Modern Capacitor Bank Protection Methods

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ABSTRACT

Capacitor banks add necessary VAr support to the power system, promoting efficient energy transfer and reducing costs of building large transmission lines. It is a significant challenge to protect capacitor banks effectively. This paper discusses various methods to protect capacitor banks, including voltage differential (87V), neutral-voltage unbalance (59NU), phase-current unbalance (60P), and neutral-current unbalance (60N). Included is a discussion on various capacitor-bank arrangements, details of staged protection, and application of differential-slope principles. Real-world examples illustrate these protection concepts.

I. Introduction

Shunt capacitor banks (SCBs) provide capacitive, reactive compensation and power-factor correction. SCBs improve the power-system voltage profile, provide better voltage regulation, reduce system losses, and postpone investments in transmission and generation facilities.

SCBs strengthen the power system, preventing blackouts and adding reactive power VAr support for the increased penetration of distributed generation wind farms. Capacitor banks are valuable assets used daily in system operation and must provide reliable operation through abnormal power-system scenarios.

Protection for SCBs must avoid false tripping for system disturbances while providing sufficient sensitivity to detect capacitor can faults and minimizing SCB damage.

SCBs have numerous, separate capacitor cans in series and parallel connections. A capacitor bank can operate with many capacitor-can failures. Typically, operations personnel continue to run the SCB after one or more capacitor cans have been removed temporarily (bank is scheduled for can replacement to restore the bank to full operation). This situation creates unbalances. Modern capacitor bank protection requires a reliable and sensitive relay that can deliver adequate protection during an inherent unbalance in the protected bank, as well as system unbalances.

Many custom applications and dedicated capacitor-bank protection relays compensate for inherent unbalance based on subtracting historical values from the operating quantities, making the relay respond to incremental, “delta” signals. The modern capacitor-bank protection relay employs dynamic compensation for unbalances among the power-system phase voltages. These differences are constantly changing and can be 2 percent or more during normal conditions, and tens of percent during major system events such as close-in faults. This protection method compensates simultaneously for the bank inherent unbalance and system unbalance, increasing both sensitivity and security of protection.

Modern capacitor-bank protection features auto-setting and self-tuning applications. Auto-setting is calculating new accurate relay constants to account for the inherent bank unbalances following bank repair and is performed in response to the user’s request and under user supervision. Self-tuning is an operation of constantly adjusting the balancing constants to maintain optimum protection sensitivity when bank reactances change slowly (in response to seasonal temperature variations and other conditions). Self-tuning applications require monitoring total changes in the balancing constants to detect slow failure modes and account for small changes that do not trigger alarms.

II. Capacitor and capacitor-bank fundamentals and operation

Relay protection of shunt capacitor banks requires knowledge of the capabilities and limitations of the capacitor unit and associated electrical equipment including bank switching devices, fuses (if present), and voltage and current sensing devices.

a) Capacitor can capabilities

The reactive power generated by a capacitor is proportional to both the applied voltage and frequency ($\text{kVAr} \approx 2\pi\ f\ V^2$). Capacitors are operated at or less than the rated voltage and frequency to prevent mechanical damage. IEEE Std 18-2012 [1] specifies voltage and frequency ratings for shunt capacitor bank connection to AC systems and provide application guidelines.

These standards specify the following parameters that apply to protection:

- Capacitor units should not give less than 100% and not more than 115% of rated reactive power at rated sinusoidal voltage and frequency
- Capacitor units should be capable of continuous operation to 110% of rated terminal RMS voltage and a crest voltage not exceeding 1.2 x √2 of rated RMS voltage, including harmonics, but excluding transients. Also, the capacitor should be able to carry 135% of nominal current

A capacitor unit, shown in Figure 1, is the building block of any SCB. The capacitor unit has many, separate capacitor elements, arranged in parallel/series combinations, housed within a steel enclosure. The internal discharge device is a resistor that dissipates the capacitor unit residual voltage, allowing switching the banks back to service. Capacitor units are available in a variety of voltage ratings (240 V to 25 kV) and sizes (2.5 kVAr to 1000 kVAr).

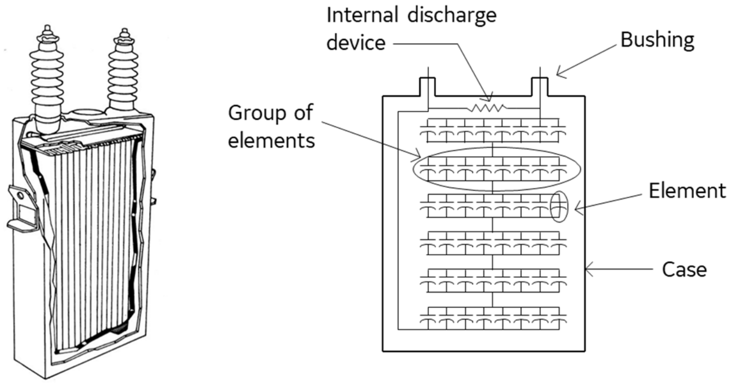


Figure 1. Capacitor unit

Capacitor unit protection is based on the capacitor element failing in a shorted mode. A failure in the capacitor element dielectric causes the foils to weld together and short circuits the other capacitor elements connected in parallel in the same group (refer to Figure 1). The remaining series capacitor elements in the unit remain in service with a larger voltage across each of these and an increased capacitor can current. If a second element fails, the process repeats resulting in an even greater voltage (and increased current) for the remaining elements.

Commonly, there are four types of capacitor unit designs:

- Externally fused
- Internally fused
- Fuseless
- Unfused

b) Externally fused capacitors

In an externally fused SCB, a separate fuse is mounted externally between the capacitor unit and the capacitor-bank fuse bus to protect each capacitor unit. The capacitor unit has a relatively high voltage because the external fuse can interrupt a high-voltage fault. Usually, the kiloVAr rating of each capacitor unit is smaller because a minimum number of parallel units are required for the bank to remain in service with a capacitor can out of service. SCBs using fused capacitors are configured using one or more series groups of parallel-connected capacitor units per phase, as shown in Figure 2.

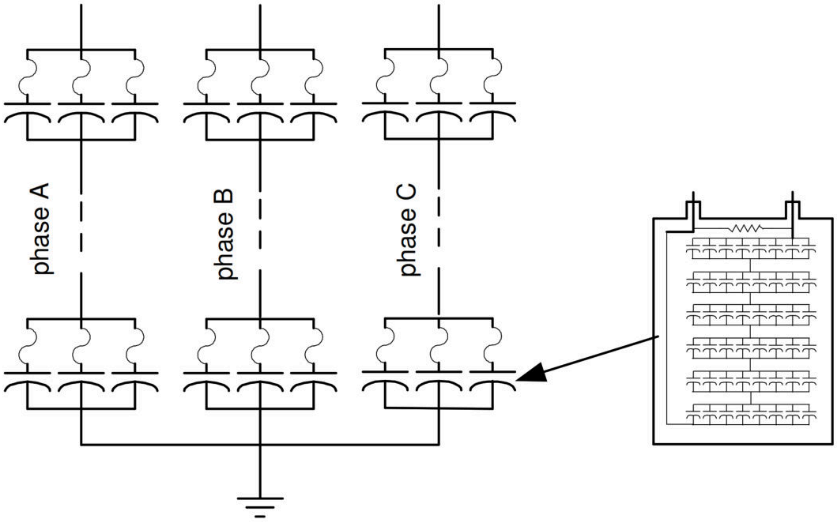


Figure 2. Externally fused shunt capacitor bank and capacitor unit

c) Internally fused capacitors

In an internally fused capacitor bank each capacitor element is fused inside the capacitor unit. A "simplified" fuse is a piece of wire sized to melt when carrying fault current and is encapsulated in a wrapper able to withstand the heat produced by the arc during the current interruption. Upon capacitor 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 greater voltage across these elements.

Figure 3 illustrates a typical capacitor bank with internally fused capacitor units. Generally, SCBs with 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 larger because the entire unit is not expected to fail.

