2003 Conference for Protective Relay Engineers - Texas A&M University
April 8-10, 2003, College Station (TX)

Shunt Capacitor Bank Fundamentals and Protection

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ABSTRACT

Shunt capacitor banks are used to improve the quality of the electrical supply and the efficient operation of the power system. Studies show that a flat voltage profile on the system can significantly reduce line losses. Shunt capacitor banks are relatively inexpensive and can be easily installed anywhere on the network.

This paper reviews principles of shunt capacitor bank design for substation installation and basic protection techniques. The protection of shunt capacitor bank includes: a) protection against internal bank faults and faults that occur inside the capacitor unit; and, b) protection of the bank against system disturbances.

Section 2 of the paper describes the capacitor unit and how they are connected for different bank configurations. Section 3 discusses bank designs and grounding connections. Bank protection schemes that initiate a shutdown of the bank in case of faults within the bank that may lead to catastrophic failures are presented in Section 4. The paper does not address the means (fuses) and strategies to protect individual elements or capacitor units, nor the protection of capacitor filter banks. System disturbances and basic capacitor bank control strategies are also discussed.

1. INTRODUCTION

Shunt capacitor banks (SCB) are mainly installed to provide capacitive reactive compensation/ power factor correction. The use of SCBs has increased because they are relatively inexpensive, easy and quick to install and can be deployed virtually anywhere in the network. Its installation has other beneficial effects on the system such as: improvement of the voltage at the load, better voltage regulation (if they were adequately designed), reduction of losses and reduction or postponement of investments in transmission.

The main disadvantage of SCB is that its reactive power output is proportional to the square of the voltage and consequently when the voltage is low and the system need them most, they are the least efficient.

2. THE CAPACITOR UNIT AND BANK CONFIGURATIONS

2.1 The Capacitor Unit

The capacitor unit, Fig. 1, is the building block of a shunt capacitor bank. The capacitor unit is made up of individual capacitor elements, arranged in parallel/ series connected groups, within a steel enclosure. The internal discharge device is a resistor that reduces the unit residual voltage to 50V or less in 5 min. Capacitor units are available in a variety of voltage ratings (240 V to 24940V) and sizes (2.5 kvar to about 1000 kvar).

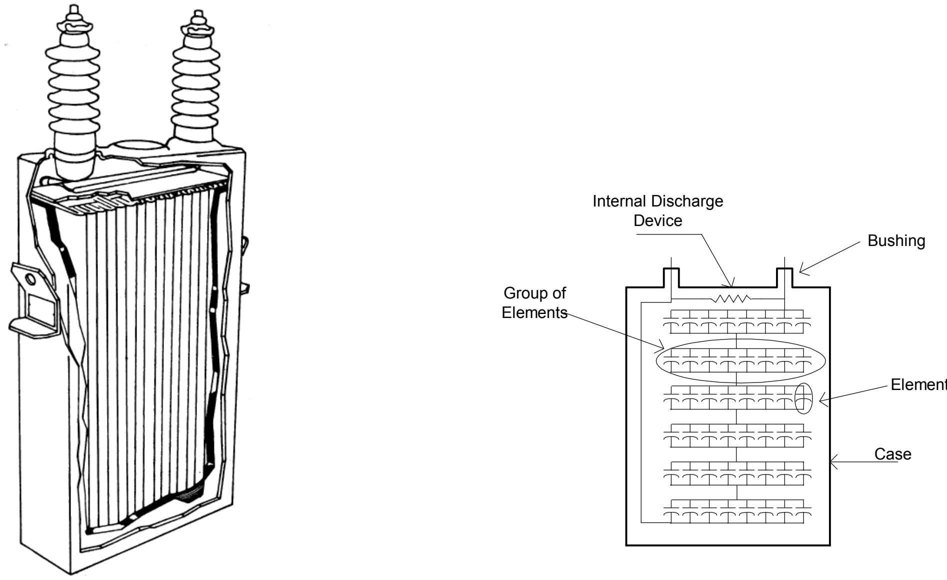


Fig 1 – The capacitor Unit

2.1.1 Capacitor unit capabilities

Relay protection of shunt capacitor banks requires some knowledge of the capabilities and limitations of the capacitor unit and associated electrical equipment including: individual capacitor unit, bank switching devices, fuses, voltage and current sensing devices.

Capacitors are intended to be operated at or below their rated voltage and frequency as they are very sensitive to these values; the reactive power generated by a capacitor is proportional to both of them (kVar $\approx 2\pi f V^2$). The IEEE Std 18-1992 and Std 1036-1992 specify the standard ratings of the capacitors designed for shunt connection to ac systems and also provide application guidelines.

These standards stipulate that:

a) Capacitor units should be capable of continuous operation up to 110% of rated terminal rms voltage and a crest voltage not exceeding 1.2 x $\sqrt{2}$ of rated rms voltage, including harmonics but excluding transients. The capacitor should also be able to carry 135% of nominal current.

b) Capacitors units should not give less than 100% nor more than 115% of rated reactive power at rated sinusoidal voltage and frequency.

c) Capacitor units should be suitable for continuous operation at up to 135%of rated reactive power caused by the combined effects of:
   - Voltage in excess of the nameplate rating at fundamental frequency, but not over 110% of rated rms voltage.
   - Harmonic voltages superimposed on the fundamental frequency.
   - Reactive power manufacturing tolerance of up to 115% of rated reactive power.

2.2 Bank Configurations

The use of fuses for protecting the capacitor units and it location (inside the capacitor unit on each element or outside the unit) is an important subject in the design of SCBs. They also affect the failure mode of the capacitor unit and influence the design of the bank protection. Depending on the application any of the following configurations are suitable for shunt capacitor banks:

a) Externally Fused

An individual fuse, externally mounted between the capacitor unit and the capacitor bank fuse bus, typically protects each capacitor unit. The capacitor unit can be designed for a relatively high voltage because the external fuse is capable of interrupting a high-voltage fault. Use of capacitors with the highest possible voltage rating will result in a capacitive bank with the fewest number of series groups.

