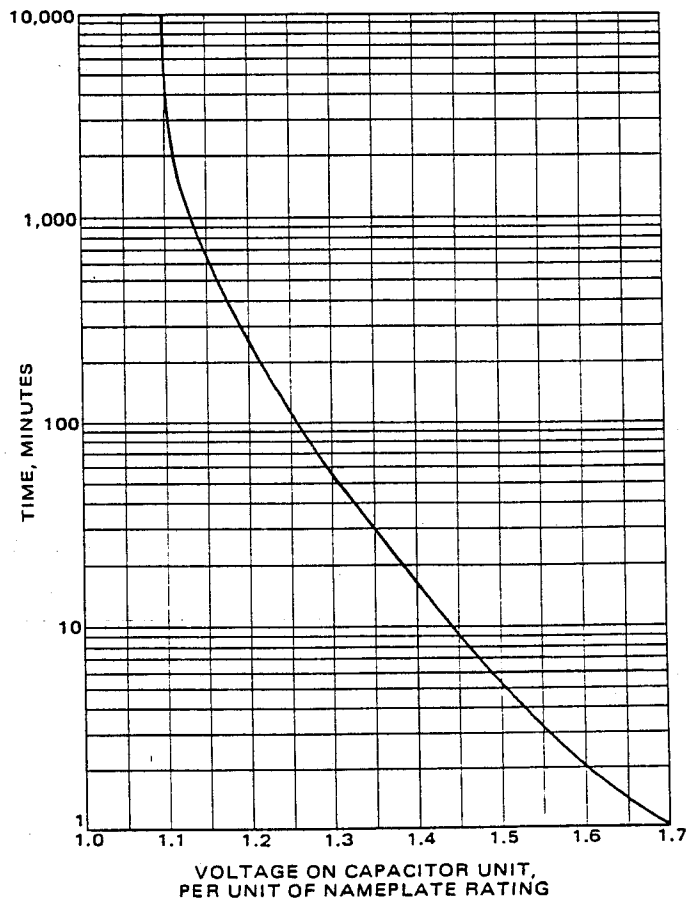


Figure 2. Permissible operating time of capacitor units versus per-unit overvoltage.

Past Approaches to the Prevention of Cascading Failures

Many sensing systems and bank configuration combinations have been used in an attempt to automatically switch the bank out of service before cascading failures occur, with varying degrees of success and with varying problems. The next figures illustrate some of the better-known approaches. Figure 3 shows a split ungrounded-wye capacitor bank from which a control signal is derived by means of a current transformer connected between the neutral (common) connection of each "half" of the capacitor bank. Actually, there are two banks with a common neutral. Removal of a single capacitor unit from either one of the two banks will cause current to flow in the neutral, which can be detected at the current transformer. An inherent advantage of this scheme is that it is unaffected by system voltage unbalance. But this approach may require extra real estate. Also, it can produce capacitor-unit fuse coordination problems due to a reduction of available fault current. And from the automated-control standpoint, the splitting of a bank doubles the voltage increase imposed by an isolated capacitor unit on the remaining capacitor units in a group. For example, an 8100-kvac, 69-kv split bank would have a group voltage of 1.105 per unit upon the loss of the first capacitor unit in the bank — leaving no margin for a warning alarm. Instead, the capacitor bank should be taken out of service. Conversely, the same size capacitor bank "unsplit" would have a group voltage of 1.05 per unit upon the loss of one capacitor unit — leaving sufficient margin for continued operation after a warning alarm.

Some users have chosen smaller capacitor units in an effort to tolerate loss of more than one unit where the bank is split. This is grossly uneconomical. In a typical recent case, use of 100-kvac units raised the price of a 12,000-kvac bank 68 percent over the price of this same bank using 200-kvac units.