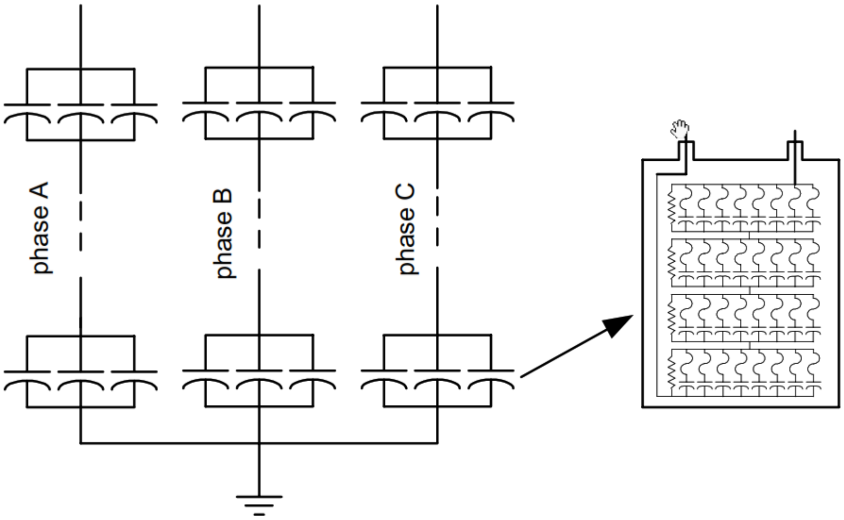


Figure 3. Internally fused shunt capacitor bank and capacitor unit

d) Fuseless capacitor banks

Fuseless capacitor banks are the most prevalent design today. The capacitor units are connected in series strings between phase and neutral, as shown in Figure 4. There are more capacitor elements in series to achieve larger bank voltages.

The expected failure mode of the capacitor unit element is a short circuit, where the remaining capacitor elements absorb the larger voltage. For example, if 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 the string. If one capacitor element fails, this element shorts and the voltage across the remaining elements is 48/47 of the previous value, or about

2% greater. The capacitor bank remains in service. However, successive element failures aggravate the problem and eventually lead to protection removing the capacitor bank from service.

Usually, fuseless SCBs are applied at 34.5 kV and greater. Each string has more than 10 elements in series to ensure the remaining elements do not exceed 110% rating if an element in the string shorts.

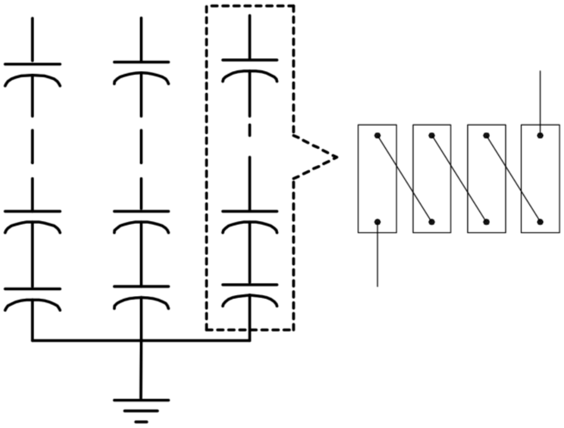


Figure 4. Fuseless shunt capacitor bank and series string

e) Unfused capacitors

In unfused capacitor banks there is a series/parallel connection of the capacitor units. This design does not require as many capacitor units in parallel as an externally fused bank and is less cost. Usually, this unfused approach is used on banks at less than 34.5 kV, where series strings of capacitor units are not practical, and at higher voltages with modest parallel kVAr requirements.

f) SCB design considerations for protection

Protection of shunt capacitor banks requires an understanding of capacitor-bank design and capacitor-unit connections (series and parallel). For series connections, the minimum number of series-connected groups is such that the complete bypass of the group does not subject the other remaining capacitors to a permanent overvoltage of more than 110%. For parallel connections, 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 in the group. The value of 110% is the maximum continuous overvoltage capability of capacitor units as per IEEE Std 18-2012 and IEEE Std 1036-2020 [2].

The maximum number of capacitor units that may be placed in parallel per group is limited by the rate of discharge current if a capacitor unit fails. When a capacitor bank unit fails other capacitors in the same parallel group contain some amount of charge. This charge drains as a high-frequency transient current that flows through the failed capacitor unit. The capacitor can fuseholder (when used) and the failed capacitor unit must withstand this discharge transient. The discharge transient from a large number of paralleled capacitors can be sufficient to rupture the failed capacitor unit and to explode a fuseholder—this can damage adjacent capacitor units and cause a major bus fault within the bank. To minimize the probability of this damage the standards impose a limit to the total maximum energy stored in a parallel-connected group to 4650 kVAr. Thus, more capacitor groups at a lower voltage rating connected in series (with fewer units in parallel per group) is a suitable solution. However, this connection reduces sensitivity of unbalance protection schemes. Splitting the bank into two sections as a double wye allows for better unbalance detection scheme.

Two prevalent designs of SCBs are the externally fused bank and the fuseless bank. There are advantages to each design.

i. Externally fused bank

Typically, externally fused banks have larger unbalance current when a unit fails and operates a fused disconnect device. This design is a simpler bank configuration and provides an easy method for field identification of a failed unit. Also, a fused bank requires less sensitive unbalance protection because the fuse is the principal method used for isolating a can failure. However, externally fused banks have a greater initial cost and larger maintenance costs. Fuses are exposed to the environment and thus become less reliable, requiring more maintenance to ensure correct operation.

ii. Fuseless bank

Fuseless capacitor banks are increasingly popular. Eliminating the fused connection results in a less initial cost, reduced maintenance costs, smaller bank footprint, and fewer losses. Typically, this bank design makes catastrophic can rupture less likely because the discharge energy of a failed element is small.

The fuseless bank has two main disadvantages that increase the emphasis on sensitive relaying protection. There is no visual indication of a failed capacitor unit. In addition, an element failure results in an overvoltage condition that stresses the remaining elements. Without a fuse as a means of isolating the failed capacitor the protective relay must be sufficiently sensitive to detect a failed element and alarm before additional elements fail and cause a higher overvoltage condition on the remaining units. Therefore, it is especially important to employ a sensitive protective relay that correctly isolates a bank for a failed element. Also, faulted phase identification assists field personnel in locating a failed capacitor can without having to test the entire bank.

The optimum connection for a SCB depends on the best use of the available voltage ratings of capacitor units, fusing, and protective relaying. Virtually all HV and EHV banks are connected in one of the two wye configurations listed below [3,4]. However, distribution capacitor banks can be connected in wye or delta. Some banks use an H configuration on each of the phases with a current transformer in the connecting branch to detect unbalance.

g) Grounded, wye-connected banks

Grounded wye capacitor banks are series- and parallel-connected capacitor units per-phase and provide a low-impedance path to ground. This offers some protection from surge overvoltages and transient overcurrents. When a capacitor bank becomes too large, making the parallel energy of a series group too high for the capacitor units or fuses (greater than 4650 kVAr), the bank is split into two wye sections. The characteristics of the grounded double wye are similar to a grounded single-wye bank. Connect the two neutrals directly with a single path to ground.

The double-wye design facilitates better protection methods. Even with inherent unbalances, the two banks respond similarly to system events. Therefore, protection methods based on comparing one split-phase versus the other are more sensitive and less prone to system events (an example is phase-current balance, ANSI 50B).

h) Ungrounded, wye-connected banks

Ungrounded, wye-connected SCBs have advantages over the grounded configurations. Ungrounded wye banks do not permit zero-sequence currents, third-harmonic currents, and large capacitor discharge currents during system ground faults. (However, phase-to-phase faults can still occur and result in large discharge currents.) Another advantage is that overvoltages appearing at the CT secondaries are not as large as grounded banks.

However, the neutral must be insulated for full line voltage because it is momentarily at phase-to-phase potential when the bank is switched or when one capacitor unit fails in a bank configured with a single group of units. Switches must be rated at phase-to-phase potential and this voltage stress and insertion current surges can cause switch failure.

Protection uses the voltage from the common point to ground for Compensated bank neutral voltage unbalance 59NU and bank phase overvoltage 59B. This is a neutral (or resistive) potential device as shown in Figure 18.

i) Delta-connected banks

Generally, delta-connected banks are used only at distribution 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.

j) H-configuration

Some larger banks use an H-configuration in each phase with a CT (current transformer) connected between the two strings to compare the current through each string. As long as all capacitors balance, no current flows through the CT. Current flows through the current transformer if a capacitor fuse operates or an element fails and shorts. This bridge connection enables sensitive protection. Large banks with many capacitor units in parallel employ the H configuration.

k) Tapped configuration

Larger banks use a tapped configuration in each phase with voltage transformers connected from phase-to-ground and from tap-to-ground. The ratio of these two voltages remains constant during nominal operation—no fuses have opened, and no elements have shorted. The ratio changes with any capacitor failure in the phase, providing sensitive protection.