A failure of a capacitor element welds the foils together and short circuits the other capacitor elements connected in parallel in the same group. The remaining capacitor elements in the unit remain in service with a higher voltage across them than before the failure and an increased in capacitor unit current. If a second element fails the process repeats itself resulting in an even higher voltage for the remaining elements. Successive failures within the same unit will make the fuse to operate, disconnecting the capacitor unit and indicating the failed one.

Externally fused SCBs are configured using one or more series groups of parallel-connected capacitor units per phase (Fig. 2). The available unbalance signal level decreases as the number of series groups of capacitors is increased or as the number of capacitor units in parallel per series group is increased. However, the kiloVar rating of the individual capacitor unit may need to be smaller because a minimum number of parallel units are required to allow the bank to remain in service with one fuse or unit out.

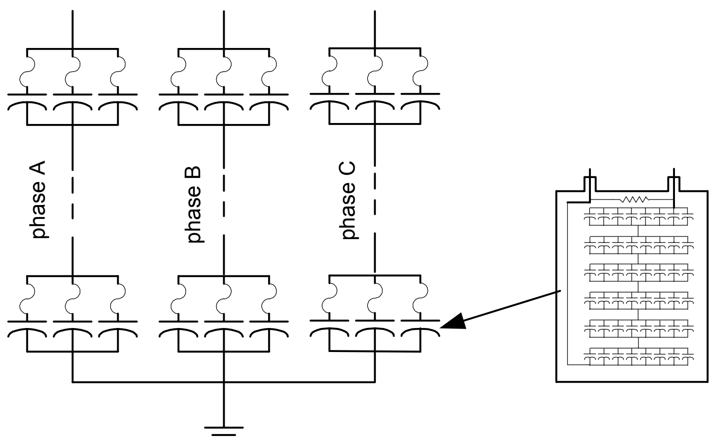


Fig. 2 – Externally fused shunt capacitor bank and capacitor unit

b) Internally Fused

Each capacitor element is fused inside the capacitor unit. The fuse is a simple piece of wire enough to limit the current and encapsulated in a wrapper able to withstand the heat produced by the arc. Upon a capacitor element failure, the fuse removes the affected element only. The other elements, connected in parallel in the same group, remain in service but with a slightly higher voltage across them.

Fig. 3 illustrates a typical capacitor bank utilizing internally fused capacitor units. In general, banks employing internally fused capacitor units are configured with fewer capacitor units in parallel and more series groups of units than are used in banks employing externally fused capacitor units. The capacitor units are normally large because a complete unit is not expected to fail.

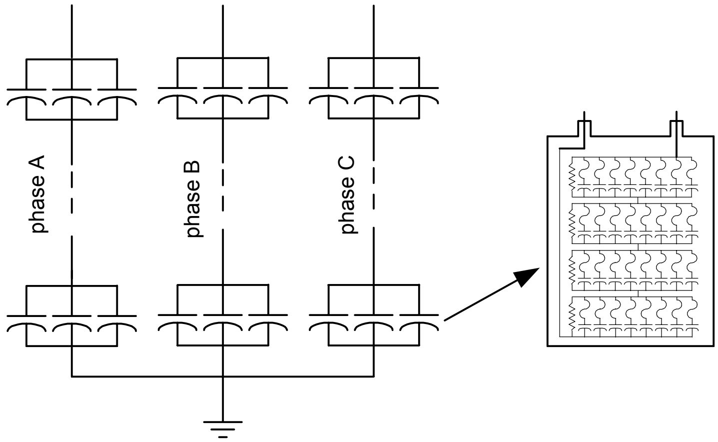


Fig 3 – Internally fused shunt capacitor bank and capacitor unit

c) Fuseless Shunt Capacitor Banks

The capacitor units for fuseless capacitor banks are identical to those for externally fused described above. To form a bank, capacitor units are connected in series strings between phase and neutral, shown in Fig. 4.

The protection is based on the capacitor elements (within the unit) failing in a shorted mode, short- circuiting the group. When the capacitor element fails it welds and the capacitor unit remains in service. The voltage across the failed capacitor element is then shared among all the remaining capacitor element groups in the series. For example, is there are 6 capacitor units in series and each unit has 8 element groups in series there is a total of 48 element groups in series. If one capacitor element fails, the element is shortened and the voltage on the remaining elements is 48/47 or about a 2% increase in the voltage. The capacitor bank continues in service; however, successive failures of elements will lead to the removal of the bank.

The fuseless design is not usually applied for system voltages less than about 34.5 kV. The reason is that there shall be more than 10 elements in series so that the bank does not have to be removed from service for the failure of one element because the voltage across the remaining elements would increase by a factor of about E (E – 1), where E is the number of elements in the string.

The discharge energy is small because no capacitor units are connected directly in parallel. Another advantage of fuseless banks is that the unbalance protection does not have to be delayed to coordinate with the fuses.

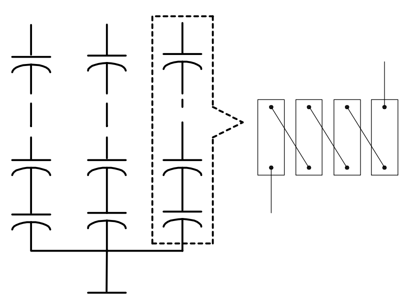


Fig 4 – Fuseless shunt capacitor bank and series string

d) Unfused Shunt Capacitor Banks

Contrary to the fuseless configuration, where the units are connected in series, the unfused shunt capacitor bank uses a series/parallel connection of the capacitor units. The unfused approach would normally be used on banks below 34.5 kV, where series strings of capacitor units are not practical, or on higher voltage banks with modest parallel energy. This design does not require as many capacitor units in parallel as an externally fused bank.