Grounded-wye banks can be protected by means of a current transformer in the neutral (Figure 4). However, energization of grounded-wye capacitor banks is unavoidably accompanied by extremely high inrush currents

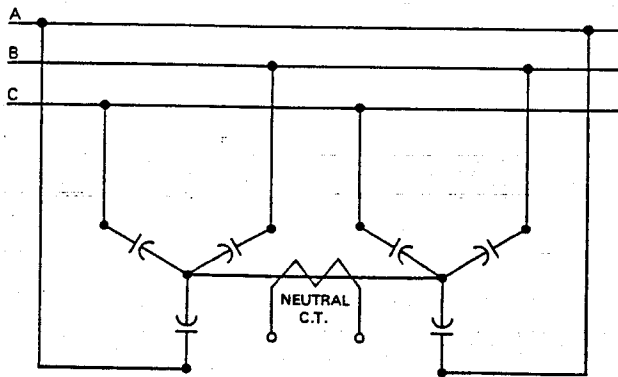


Figure 3. Split ungrounded-wye capacitor bank with current transformer in common neutral.

between the bank neutral and ground — particularly where parallel banks are already energized. Currents can be on the order of thousands of amperes. Various undesirable side effects have been recorded, such as spurious relay operation, charged substation fences, and ground-mat problems. Furthermore, adequate surge protection of the current transformer itself and the sensing equipment connected to its secondary terminals is difficult to achieve. As an alternative, the use of three voltage-sensing devices to measure group voltage has been successful (Figure 5), but the cost can only be justified on extremely large banks.

Finally, some users have applied capacitor units at less than their rated voltage in order to avoid overvoltage stresses and thus to lengthen capacitor-unit life even with one or more units removed from service. Such undervoltage application is costly because a capacitor's reactive effect is a function of the square of the applied voltage. For example, a capacitor unit operating at 90 percent of its nameplate voltage yields only 81 percent of its rated kvac capacity. This practice can be abandoned in favor of full-voltage operation through the use of a protective system capable of sensing the loss of individual capacitor units and removing the bank from service when conditions leading to a cascading failure pattern exist.

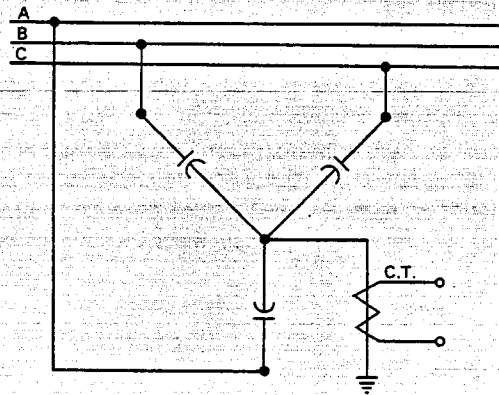


Figure 4. Grounded-wye capacitor bank with neutral-current sensing.

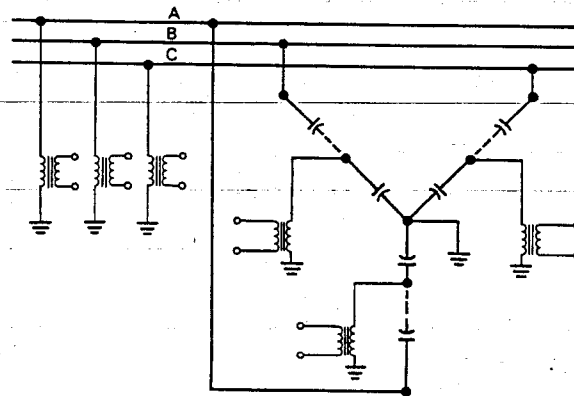


Figure 5. Grounded-wye capacitor bank with group-voltage sensing.

The S&C Protective System for Ungrounded-Wye Banks

Historically, ungrounded capacitor banks have been preferred by many electric utilities because of considerations of telephone influence voltage and because they do not add a contribution to system phase-to-ground fault levels. Therefore, the initial production model of the S&C protective system was designed for ungrounded banks (Figure 6).

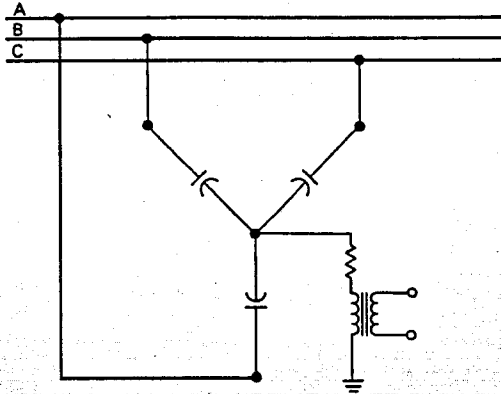


Figure 6. Ungrounded-wye capacitor bank with neutral-voltage sensing.