III. Capacitor-bank protection

SCBs have a large number of separate capacitor elements connected in a series/parallel arrangement to distribute the system voltage equally among the elements. Equal voltage distribution is important because capacitor elements fail rapidly when the impressed voltage exceeds 110%. Manufacturers maintain strict tolerances to obtain balanced voltages parallel groups having a uniform total capacitance. However, once in service, particular elements can fail randomly, upsetting the balance, increasing the stress on other elements, and causing premature failure. Failure further unbalances the bank, leading to cascading bank failure.

The purpose of capacitor unbalance protection is to detect unbalance caused by element failures as soon as practical, and to alarm for this condition (so that maintenance personnel can schedule a repair for a convenient time) or to remove the bank from service to prevent deterioration of the healthy elements. A comprehensive method would be to measure directly the voltage across each element, detecting an abnormally high voltage on any and all elements. However, this approach is uneconomical because a large number of voltage transducers would be necessary. Modern Capacitor bank protection methods use available CT and VTs (voltage transformers), depending on the particular SCB configuration. The challenge faced by all capacitor unbalance protection methods is achieving sufficient sensitivity with fewer monitoring points, and compensation for the increased effects of inherent unbalance from manufacturing tolerance and power-system voltage unbalance. SCB protection includes both bank and system protection schemes.

a) Bank protection

Bank protection is for faults within the capacitor bank itself. Bank protection includes the following:

- Disconnect a faulted capacitor unit or capacitor elements
- Shutdown (trip) bank for SCB faults that can lead to a catastrophic failure
- Disconnect the entire shunt capacitor bank to prevent further damage to the capacitors due to abnormal system conditions
- Generate alarms to indicate unbalance within the bank

In externally fused capacitor banks, several capacitor element breakdowns can occur before the fuse removes the entire unit. The external fuse operates when a capacitor unit becomes (essentially) short circuited, isolating the faulted unit. Protective relay unbalance elements remove the bank from service when the resulting overvoltage becomes excessive on the remaining healthy capacitor units.

Internally fused capacitor banks have fuses that disconnect a capacitor before element breakdown occurs. The risk of successive faults is small because the fuse isolates the faulty element within a few cycles. Unbalance protection removes the bank from service when the resulting unbalanced voltage becomes excessive on the remaining healthy capacitor elements or units.

For fuseless and unfused capacitor banks, a failed capacitor is a short-circuit weld, which increases the voltage stress on the remaining capacitors elements/units. Unbalance protection removes the bank from service when the resulting voltage becomes excessive.

b) System protection

System protection schemes protect the capacitor bank from stresses caused by the power system and protect the substation and power system from stresses caused by SCB operation. System protection includes the following:

- Limit power-system overvoltage
- Restrict excessive transient overcurrents
- Disconnect the bank for a major fault within the SCB
- Generate alarms for these conditions

c) Voltage differential (ANSI 87V)

The voltage-differential function 87V is based on a voltage-divider principle. A healthy capacitor string has a constant and known match factor between its full tap (typically the bus voltage) and an auxiliary tap used by the protection, as shown in Figure 5. Any single element failure results in a difference between the measured factor and its value when the bank is healthy. The protection is for both grounded and ungrounded banks. For ungrounded banks, the neutral point voltage (VX) must be measured by the relay and used to derive the voltage across the string.

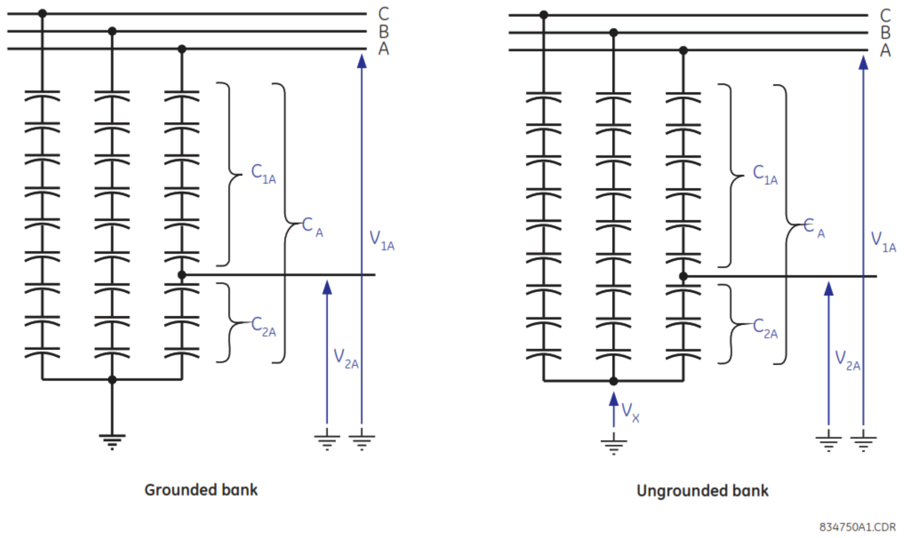


Figure 5. Measuring points for voltage differential 87V protection

The voltage-differential protection uses the following operating signal for grounded banks:

$$V_{op(A)} = |V_{1A} - k_A V_{2A}| \qquad (1$$

The voltage-differential protection uses the following operating signal for ungrounded banks:

$$V_{op(A)} = \left|\left(\overline{V_{1A}} - \overline{V_X}\right) - \left(k_A \overline{V_{2A}} - \overline{V_X}\right)\right| \qquad (2$$

Identical relations apply to Phase B and Phase C. The ungrounded case is similar except that all voltages have V_X subtracted.

Sensitivity is the key performance parameter. A modern protection relay approach is to measure with a simple integration method in addition to the standard hysteresis approach to adjust for signal chattering at the boundary of operation.

Voltage-based capacitor protection functions are set sensitively. The modern capacitor-bank relay measures both the bus and tap voltages accurately to deliver protection sensitivity. Select the VT ratios so that the resultant secondary voltages are in the region of maximum relay accuracy, and the two VTs work within their maximum class accuracy under nominal system voltage. Select carefully the VT for the tap voltage to minimize VT and relay errors. Relay setting range for the ratio-matching factor is another condition that limits selection of this VT ratio.

i. Auto-setting and self-tuning

While SCBs can have a designed tap at the mid-point or the one-third point, manufacturing tolerances result in the actual tap ratio being slightly different from the design target. To prevent a spurious component in the operating signal, the match factor settings must correspond to the actual rather than the design tap ratio. As a convenient alternative to manually determining the optimum match factor settings, the relay calculates these settings automatically from measurements while the capacitor is in-service. The relay sets the operate signal to zero in Equations (1 and (2, and solves for the match factor kA (and kB, and kC) using the average of several successive voltage measurements. Additionally, this technique compensates for instrumentation errors. When the auto-set command is executed, the capacitor is in a balanced state, when the operating signal is zero. Following the auto-set command, the protection measures changes from the state that existed at the time of the auto-set command.

d) Compensated bank neutral voltage unbalance (ANSI 59NU)

The neutral voltage unbalance function is applicable to ungrounded banks as shown in Figure 6. This function responds to an overvoltage condition of the neutral-point voltage. If the capacitor-bank and the power-system voltages balance, the neutral-point voltage is zero. If a capacitor element in the bank fails, then the bank becomes unbalanced and the neutral voltage increases.