3. CAPACITOR BANK DESIGN

The protection of shunt capacitor banks requires understanding the basics of capacitor bank design and capacitor unit connections. Shunt capacitors banks are arrangements of series/paralleled connected units. Capacitor units connected in paralleled make up a group and series connected groups form a single-phase capacitor bank.

As a general rule, the minimum number of units connected in parallel is such that isolation of one capacitor unit in a group should not cause a voltage unbalance sufficient to place more than 110% of rated voltage on the remaining capacitors of the group. Equally, the minimum number of series connected groups is that in which the complete bypass of the group does not subject the others remaining in service to a permanent overvoltage of more than 110%.

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

The discharge transient from a large number of paralleled capacitors can be severe enough to rupture the failed capacitor unit or the expulsion fuse holder, which may result in damage to adjacent units or cause a major bus fault within the bank. To minimize the probability of failure of the expulsion fuse holder, or rupture of the capacitor case, or both, the standards impose a limit to the total maximum energy stored in a paralleled connected group to 4659 kVar. In order not to violate this limit, more capacitor groups of a lower voltage rating connected in series with fewer units in parallel per group may be a suitable solution. However, this may reduce the sensitivity of the unbalance detection scheme. Splitting the bank into 2 sections as a double Y may be the preferred solution and may allow for better unbalance detection scheme. Another possibility is the use of current limiting fuses.

The optimum connection for a SCB depends on the best utilization of the available voltage ratings of capacitor units, fusing, and protective relaying. Virtually all substation banks are connected wye. Distribution capacitor banks, however, may be connected wye or delta. Some banks use an H configuration on each of the phases with a current transformer in the connecting branch to detect the unbalance.

3.1 Grounded Wye-Connected Banks

Grounded wye capacitor banks are composed of series and parallel-connected capacitor units per phase and provide a low impedance path to ground. Fig. 5 shows typical bank arrangements.

Advantages of the grounded capacitor banks include:

- Its low-impedance path to ground provides inherent self-protection for lightning surge currents and give some protection from surge voltages. Banks can be operated without surge arresters taking advantage of the capability of the capacitors to absorb the surge.
- Offer a low impedance path for high frequency currents and so they can be used as filters in systems with high harmonic content. However, caution shall be taken to avoid resonance between the SCB and the system.
- Reduced transient recovery voltages for circuit breakers and other switching equipment.

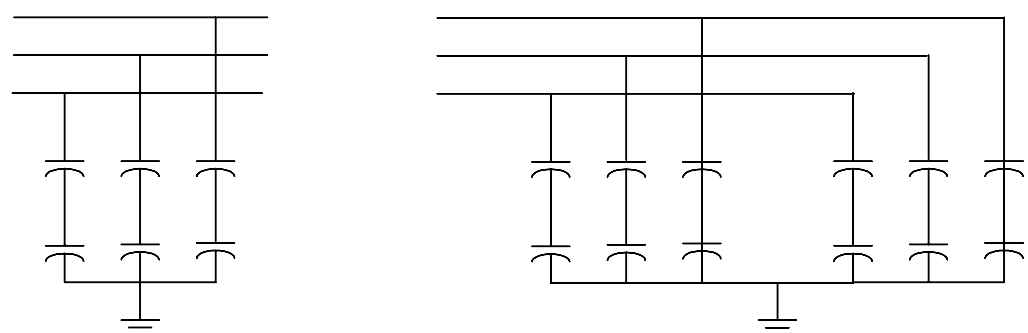
Some drawbacks for grounded wye SCB are:

- Increased interference on telecom circuits due to harmonic circulation.

- Circulation of inrush currents and harmonics may cause misoperations and/or over-operation on protective relays and fuses.
- Phase series reactors are required to reduce voltages appearing on the CT secondary due to the effect of high frequency, high amplitude currents.

Multiple Units in Series Phase to Ground – Double Wye
When a capacitor bank becomes too large, making the parallel energy of a series group too great (above 4650 kvar) for the capacitor units or fuses, the bank may be split into two wye sections. The characteristics of the grounded double wye are similar to a grounded single wye bank. The two neutrals should be directly connected with a single connection to ground.

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



Multiple units grounded single Wye Multiple units grounded double Wye

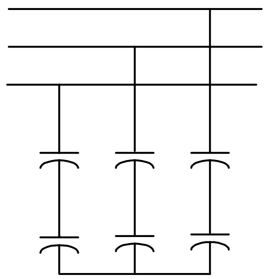
Fig. 5 - Grounded Wye Shunt Capacitor Banks

3.2 Ungrounded Wye-Connected Banks
Typical bank arrangements of ungrounded Wye SCB are shown in Fig. 6. Ungrounded wye banks do not permit zero sequence currents, third harmonic currents, or large capacitor discharge currents during system ground faults to flow. (Phase-to-phase faults may still occur and will result in large discharge currents). Other advantage is that overvoltages appearing at the CT secondaries are not as high as in the case of grounded banks. However, the neutral should be insulated for full line voltage because it is momentarily at phase potential when the bank is switched or when one capacitor unit fails in a bank configured with a single group of units. For banks above 15kV this may be expensive.

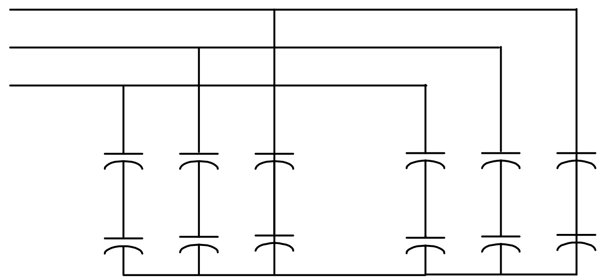
a) Multiple Units in Series Phase to Neutral - Single Wye
Capacitor units with external fuses, internal fuses, or no fuses (fuseless or unfused design) can be used to make up the bank. For unbalance protection schemes that are sensitive to system voltage unbalance, either the unbalance protection time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

b) Multiple units in series phase to neutral-double wye
When a capacitor bank becomes too large for the maximum 4650 kvar per group the bank may be split into two wye sections. When the two neutrals are ungrounded, the bank has some of the

characteristics of the ungrounded single-wye bank. These two neutrals may be tied together through a current transformer or a voltage transformer. As for any ungrounded why bank, the neutral instrument transformers should be insulated from ground for full line-to-ground voltage, as should the phase terminals.