With ungrounded-wye banks, a voltage appears between the neutral and ground upon the loss of one or more individual capacitor units. This voltage provides the signal to which the protective system responds. Ideally, the protective system should provide an alarm signal upon loss of one capacitor unit and it should provide for removal of the entire bank from service upon loss of capacitor units in numbers such that remaining units are subjected to excessive voltage. To attain this ideal, attention must be given to the design of the capacitor bank itself, as will be shown later.

The S&C protective system comprises the following elements in combination:

1. Individual capacitor-unit fuses to remove faulted units from service.
2. Utilization of the bank-switching Circuit-Switcher for de-energization of the entire bank as directed by the control panel.
3. A resistance-type potential device, connected between the capacitor bank neutral and ground, with an output suitable for use with the control panel.
4. The control panel itself, for sensing the neutral-to-ground voltage and supplying alarm- and switching-signal control.

(While not a part of the system described, power fuses are also employed in most installations for fault protection for the entire bank.)

In operation, the control panel senses the neutral-to-ground voltage resulting from the loss of an individual capacitor unit and provides for activation of a suitable alarm circuit. Assuming that the loss of one capacitor unit does not produce more than a 10-percent overvoltage on the capacitor units remaining in its group, the capacitor bank can continue in operation until repairs are effected. Should additional capacitor units in the same group fail, causing an overvoltage in excess of 10 percent to develop, the control panel will actuate the opening control circuit of the bank-switching Circuit-Switcher to remove the entire bank from service.

The design of the capacitor bank itself is a vital element in making possible the operating sequence just described. Table I summarizes the effects of several different configurations of a 46-kv, 8100-kvac capacitor bank. It can be

TABLE I. ANALYSIS OF CURRENTS AND VOLTAGES FOR VARIOUS CONFIGURATIONS OF A 46-KV, 8100-KVAC CAPACITOR BANK

Capacitor Unit Size, KVAC	Capacitor Unit Voltage, KV	Nominal Voltage Used, Percent	Nominal Kvac Used, Percent	Group Overvoltage, Percent for Loss of			Neutral-to-Ground Voltage, Volts for Loss of			Fuse Current in Faulted Unit, Per Unit	Energy Discharge into Faulted Unit, Joules
				1 Unit	2 Units	3 Units	1 Unit	2 Units	3 Units		
100-KVAC UNITS	19.92	66.66	44.44	-31.8	-30.2	-28.6	150.90	308.82	474.25	45.00	3536.19
	13.28	100.00	99.99	5.0	10.5	16.7	331.98	698.90	1106.59	21.00	3713.00
	12.47	70.97	50.40	-25.8	-22.3	-18.4	171.34	358.89	565.07	23.14	2406.30
	9.96	88.85	79.00	-5.0	2.1	10.3	262.95	565.07	915.80	15.43	2514.62
	7.96	83.41	69.57	-9.5	0.0	11.2	241.44	531.16	885.27	12.00	1845.47
	6.64	100.00	99.99	13.5	31.2	-	358.89	829.94	-	8.40	1856.50
150-KVAC UNITS	19.92	66.66	44.44	-30.0	-28.6	-25.9	228.95	474.25	737.73	30.00	3536.19
	13.28	100.00	99.99	8.0	17.4	28.6	531.16	1154.70	1897.01	13.50	3580.39
	12.47	70.97	50.40	-24.1	-18.4	-11.9	262.95	565.07	915.80	15.43	2406.30
	9.96	88.85	79.00	- 1.5	10.3	25.5	408.59	915.80	1562.24	10.29	2514.62
	7.96	83.41	69.57	- 5.3	9.4	29.8	358.89	829.94	1475.45	8.40	1937.74
	6.64	100.00	99.99	20.0	50.0	-	531.16	1327.91	-	6.00	1989.11
200-KVAC UNITS	19.92	66.66	44.44	-30.2	-26.8	-23.1	308.82	647.76	1021.47	22.50	3536.19
	13.28	100.00	99.99	10.5	23.5	-	698.90	1562.24	-	10.50	3713.00
	12.47	70.97	50.40	-22.3	-14.2	- 4.2	358.89	792.78	1327.91	11.57	2406.30
	9.96	88.85	79.00	2.12	20.0	45.4	565.07	1327.91	2414.37	7.71	2514.62
	7.96	83.41	69.58	0.09	25.1	66.8	531.16	1327.91	2655.81	6.00	1845.47
	6.64	100.00	99.99	26.3	71.4	-	698.90	1897.01	-	4.80	2121.71

quickly seen that only two of the capacitor-unit voltage selections can provide full-rated-voltage operation. Furthermore, only with 100-kvac or 150-kvac capacitor units rated 13.28 kv is the group overvoltage less than 10 percent with one capacitor unit removed. Since economy dictates the use of the largest possible capacitor-unit size, the 150-kvac units would be selected.