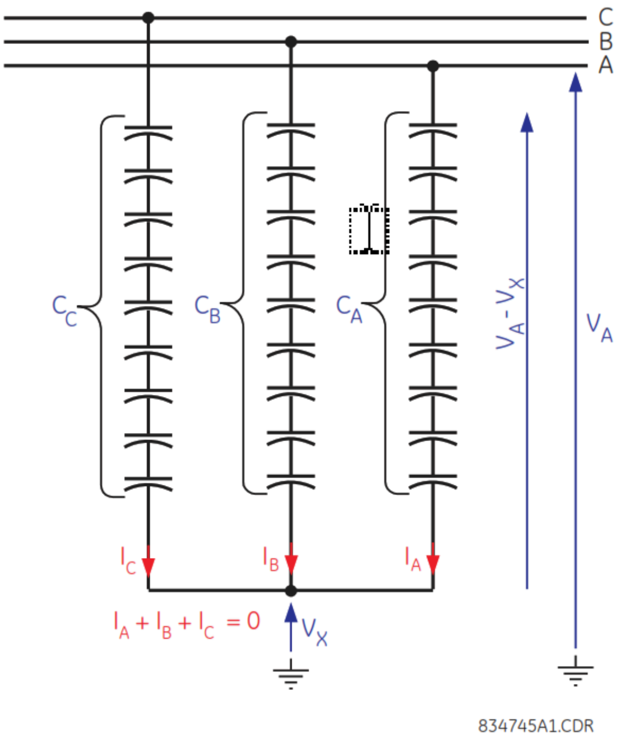


Figure 6. Compensated bank neutral overvoltage 59NU

The operate signal for the neutral voltage unbalance protection is the following:

$$V_{OP} = \frac{1}{3}\left|\overline{V_X}(1 + k_{AB} + k_{AC}) - 3\overline{V_0} + \overline{V_B}(1 - k_{AB}) + \overline{V_C}(1 - k_{AC})\right| \qquad (3$$

The restraint signal for the neutral voltage unbalance protection is the following:

$$V_{REST} = |\overline{V_X} + \overline{V_0}| \qquad (4$$

In these equations, kAB and kAC represent capacitor-bank unbalance ratio settings.

These equations involve phasors, not magnitudes; the protection relay creates the vector sum of the voltages.

The neutral voltage unbalance protection operates when the operate signal is greater than the set pickup level and the operate signal is greater than the set percentage of the restraint signal, all for the set pickup delay.

Sensitivity is the key performance parameter. A modern protection relay approach is to measure with a simple integration method in addition to the standard hysteresis approach to adjust for signal chattering at the boundary of operation.

In addition, a slope characteristic deals with measurement errors for the involved voltages under large system unbalances, such as during a close-in external fault (see Figure 7).

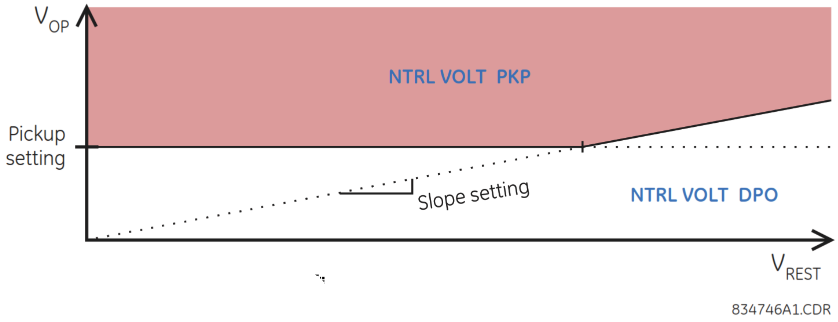


Figure 7. Neutral overvoltage 59NU restraint

The following characteristics apply to the compensated bank neutral voltage unbalance 59NU function [4]:

- Reporting *k*-factors (pre- fault and fault values) to aid troubleshooting and repair. The single-element function does not indicate explicitly the affected phase
- Apply appropriate security measures for sensitive and secure operation: appropriate restraint signal accompanying the operating signal. Setting range should allow disabling the restraint
- Provide several independent pickup thresholds for alarming and tripping
- Offer inherent bank unbalance constants (*k*-values) set-able per phase
- Both auto-setting and self-tuning applications are possible as long as the neutral point voltage is non-zero and measured with adequate accuracy
- Calculate k factors automatically under manual supervision of the user, either locally or remotely (auto-setting), or continuously in a slow adjusting loop (self-tuning)

i. Auto-setting command

As a convenient alternative to manually determining the unbalance ratio settings, the modern capacitor-bank protection relay calculates these settings automatically from measurements while the capacitor is in-service.

The technique the relay uses is to set the operate signal variable in Equation (3 to zero and solve for the unbalance ratio k-values using the average of several successive measurements of the voltages. Determination of the two k-values using only one equation is possible because the k-values are real, so the complex-valued equation can be separated into real and imaginary parts, with the same two k-values in each. A solution exists as long as the cross product of the B and C-phase voltages is non-zero; that is, the capacitor bank is in-service.

However, the assumption made here is that when the auto-set command is executed, the capacitor is in a balanced state, wherein the operating signal ought to be zero. Following the auto-set command, the protection measures changes from the state that existed at the time the auto-set command executed.

e) Phase current unbalance (ANSI 60P)

Phase current unbalance detects the balance between interconnected and identical phase strings, for both grounded and ungrounded SCBs. A window CT measures the vectorial difference between the two string currents per phase as shown in Figure 8.

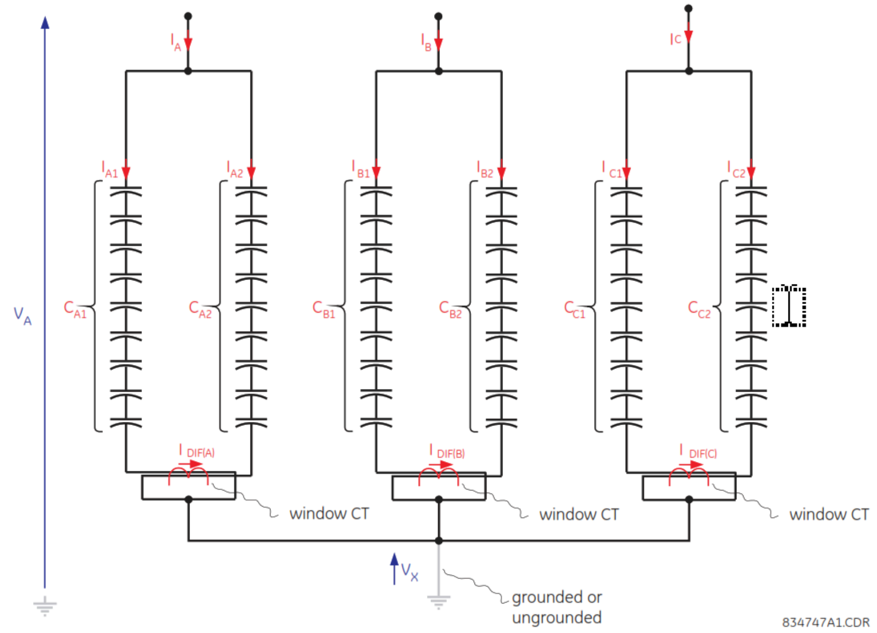


Figure 8. Phase current unbalance 60P

While the two strings currents are identical, the measured current is zero. The failure of an element in either string results in a difference current, which the protection relay senses. An inherent difference current exists because of string mismatched from manufacturing tolerances. A compensation factor, kA for this inherent unbalance current is available to increase the sensitivity of the function.

The phase current unbalance function uses the following operate signal:

$$I_{OP(A)} = \left|\overline{I_{DIF(A)}} - k_A \overline{I_A}\right| \qquad (5$$

In this equation, kA is the capacitor bank leg-A inherent unbalance factor setting.

The protection operates when the operate signal is greater than the set pickup level for the set pickup delay. Identical relations apply to phases B and C.

Sensitivity is the key performance parameter. A modern protection relay approach is to measure with a simple integration method in addition to the standard hysteresis approach to adjust for signal chattering at the boundary of operation.

The following characteristics apply to the phase current balance 60P function [4]:

- Support separate, per-phase settings
- Indicate the affected phase, and report the change in the current division ratio, k (pre-fault and fault values) to aid troubleshooting and repairs of the bank
- Apply appropriate security measures for sensitive and secure operation: appropriate restraint signal accompanies the operating signal. Setting range should allow disabling the restraint
- Provide several independent pickup thresholds for alarming and tripping
- Offer current dividers (k-values) set separately per phase.
- Both auto-setting and self-tuning applications are possible as long as the neutral point voltage is non-zero and measured with adequate accuracy
- Calculate k factors automatically under manual supervision of the user, either locally or remotely (auto-setting), or continuously in a slow adjusting loop (self-tuning)

i. Auto-setting

As a convenient alternative to manually determining inherent unbalance factor settings, the relay calculates these settings automatically from measurements while the capacitor is in-service. The technique that the relay uses is to set the operate signal variable to zero in Equation (5 and solve for the inherent unbalance factor kA using the average of several successive measurements of the currents.