Multiple units ungrounded single Wye



Multiple units ungrounded double Wye

Fig. 6 - Ungrounded Wye Shunt Capacitor Banks

3.3 Delta-connected Banks
Delta-connected banks are generally used only at distributions voltages and are configured with a single series group of capacitors rated at line-to-line voltage. With only one series group of units no overvoltage occurs across the remaining capacitor units from the isolation of a faulted capacitor unit. Therefore, unbalance detection is not required for protection and they are not treated further in this paper.

3.4 H Configuration
Some larger banks use an H configuration in each phase with a current transformer connected between the two legs to compare the current down each leg. As long as all capacitors are normal, no current will flow through the current transformer. If a capacitor fuse operates, some current will flow through the current transformer. This bridge connection can be very sensitive. This arrangement is used on large banks with many capacitor units in parallel.

4. CAPACITOR BANK PROTECTION

The protection of SCB's involves: a) protection of the bank against faults occurring within the bank including those inside the capacitor unit; and, b) protection of the bank against system disturbances and faults.

This paper only discusses relay based protection schemes that provide alarm to indicate an unbalance within the bank and initiate a shutdown of the bank in case of faults that may lead to catastrophic failures. It does not deal with the means and strategies to protect individual elements or capacitor units.

The protection selected for a capacitor bank depends on bank configuration, whether or not the capacitor bank is grounded and the system grounding.

4.1 Capacitor Unbalance Protection
The protection of shunt capacitor banks against internal faults involves several protective devices/ elements in a coordinated scheme. Typically, the protective elements found in a SCB for internal faults are: individual fuses (not discuss in this paper), unbalance protection to provide alarm/ trip and overcurrent elements for bank fault protection.

Removal of a failed capacitor element or unit by its fuse results in an increase in voltage across the remaining elements/ units causing an unbalance within the bank. A continuous overvoltage (above 1.1pu) on any unit shall be prevented by means of protective relays that trip the bank. Unbalance protection normally senses changes associated with the failure of a capacitor element or unit and removes the bank from service when the resulting overvoltage becomes excessive on the remaining healthy capacitor units.

Unbalance protection normally provides the primary protection for arcing faults within a capacitor bank and other abnormalities that may damage capacitor elements/ units. Arcing faults may cause substantial damage in a small fraction of a second. The unbalance protection should have minimum intentional delay in order to minimize the amount of damage to the bank in the event of external arcing.

In most capacitor banks an external arc within the capacitor bank does not result in enough change in the phase current to operate the primary fault protection (usually an overcurrent relay) The sensitivity requirements for adequate capacitor bank protection for this condition may be very demanding, particularly for SBC with many series groups. The need for sensitive resulted in the development of unbalance protection where certain voltages or currents parameters of the capacitor bank are monitored and compared to the bank balance conditions.

Capacitor unbalance protection is provided in many different ways, depending on the capacitor bank arrangement and grounding. A variety of unbalance protection schemes are used for internally fused, externally fused, fuseless, or unfused shunt capacitor.

a) Capacitor Element Failure Mode

For an efficient unbalance protection it is important to understand the failure mode of the capacitor element. In externally fused, fuseless or unfused capacitor banks, the failed element within the can is short-circuited by the weld that naturally occurs at the point of failure (the element fails short-circuited). This short circuit puts out of service the whole group of elements, increasing the voltage on the remaining groups. Several capacitor elements breakdowns may occur before the external fuse (if exists) removes the entire unit. The external fuse will operate when a capacitor unit becomes essentially short circuited, isolating the faulted unit.

Internally fused capacitors have individual fused capacitor elements that are disconnected when an element breakdown occurs (the element fails opened). The risk of successive faults is minimized because the fuse will isolate the faulty element within a few cycles. The degree of unbalance introduced by an element failure is less than that which occurs with externally fused units (since the amount of capacitance removed by blown fuse is less) and hence a more sensitive unbalance protection scheme is required when internally fused units are used.

b) Schemes with Ambiguous Indication

A combination of capacitor elements/ units failures may provide ambiguous indications on the conditions of the bank. For instance, during steady state operation, negligible current flows through the current transformer between the neutrals of an ungrounded wye-wye capacitor bank for a balanced bank, and this condition is correct. However, the same negligible current may flow through this current transformer if an equal number of units or elements are removed from the same phase on both sides of the bank (Fig. 7). This condition is undesirable, and the indication is obviously ambiguous.

Where ambiguous indication is a possibility, it is desirable to have a sensitive alarm (preferably one fuse operation for fused banks or one faulted element for fuseless or unfused banks) to minimize the probability of continuing operation with canceling failures that result in continuing, undetected overvoltages on the remaining units.

It may also be desirable to set the trip level based on an estimated number of canceling failures in order to reduce the risk of subjecting capacitor units to damaging voltages and requiring fuses to operate above their voltage capability when canceling failures occur.