Note, however, that 200-kvac capacitor units rated 13.28 kv produce only a 10.5-percent overvoltage upon the loss of one unit. If unscheduled dropping of the entire bank can be tolerated or if the bank is located so that immediate attention can be given upon the loss of one capacitor unit, it is quite possible that the 200-kvac units would be the best choice.

The capacitor bank in the foregoing example is not necessarily representative of banks in general usage, but the analytical procedure is valid for any bank size and voltage. (While the nominal system voltage was used in this example, analyses should always be based on the highest anticipated continuous operating voltage.) As a point of interest, such calculations demonstrate that even the larger banks on the order of 60,000 kvac at 138 kv can be arranged so that the loss of individual capacitor units can be sensed. Table II, for example, shows design parameters for a

138-kv, 60,000-kvac capacitor bank that yields a neutral-to-ground potential of 275 volts upon loss of one capacitor unit.

The first inclination for detecting neutral-voltage displacement might be to use a distribution transformer connected between neutral and ground. The transformer would appear to see very little voltage, so that a reduced-voltage, reduced-BIL unit rated, say, 7200/120 volts might be used. Such a selection is based not only on cost but on a desire for the sensing device to have a low turns ratio in order to obtain adequate sensitivity for sensing the small neutral voltage caused by the loss of one or two units. This has been tried by some users, only to find that the transformer gets into trouble. Analysis has shown (Table III) that a voltage of up to 2.4 times peak system phase-to-neutral voltage can occur between the capacitor-bank neutral and ground during switching of the bank. This will drive the transformer into saturation. The exciting current can easily increase to a hundred times full-load current or more, resulting in disastrous transformer failure. As a solution, a fully rated transformer might be used — but at a higher cost. Unfortunately, this reduces sensitivity to a very low level, as the transformer must sense voltages as low as one or two percent of its rating. This leads to the conclusion that a non-saturating potential measuring device with suitable BIL and adequate sensitivity should be utilized.

TABLE II. DESIGN PARAMETERS FOR A THREE-PHASE UNGROUNDED-WYE CAPACITOR BANK RATED 138 KV, 60,000 KVAC

Nominal Design Criteria	Nominal Capacitance Bank Kvac		60000.00	
	Nominal System Line-to-Line Voltage (kv)		138.00	
	Nominal System Line-to-Neutral Voltage (kv)		79.67	
	Nominal Capacitor-Unit Kvac Rating		200.00	
	Nominal Capacitor-Unit Voltage Rating (kv)		13.28	
	Adjusted Capacitor Bank Kvac		61191.30	
	Normal Current in Each Phase (amps)		256.01	
	Number of Series Groups per Phase		6	
	Number of Capacitor Units in Parallel per Series Group		17	
	Adjusted Capacitor Unit Kvac		199.97	
Adjusted Capacitor Unit Voltage (kv)		13.28		
Nominal Current in Each Capacitor Unit (amps)		15.06		
Capacitor Overvoltage and Neutral Displacement Caused by Loss of Units	Number of Capacitors Removed from Series Groups	Overvoltage P.U. ①	Neutral Voltage	
			P.U. ②	Volts
	0	0.99993	0.00000	0.0
	1	1.05510	0.00345	274.74
	2	1.11671	0.00730	581.56
	3	1.18596	0.01163	926.45
Fuse Current, Energy Discharge, and Capacitor Overvoltage Caused by Faulted Capacitor Unit in Group	Fuse Current for Faulted Capacitor Unit (P.U. ③)		19.13	
	Voltage Across Remaining Capacitor Units Upon Shorting of a Capacitor Unit in One Series Group (P.U. ①)		1.12	
	Max Energy Discharge in Faulted Capacitor Unit (Joules)		9017.29	

① 1 P.U. voltage equals nominal capacitor-unit voltage rating.

② 1 P.U. voltage equals nominal line-to-neutral voltage.

③ 1 P.U. current equals normal current in each capacitor unit. Note: Neglect discharge current from parallel capacitor units in the faulted series group.