However, the assumption made here is that when the auto-set command is executed, the capacitor is in an acceptably balanced state, when the operating signal ought to be zero. Following the auto-set command, the protection measures changes from the state that existed at the time the auto-set command executed.

f) Neutral current unbalance (ANSI 60N)

Neutral current unbalance is based on the balance between interconnected neutral currents of two parallel banks, for both grounded and ungrounded installations as shown in Figure 9. The grounded bank and ungrounded bank protections are similar. A window CT measures the vector difference between the two neutral currents for grounded-wye configurations.

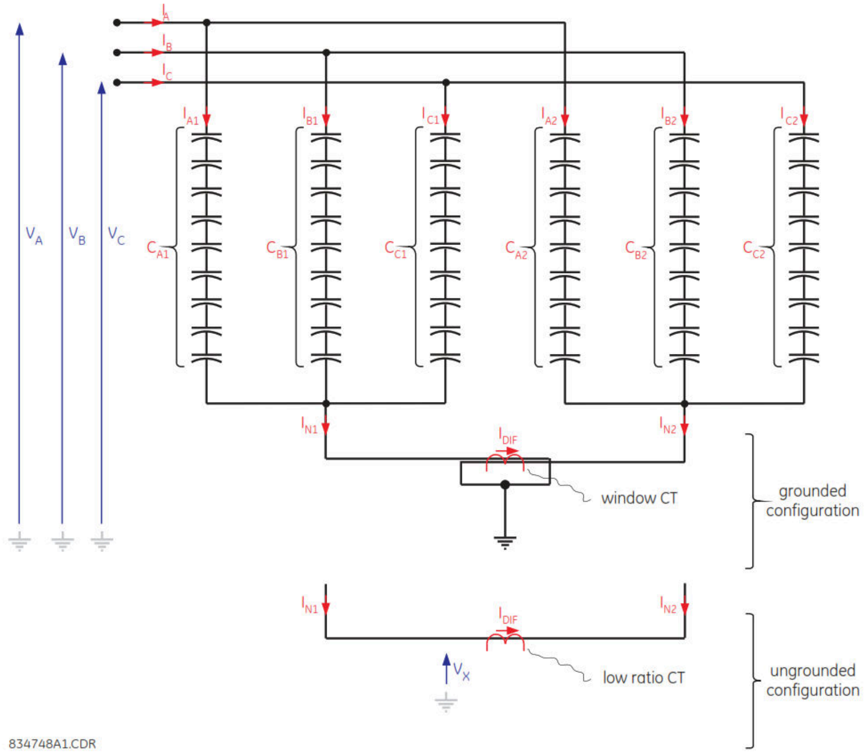


Figure 9. Neutral current unbalance 60N

If the two banks are identical, then the inter-neutral current is zero. The failure of an element in either bank then results in inter-neutral current, which the protection relay senses. A circulating zero-sequence current can be present because of manufacturing-tolerance mismatch in the two parallel banks. A compensation factor, k_A, is available for this inherent unbalance current to increase the sensitivity of the function.

The neutral current unbalance protection uses the following operate signal for the grounded case:

$$I_{OP} = \left|\overline{I_{DIF}} - k_1\overline{I_1} - k^*_1\overline{I_2}\right| \qquad (6$$

The neutral current unbalance protection uses the following restraint signal for the grounded case:

$$I_{REST} = |I_0| \qquad (7$$

where k1 is the vector capacitor bank positive sequence inherent unbalance factor setting, and k1* is the complex conjugate of k1.

Assume $C_{A1} \cong C_{A2}$. Then this relationship exists:

$$I_{OP}(pu) = \frac{I_A}{2} \cdot \Delta C(pu) \qquad (8$$

where $\Delta C(pu)$ is the capacitance change as a per-unit value of the string capacitance, and $I_{OP}(pu)$ is the operating signal resulting from the failure in per-unit of the nominal current of the differential source. I_A

represents the Phase A terminal current on the same base. When the system is normal (no fault), I_A is the capacitor bank rated primary per-phase current I_{rated} converted to the differential source base. For example, $I_A = I_{rated} / I_{base}$, where I_{base} is the differential CT primary current rating. With a nominal, balanced system:

$$I_{OP}(pu) = \frac{I_{rated}}{2I_{base}} \cdot \Delta C(pu) \qquad (9$$

Note that under external fault conditions, sensitivity can be much different from the non-fault sensitivity.

i. Ungrounded bank

There is a different signal in the ungrounded configuration. For the grounded configuration $I_{DIF} = I_{N1} - I_{N2}$, with the ungrounded configuration $I_{DIF} = I_{N1} = -I_{N2}$. Thus, the operating current becomes the following:

$$I_{OP}(pu) = \frac{I_A}{4} \cdot \Delta C(pu) \qquad (10$$

$$I_{OP}(pu) = \frac{I_{rated}}{4I_{base}} \cdot \Delta C(pu) \qquad (11$$

When applied to ungrounded configurations, there are the following specifications:

- The phase voltages in the development calculations must have the neutral voltage V_X subtracted. Eventually these voltages cancel from the calculations; the outcome is unaffected
- A low-ratio CT is used for the ungrounded-wye configurations in place of a window type CT as shown in Figure 9; there is no requirement to form the difference of the primary neutral currents
- The operating signal is half of the grounded case
- With the grounded configuration, the two banks must be nominally identical. With the ungrounded configuration the two banks need not be identical, although ideally each are balanced. In this situation, the base for ΔC(pu) is the capacitance of the string that has the element failure, so the larger bank has a lesser sensitivity than the smaller bank

ii. Restraint

Severe system voltage unbalance, such as can occur during near-by bolted ground faults, can exacerbate measurement error, resulting in a spurious operating signal. To prevent operation under these conditions, the relay applies percent restraint supervision using a restraint signal that is the magnitude of the zero-sequence current, as shown in Figure 10.

Typically, a few percent of slope are sufficient to ensure security of the function. The factor compensating for the inherent bank unbalance zeroes out the operating signal under balanced bank currents. If the currents contain a significant zero-sequence component, the quality of compensation is less, justifying the need for the restraint, and this slope setting.

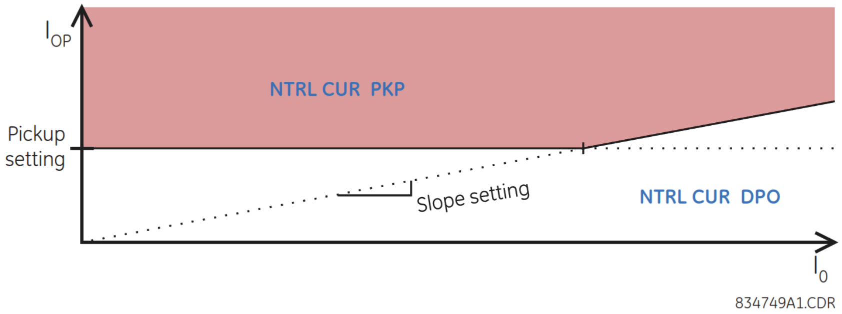


Figure 10. Neutral current unbalance 60N restraint

The following characteristics apply to the neutral current balance 60N function [4]:

- The single-element function does not indicate explicitly the affected phase

- Apply appropriate security measures for sensitive and secure operation: appropriate restraint signal accompanying the operating signal. Setting range should allow disabling the restraint
- Provide several independent pickup thresholds for alarming and tripping
- Offer the positive-sequence compensating factor k1 as a setting
- Calculate k factors automatically under manual supervision of the user, either locally or remotely (auto-setting), or continuously in a slow adjusting loop (self-tuning)

iii. Auto-setting

As a convenient alternative to manually determining the unbalance k-factor settings, the relay can calculate automatically these settings from its own measurements while the capacitor is in-service. The relay sets the operate signal variable to zero in Equation (6 and solves for the unbalance factor k_1 using the average of several successive current measurements.