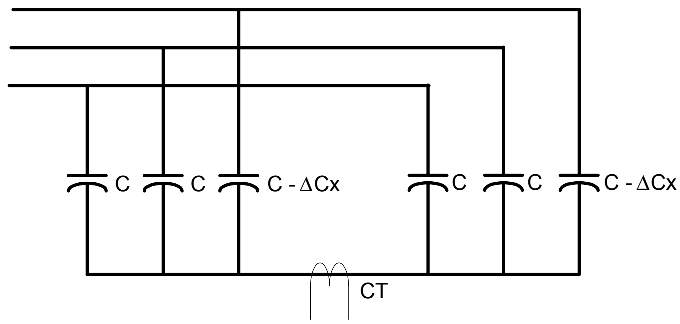


Fig. 7 – Compensating failures in the same phase result in no unbalance signal

c) Undetectable Faults

For certain capacitor bank configurations some faults within the bank will not cause an unbalance signal and will go undetected. For example: a) rack-to-rack faults for banks with two series groups connected phase-over-phase and using neutral voltage or current for unbalance protection; and, b) rack-to-rack faults for certain H-bridge connections.

d) Inherent Unbalance and System Unbalance

In practice, the unbalance seen by the unbalance relay is the result of the loss of individual capacitor units or elements and the inherent system and bank unbalances. The primary unbalance, which exists on all capacitor bank installations (with or without fuses), is due to system voltage unbalance and capacitor manufacturing tolerance. Secondary unbalance errors are introduced by sensing device tolerances and variation and by relative changes in capacitance due to difference in capacitor unit temperatures in the bank.

The inherent unbalance error may be in the direction to prevent unbalance relay operation, or to cause a false operation. The amount of inherent unbalance for various configurations may be estimated using the equations provided in reference (1).

If the inherent unbalance error approaches 50% of the alarm setting, compensation should be provided in order to correctly alarm for the failure of one unit or element as specified. In some cases, a different bank connection can improve the sensitivity without adding compensation. For example, a wye bank can be split into a wye-wye bank, thereby doubling the sensitivity of the protection and eliminating the system voltage unbalance effect.

A neutral unbalance protection method with compensation for inherent unbalance is normally required for very large banks. The neutral unbalance signal produced by the loss of one or two individual capacitor units is small compared to the inherent unbalance and the latter can no longer be considered negligible. Unbalance compensation should be used if the inherent unbalance exceeds one half of the desired setting.

Harmonic voltages and currents can influence the operation of the unbalance relay unless power frequency band-pass or other appropriate filtering is provided.

e) Unbalance Trip Relay Considerations

The time delay of the unbalance relay trip should be minimized to reduce damage from an arcing fault within the bank structure and prevent exposure of the remaining capacitor units to overvoltage conditions beyond their permissible limits.

The unbalance trip relay should have enough time delay to avoid false operations due to inrush, system ground faults, switching of nearby equipment, and non-simultaneous pole operation of the energizing switch. For most applications, 0.1s should be adequate. For unbalance relaying systems that would operate on a system voltage unbalance, a delay slightly longer than the upstream protection fault clearing time is required to avoid tripping due to a system fault. Longer delays increase the probability of catastrophic bank failures.

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

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

f) Unbalance Alarm Relay Considerations
To allow for the effects of inherent unbalance within the bank, the unbalance relay alarm should be set to operate at about one-half the level of the unbalance signal determined by the calculated alarm condition based on an idealized bank. The alarm should have sufficient time delay to override external disturbances.

4.1.1 Unbalance Protection Methods for Ungrounded Wye Banks

a) Unbalance Protection for Ungrounded Single Wye Banks
The simplest method to detect unbalance in single ungrounded Wye banks is to measure the bank neutral or zero sequence voltage. If the capacitor bank is balanced and the system voltage is balance the neutral voltage will be zero. A change in any phase of the bank will result in a neutral or zero sequence voltage.

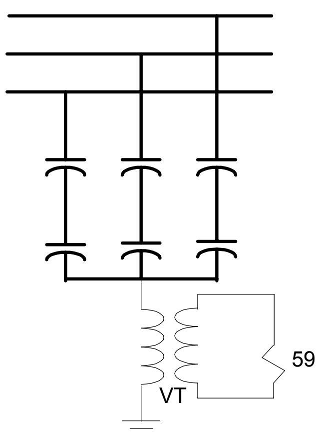


Fig. 8 (a)

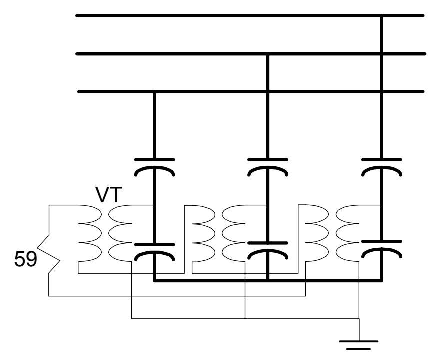


Fig. 8 (b)

Fig. 8 (a) shows a method that measures the voltage between capacitor neutral and ground using a VT and an overvoltage relay with 3th harmonic filter. It is simple but suffers in presence of system voltage unbalances and inherent unbalances. The voltage-sensing device is generally a voltage transformer but it could be a capacitive potential device or resistive potential device. The voltage-sensing device should be selected for the lowest voltage ratio attainable, while still being able to withstand transient and continuous overvoltage conditions to obtain the maximum unbalance detection sensitivity. However, a voltage transformer used in this application should be rated for full system voltage because the neutral voltage can under some conditions rise to as high as 2.5 per unit during switching.

An equivalent zero sequence component that eliminate the system unbalances can be derived utilizing three voltage-sensing devices with their high side voltage wye-connected from line to ground, and the secondaries connected in a broken delta. The voltage source VTs can be either at a tap in the capacitor bank or used the VTs of the bank bus.

Figs. 8 (b) shows a neutral unbalance relay protection scheme for an ungrounded wye capacitor bank, using three phase-to-neutral voltage transformers with their secondaries connected in broken delta to an overvoltage relay. Compared to the scheme in Fig. 8(a), this scheme has the advantage of not being sensitive to system voltage unbalance. Also, the unbalance voltage going to the overvoltage relay is three times the neutral voltage as obtained from Fig 8(a). For the same voltage transformer ratio, there is a gain of three in sensitivity over the single neutral-to-ground voltage transformer scheme. The voltage transformers should be rated for line-to-line voltage.