When the auto-set command is executed, the capacitor is in a balanced state, with the operating signal at zero. Following the auto-set command, the protection measures changes from the state that existed at the time of the auto-set command.

g) Bank phase overvoltage (59B)

Ideally, a bank overvoltage protection measures the voltage across each capacitor string, providing an accurate interpretation of the voltage across each element in the string. (The assumption is that the string voltage divides equally across the capacitor elements). For grounded-wye capacitor banks the measurement is simply placing a VT to measure the three, system, phase-to-ground voltages. For instance, assuming that the bank is healthy, the elements shown in the grounded banks of Figure 11 are each stressed at one-ninth of system phase-to-ground voltage, allowing the inference that the elements are overstressed when the system phase-to-ground voltage exceeds nine times the element safe operating voltage limit. The true RMS value of these phase-to-ground quantities are what the bank phase overvoltage protection measures when the bus source is set for wye VTs and the bank overvoltage protection ground setpoint is set to grounded.

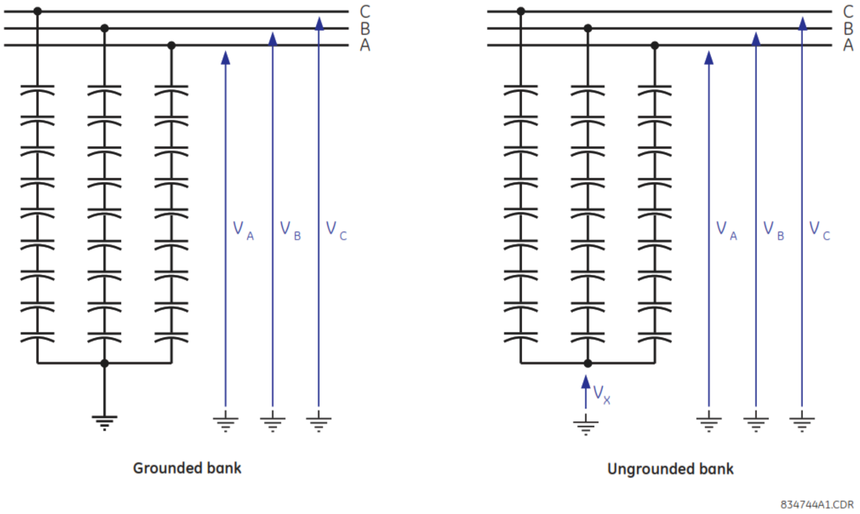


Figure 11. Bank overvoltage 59B protection for grounded and ungrounded banks

For a capacitor bank that is ungrounded, the voltage across the string is equal to the difference between the system phase-to-ground voltage and the bank neutral voltage. Elements in the ungrounded banks are overstressed when this voltage exceeds the element safe operating voltage limit times the number of elements (in the Figure 11 example, 9 times).

When the neutral voltage of an ungrounded wye capacitor bank is not measured or used, then the string voltage is 1/3 of the difference of the phase-to-phase bus voltages:

$$\frac{1}{3}|V_{AB} - V_{CA}|\text{RMS};\ \frac{1}{3}|V_{BC} - V_{AB}|\text{RMS};\ \frac{1}{3}|V_{CA} - V_{BC}|\text{RMS} \qquad (12$$

When the bus VTs are delta-connected, the string voltages for an ungrounded, balanced bank are the voltages of Equation (12.

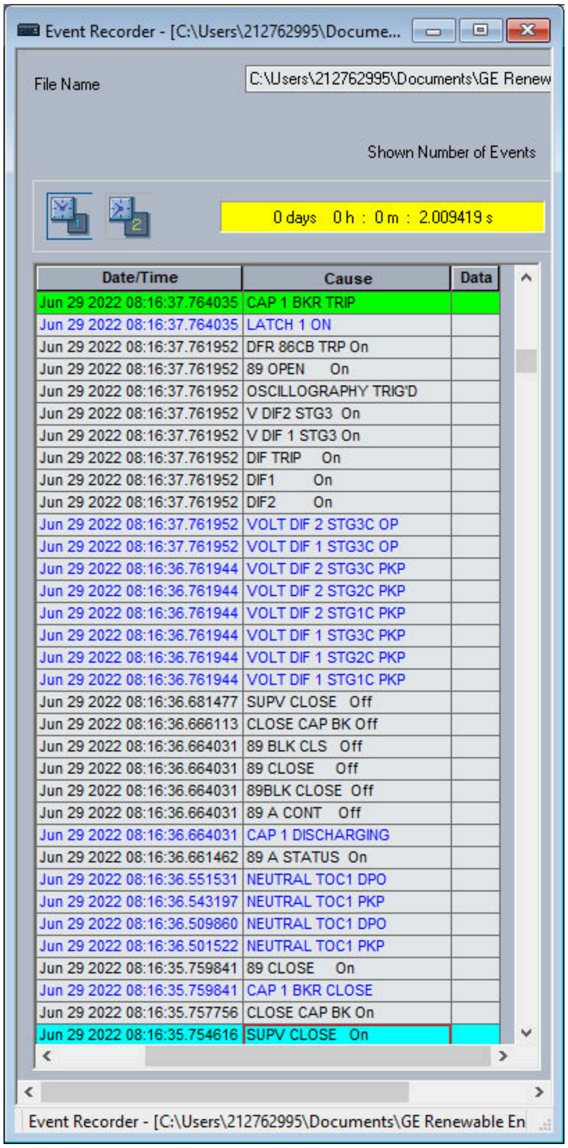
IV. Real-world examples

Real-world examples show the value of applying modern capacitor-bank protection principles. The following are actual SCB protection events. Additional information on capacitor-bank protection can be found in IEEE Std C37.99-2012, IEEE Guide for the Protection of Shunt Capacitors Banks [5].

a) Voltage differential trip, 87V

The protection relay tripped the bank on Phase-C, 87V voltage differential upon closure of the bank connection switches. Operations issued a supervisory close at 8:16:35.754616, as shown in the event record of Figure 12. The relay detects some residual charge in the SCB and issues CAP 1 DISCHARGING. This is a programmable delay that inhibits closing after the bank has been switched out of service until the bank has had time to discharge any trapped charge. If the capacitor is closed with trapped charge of opposite polarity from the system voltage at that instant, larger than normal transients can occur. The discharge timer in this case was 5 minutes and the bank had previously been in service, opened and then closed.

The SCB switch closes (89 A STATUS ON), and the 87V VOLT DIF 1, Stage 1, Stage 2, and Stage 3 pickup in 100 ms from the lack of differential balance. This is because there is no cap-bank voltage detected on Phase C, as shown in Figure 13. Settings, shown in Figure 14, list pickups for Stage 1, Stage 2, and Stage 3 at 0.108 and less, so a complete loss of phase picks up these elements. After the programmed 1-second delay for Stage 3, the relay trips the cap bank.

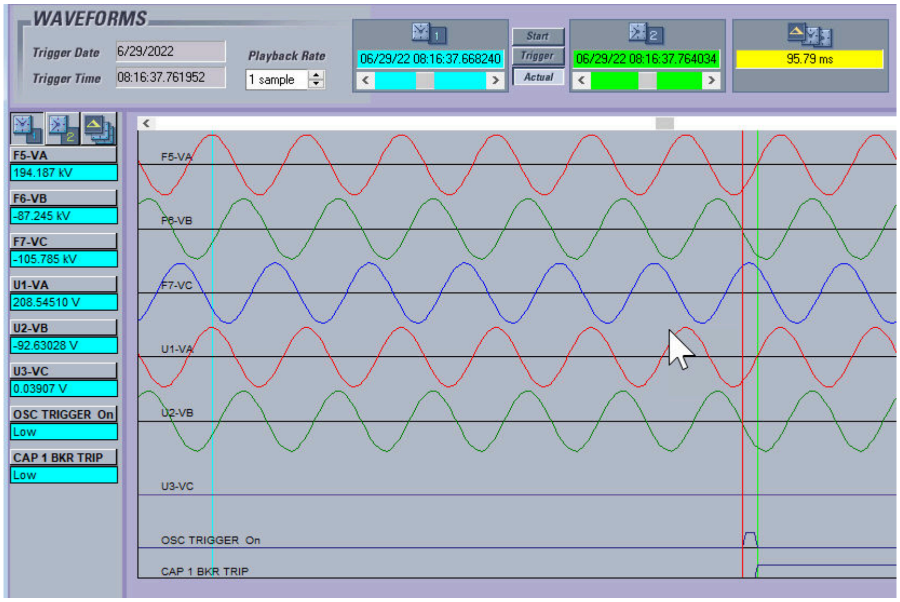


File Name: C:\Users\212762995\Documents\GE Renew

0 days 0 h : 0 m : 2.009419 s

Date/Time	Cause	Data
Jun 29 2022 08:16:37.764035	CAP 1 BKR TRIP	
Jun 29 2022 08:16:37.764035	LATCH 1 ON	
Jun 29 2022 08:16:37.761952	DFR 86CB TRP On	
Jun 29 2022 08:16:37.761952	89 OPEN On	
Jun 29 2022 08:16:37.761952	OSCILLOGRAPHY TRIG'D	
Jun 29 2022 08:16:37.761952	V DIF2 STG3 On	
Jun 29 2022 08:16:37.761952	V DIF 1 STG3 On	
Jun 29 2022 08:16:37.761952	DIF TRIP On	
Jun 29 2022 08:16:37.761952	DIF1 On	
Jun 29 2022 08:16:37.761952	DIF2 On	
Jun 29 2022 08:16:37.761952	VOLT DIF 2 STG3C OP	
Jun 29 2022 08:16:37.761952	VOLT DIF 1 STG3C OP	
Jun 29 2022 08:16:36.761944	VOLT DIF 2 STG3C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 2 STG2C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 2 STG1C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 1 STG3C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 1 STG2C PKP	
Jun 29 2022 08:16:36.761944	VOLT DIF 1 STG1C PKP	
Jun 29 2022 08:16:36.681477	SUPV CLOSE Off	
Jun 29 2022 08:16:36.666113	CLOSE CAP BK Off	
Jun 29 2022 08:16:36.664031	89 BLK CLS Off	
Jun 29 2022 08:16:36.664031	89 CLOSE Off	
Jun 29 2022 08:16:36.664031	89BLK CLOSE Off	
Jun 29 2022 08:16:36.664031	89 A CONT Off	
Jun 29 2022 08:16:36.664031	CAP 1 DISCHARGING	
Jun 29 2022 08:16:36.661462	89 A STATUS On	
Jun 29 2022 08:16:36.551531	NEUTRAL TOC1 DPO	
Jun 29 2022 08:16:36.543197	NEUTRAL TOC1 PKP	
Jun 29 2022 08:16:36.509860	NEUTRAL TOC1 DPO	
Jun 29 2022 08:16:36.501522	NEUTRAL TOC1 PKP	
Jun 29 2022 08:16:35.759841	89 CLOSE On	
Jun 29 2022 08:16:35.759841	CAP 1 BKR CLOSE	
Jun 29 2022 08:16:35.757756	CLOSE CAP BK On	
Jun 29 2022 08:16:35.754616	SUPV CLOSE On	

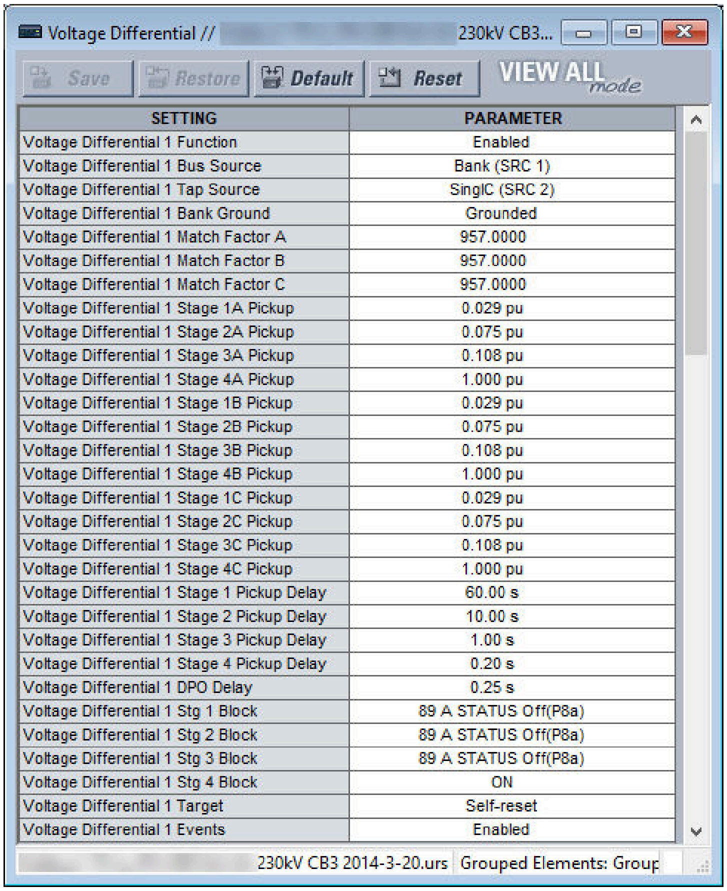
Figure 12. 87V operation event record



Trigger Date 6/29/2022
Trigger Time 08:16:37.761952
Playback Rate 1 sample
1: 06/29/22 08:16:37.668240
2: 06/29/22 08:16:37.764034
95.79 ms

F5-VA 194.187 kV
F6-VB -87.245 kV
F7-VC -105.785 kV
U1-VA 208.54510 V
U2-VB -92.63028 V
U3-VC 0.03907 V
OSC TRIGGER On Low
CAP 1 BKR TRIP Low

Figure 13. 87V operation from lack of source VC (Phase C voltage)



SETTING	PARAMETER
Voltage Differential 1 Function	Enabled
Voltage Differential 1 Bus Source	Bank (SRC 1)
Voltage Differential 1 Tap Source	SinglC (SRC 2)
Voltage Differential 1 Bank Ground	Grounded
Voltage Differential 1 Match Factor A	957.0000
Voltage Differential 1 Match Factor B	957.0000
Voltage Differential 1 Match Factor C	957.0000
Voltage Differential 1 Stage 1A Pickup	0.029 pu
Voltage Differential 1 Stage 2A Pickup	0.075 pu
Voltage Differential 1 Stage 3A Pickup	0.108 pu
Voltage Differential 1 Stage 4A Pickup	1.000 pu
Voltage Differential 1 Stage 1B Pickup	0.029 pu
Voltage Differential 1 Stage 2B Pickup	0.075 pu
Voltage Differential 1 Stage 3B Pickup	0.108 pu
Voltage Differential 1 Stage 4B Pickup	1.000 pu
Voltage Differential 1 Stage 1C Pickup	0.029 pu
Voltage Differential 1 Stage 2C Pickup	0.075 pu
Voltage Differential 1 Stage 3C Pickup	0.108 pu
Voltage Differential 1 Stage 4C Pickup	1.000 pu
Voltage Differential 1 Stage 1 Pickup Delay	60.00 s
Voltage Differential 1 Stage 2 Pickup Delay	10.00 s
Voltage Differential 1 Stage 3 Pickup Delay	1.00 s
Voltage Differential 1 Stage 4 Pickup Delay	0.20 s
Voltage Differential 1 DPO Delay	0.25 s
Voltage Differential 1 Stg 1 Block	89 A STATUS Off(P8a)
Voltage Differential 1 Stg 2 Block	89 A STATUS Off(P8a)
Voltage Differential 1 Stg 3 Block	89 A STATUS Off(P8a)
Voltage Differential 1 Stg 4 Block	ON
Voltage Differential 1 Target	Self-reset
Voltage Differential 1 Events	Enabled

[redacted] 230kV CB3 2014-3-20.urs Grouped Elements: Group

Figure 14. 87V settings

Analysis showed that there was a problem with the connecting switch knife mechanism in Phase C.

The bank is a split-wye, grounded bank. The split wye is not even, there is a single string per phase (a reference string) and then a multi-string per phase. However, the differential principle applies well, with a multiple-input 87V differential from the bus voltage to each string tap, as shown in Figure 15. The protection relay adds together the single-string and paralleled string voltage transformer (VT) bank sources from each phase to form a differential with the respective bus phase voltages.