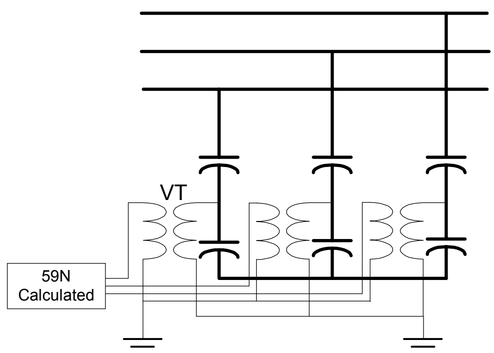


Fig. 9 (a)

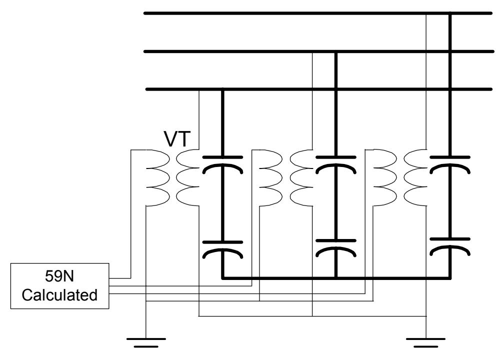


Fig. 9 (b)

Modern digital relays can calculate the zero sequence voltage from the phase voltages as shown in Fig 9 (a), eliminating the need of additional auxiliary VTs to obtain the zero sequence voltage. Fig 9 (b) shows the same principle but using the VTs on the capacitor bank bus. Although schemes shown in Fig 8(b), 9(a) and 9(b) eliminate system unbalances, they do not eliminate the inherent capacitor unbalance.

Fig. 10 shows a protection scheme that removes the system unbalance and compensate for the inherent capacitor unbalance. It is a variation of the voltage differential scheme for grounded banks described in section 4.1.2 c). The best method to eliminate the system unbalance is to split the bank in two Wyes; however, it may not be always possible or desirable. The system unbalance appears as a zero sequence voltage both at the bank terminal and at the bank neutral. The bank terminal zero sequence component is derived from 3 line VTs with their high side Wye connected and their secondaries connected in broken delta. The difference voltage between the neutral unbalance signal due to system unbalance and the calculated zero sequence from the terminal VTs will be compensated for all conditions of system unbalance. The remaining error appearing at the neutral due to manufacturers capacitor tolerance is then compensated for by means of a phase shifter.

b) Unbalance Protection for Ungrounded Double Wye Banks

Ungrounded banks can be split into two equal banks. This bank configuration inherently compensates for system voltage unbalances; however, the effects of manufacturers capacitor tolerance will affect relay operation unless steps are taken to compensate for this error.

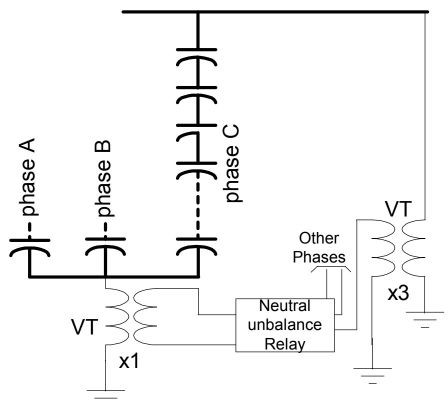


Fig. 10 – Compensated Neutral Voltage Unbalance method

Three methods of providing unbalance protection for double wye ungrounded banks are presented. Fig. 11(a) uses a current transformer on the connection of the two neutrals and an overcurrent relay (or a shunt and a voltage relay). Fig. 11(b) uses a voltage transformer connected between the two neutrals and an overvoltage relay. The effect of system voltage unbalances are avoided by both schemes, and both are unaffected by third harmonic currents or voltages when balanced. The current transformer or voltage transformer should be rated for system voltage.

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

Although a low-ratio voltage transformer would be desirable, a voltage transformer rated for system voltage is required for the ungrounded neutral. Therefore, a high turns ratio should be accepted.

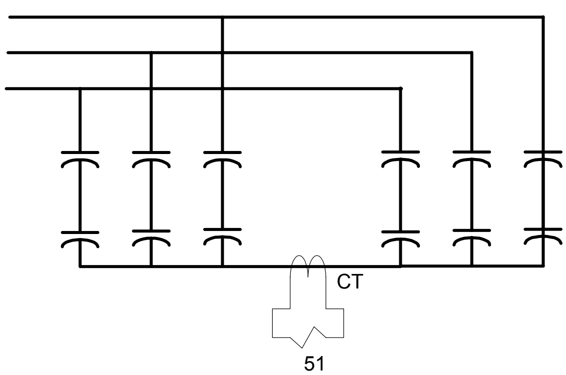


Fig.11 (a)

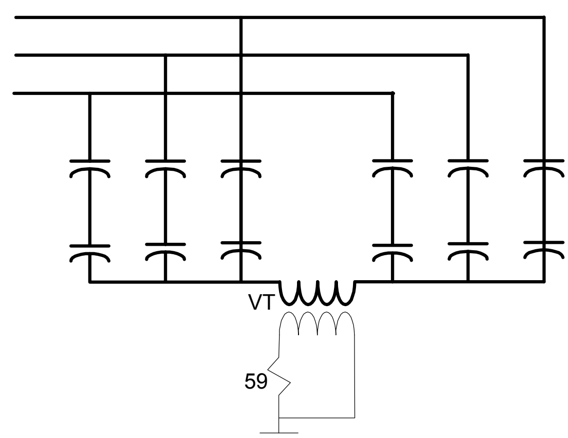


Fig. 11 (b)

Fig. 12 shows a scheme where the neutrals of the two capacitor sections are ungrounded but tied together. A voltage transformer, or potential device, is used to measure the voltage between the capacitor bank neutral and ground. The relay should have a harmonic filter.

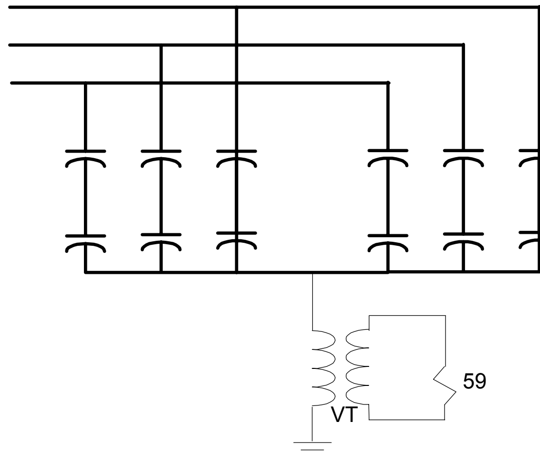


Fig. 12

4.1.2 Unbalance Protection Methods for Grounded Wye Banks

a) Unbalance Protection for Grounded Single Wye Banks

An unbalance in the capacitor bank will cause current to flow in the neutral. Fig. 13 (a) shows a protection based on a current transformer installed on the connection between the capacitor bank neutral and ground. This current transformer has unusual high overvoltage and current requirements. The ratio is selected to give both adequate overcurrent capability and appropriate signal for the protection.

The current transformer output has a burden resistor and a sensitive voltage relay. Because of the presence of harmonic currents (particularly the third, a zero sequence harmonic that flows in the neutral-to-ground connection), the relay should be tuned to reduce its sensitivity to frequencies other than the power frequency.

The voltage across the burden resistor is in phase with the neutral-to-ground current. This neutral-to-ground current is the vector sum of the three-phase currents, which are 90° out of the phase with the system phase-to-ground voltages. This scheme may be compensated for power system voltage unbalances, by accounting for the 90° phase shift, and is not unusually appropriate for very large capacitor banks requiring very sensitive settings.

Each time the capacitor bank is energized, momentary unbalanced capacitor charging currents will circulate in the phases and in the capacitor neutral. Where a parallel bank is already in service these current can be on the order of thousands Amps causing the relay to maloperate and CT to fail.

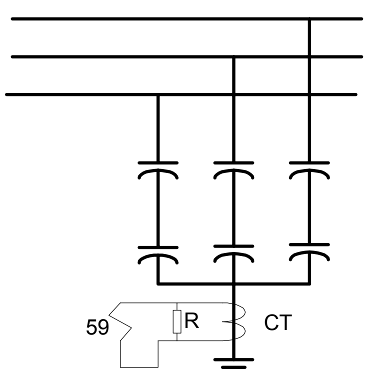


Fig. 13 (a)

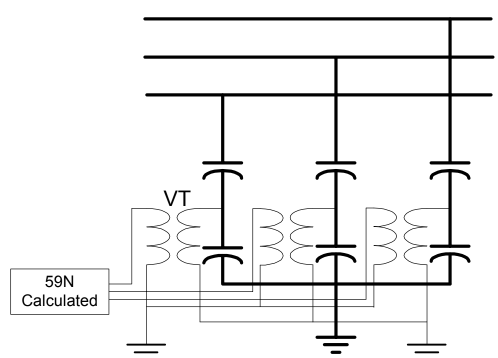


Fig. 13(b)

Fig.13 (b) presents an unbalance voltage protection scheme for single grounded wye connected SCB's 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 protection scheme consists of a voltage sensing device connected between the capacitor intermediate point and ground on each phase. A time delay voltage relay with third harmonic filter is connected to the broken delta secondaries. Modern digital relays use the calculated zero sequence voltage instead as shown in Fig. 13(b).

b) Unbalance Protection for Grounded Double Wye Banks

Fig. 14 shows a scheme where a current transformer is installed on each neutral of the two sections of a double Why SCB. The neutrals are connected to a common ground. The current transformer secondaries are cross-connected to an overcurrent relay so that the relay is insensitive to any outside condition that affects both sections of the capacitor bank in the same direction or manner. The current transformers can be subjected to switching transient currents and, therefore, surge protection is required. They should be sized for single-phase load currents if possible. (Alternatively, the connections from neutral to ground from the two wyes may be in opposite directions through a single-window current transformer).

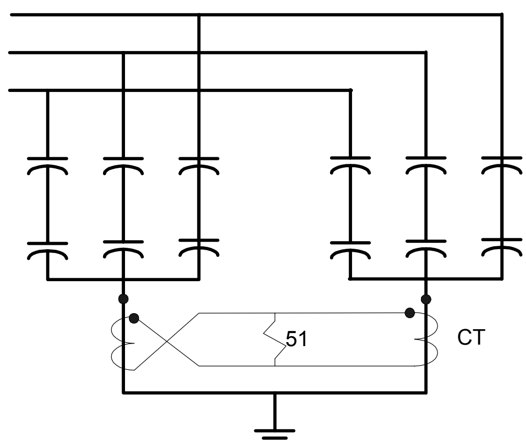


Fig. 14

c) Voltage differential protection method for grounded wye banks

On large SCBs with large number of capacitor units, it is very difficult to detect the loss of 1 or 2 capacitor units as the signal produced by the unbalance is buried in the inherent bank unbalance. The voltage differential provides a very sensitive and efficient method to compensate for both system and inherent capacitor bank unbalances in grounded wye capacitor banks. Fig. 16 shows the voltage differential scheme for a single wye-connected bank and Fig. 16 for a double wye-connected bank.

The scheme uses two voltage transformers per phase: one connected to a tap on the capacitor bank; the other, at the bank bus for single Wye banks; or, for double Wye banks, at a similar tap on the second bank. By comparing the voltages of both VTs, a signal responsive to the loss of individual capacitor elements or units is derived.

The capacitor bank tap voltage is obtained by connecting a voltage-sensing device across the ground end parallel group (or groups) of capacitors. This may be a midpoint tap, where the voltage is measured between the midpoint of the phase and ground. Alternatively, the tap voltage may be measured across low-voltage capacitors (that is, a capacitive shunt) at the neutral end of the phase.

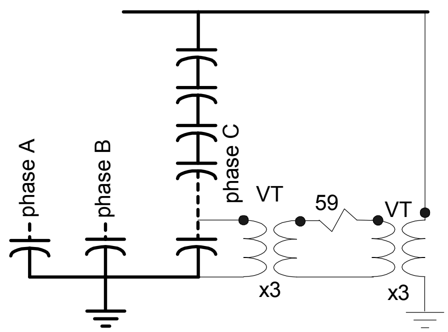


Fig. 15 – Voltage Differential Scheme for Grounded Single Wye SCB

For commissioning, after checking that all capacitors are good and no fuses have operated, the voltage levels are initially adjusted to be equal. The initial difference signal between the capacitor bank tap voltage and the bus voltage (for single Wye banks) signals is zero, and the capacitor tolerance and initial system voltage unbalance is compensated. If the system voltage unbalance should vary, the relay system is still compensated because 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. For double Wye banks, the tap voltage is compared the other Wye tap voltage.

Modern digital relay dynamically compensate secondary errors introduced by sensing device variation and temperature differences between capacitor units within the bank.

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

Tapping across the bottom series groups or a midpoint tap is not appropriate for fuseless banks with multiple strings because the strings are not connected to each other at the tap point. Tapping across the low-voltage capacitors is suitable for fuseless capacitor banks.

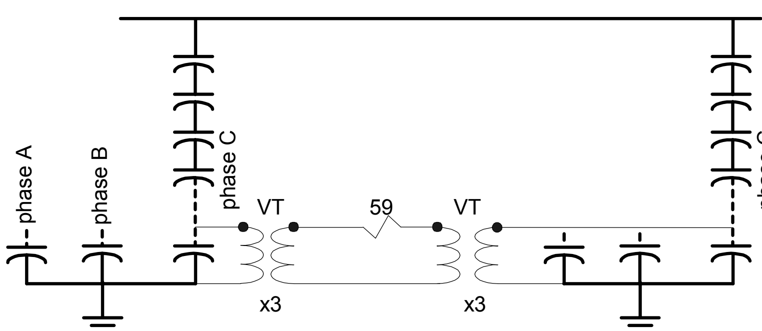


Fig. 16 – Voltage Differential Scheme for Grounded Double Wye SCB

4.2 Protection against Other Internal Bank Faults

The are certain faults within the bank that the unbalance protection will not detect or other means are required for its clearance.

a) Mid-Rack Phase to Phase Faults
Usually individual phases of a SCB are built on separate structures where phase to phase faults are unlikely. However, consider an ungrounded single Wye capacitor bank with two series groups per phase where all three phases are installed upon a single steel structure. A mid-rack fault between 2 phases as shown in Fig. 17 is possible and will go undetected. This fault does not cause an unbalance of the neutral voltage (or neutral current if grounded) as the healthy voltage is counter balance by the 2 other faulty phase voltages.

The most efficient protection for mid-rack phase to phase faults is the negative sequence current. Tripping shall be delayed to coordinate with other relays in the system.

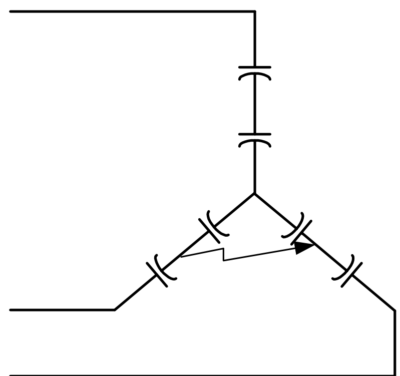


Fig. 17 – Mid-rack Fault

b) Faults on the Capacitor Bank Bus
Time overcurrent relays for phase and ground are required to provide protection for phase and ground faults on the connecting feeder (or buswork) between the bank bus and the first capacitor unit. Directional overcurrent relays looking into the bank are preferred to avoid maloperation of the TOC 51N for unbalance system faults.

4.3 Protection of the SCB Against System Disturbances and Faults

4.3.1 System Overvoltage Protection
The capacitor bank may be subjected to overvoltages resulting from abnormal system operating conditions. If the system voltage exceeds the capacitor capability the bank should be removed from service. The removal of the capacitor bank lowers the voltage in the vicinity of the bank reducing the overvoltage on other system equipment. Time delayed or inverse time delayed phase overvoltage relays are used.

4.4 Relays for Bank Closing Control
Once disconnected from the system a shunt capacitor bank cannot be re-inserted immediately due to the electrical charge trapped within the capacitor units, otherwise catastrophic damage to the circuit breaker or switch can occur. To accelerate the discharge of the bank, each individual capacitor unit has a resistor to discharge the trapped charges within 5min.

Undervoltage or undercurrent relays with timers are used to detect the bank going out of service and prevent closing the breaker until the set time has elapsed.

5. CONCLUSIONS

The protection of shunt capacitor banks uses simple, well known relaying principles such as overvoltage, overcurrents. However, it requires the protection engineer to have a good understanding of the capacitor unit, its arrangement and bank design issues before embarking in its protection.

Unbalance is the most important protection in a shunt capacitor bank, as it provides fast and effective protection to assure a long and reliable life for the bank. To accomplish its goal, unbalance protection requires high degree of sensitivity that might be difficult to achieve.

The main concepts for the design of a shunt capacitor bank and its protection have been reviewed in the paper. The latest IEEE Guide for the Protection of Shunt Capacitors Banks shall be the guiding document when implementing a protection scheme to a shunt capacitor bank.

References:
(1) IEEE Std C37.99-2000, IEEE Guide for the Protection of Shunt Capacitors Banks

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