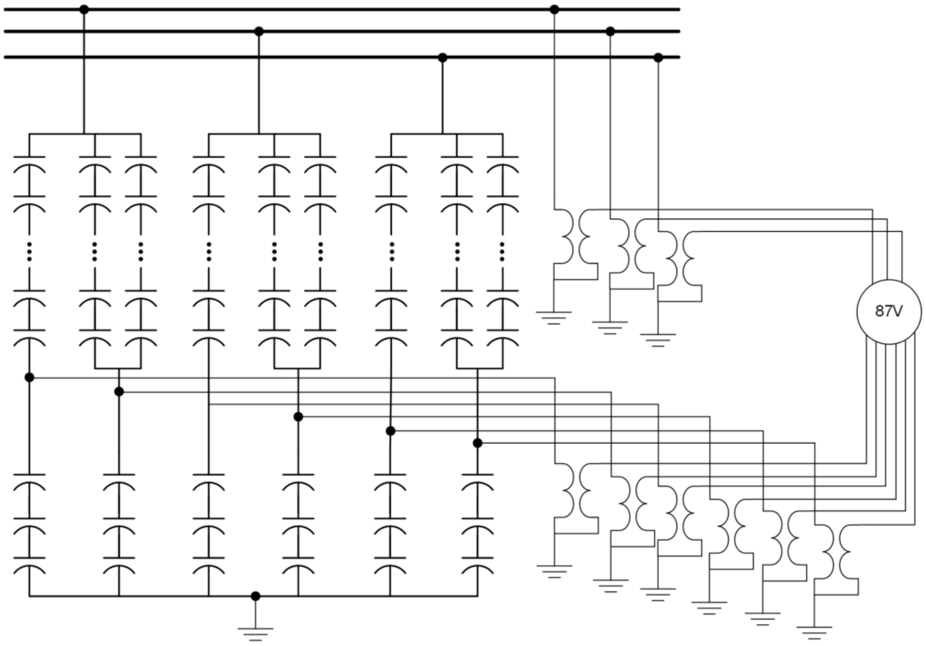
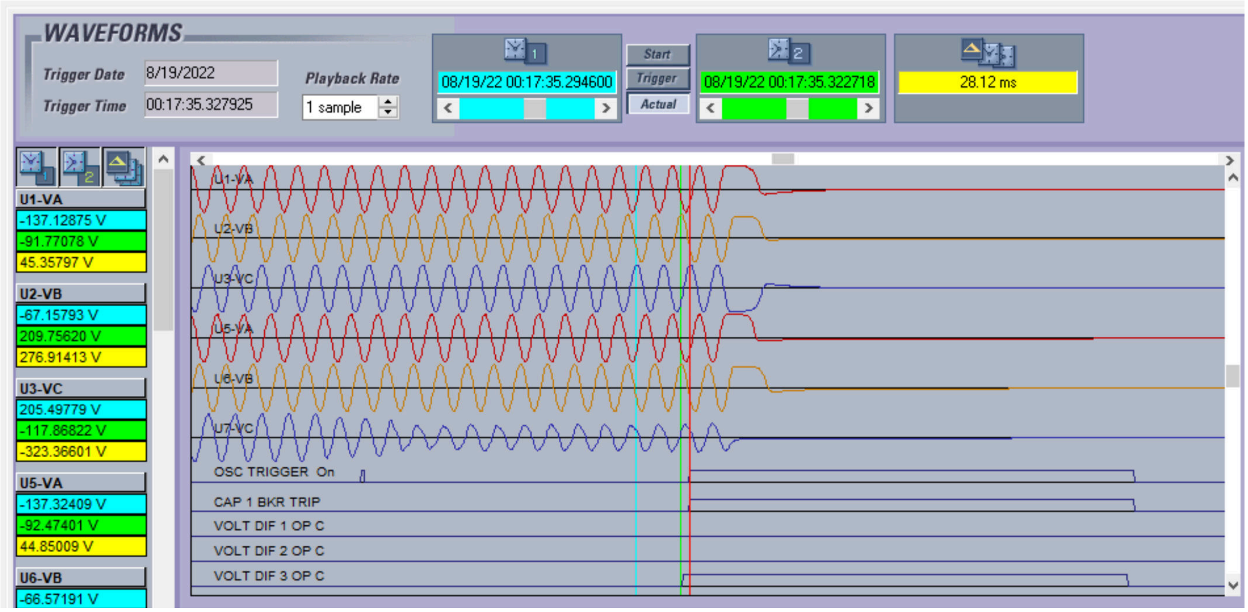


Figure 15. 87V differential connections

b) Voltage differential 87V trip while in service

The protection relay responded to a significant drop in Phase-C voltage while the capacitor bank was in operation, as shown in the oscillograph of Figure 16. This drop activated the Phase-C 87V stage elements and tripped the capacitor bank offline on Stage 4. Inspection showed that too many cans had shorted, reducing the Phase-C voltage. This sensitive and early trip protected the remaining capacitors in the group from a cascading failure.



Trigger Date 8/19/2022
Trigger Time 00:17:35.327925
Playback Rate 1 sample
1: 08/19/22 00:17:35.294600
2: 08/19/22 00:17:35.322718
28.12 ms

U1-VA	-137.12875 V -91.77078 V 45.35797 V
U2-VB	-67.15793 V 209.75620 V 276.91413 V
U3-VC	205.49779 V -117.86822 V -323.36601 V
U5-VA	-137.32409 V -92.47401 V 44.85009 V
U6-VB	-66.57191 V

Figure 16. Phase-C voltage drop during operation

This trip was the result of too many failed cans. When there is an alarm on a cap bank, field maintenance technicians take the bank out of service and troubleshoot to find any failed cans. Many times, this work is not the highest priority and operations personnel will continue to use the bank because they need voltage support in the area. Eventually, the unbalance stresses the other cans in the string causing more can failures. Then, protection trips and locks out the bank.

This SCB is a split, wye-grounded bank at 230 kV, rated at 108.5 MVAr. There is a single string per phase (a reference string) on one side of the differential, and a multi-string on the other side of the differential, as shown in Figure 15. It is large, with 216 cans in 8 strings per phase and multiple cans per string below the tap as shown in Figure 17. There are 8 cans per phase below the tap.

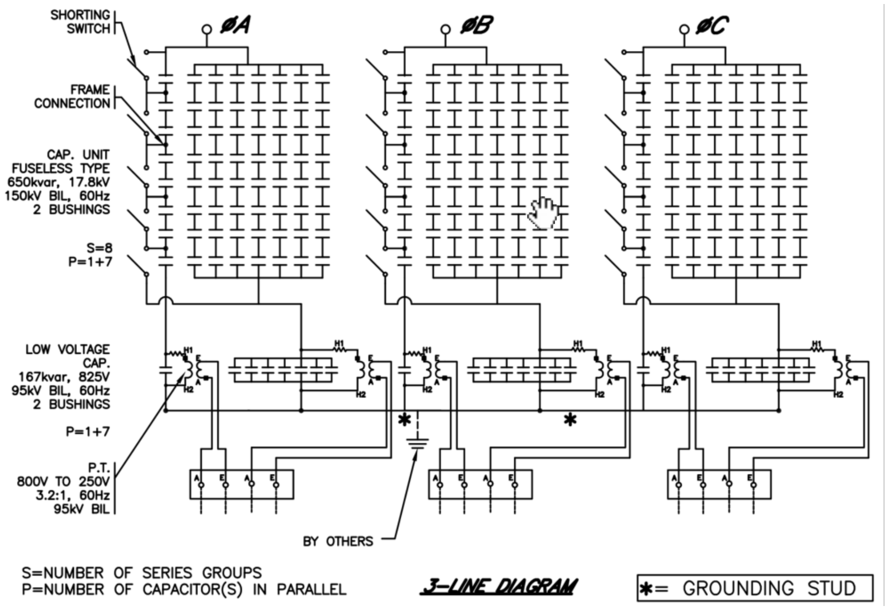


Figure 17. Grounded-wye bank detail

c) Compensated bank neutral voltage unbalance (ANSI 59NU) upon closing

Neutral voltage unbalance 59NU measures an overvoltage condition of the neutral-point voltage. If a capacitor element in the bank fails, then the bank becomes unbalanced and the neutral voltage increases. The example SCB is shown in Figure 18. A resistive potential device provides the neutral voltage to the protective relay input 59N (which has a large impedance and does not ground the bank).

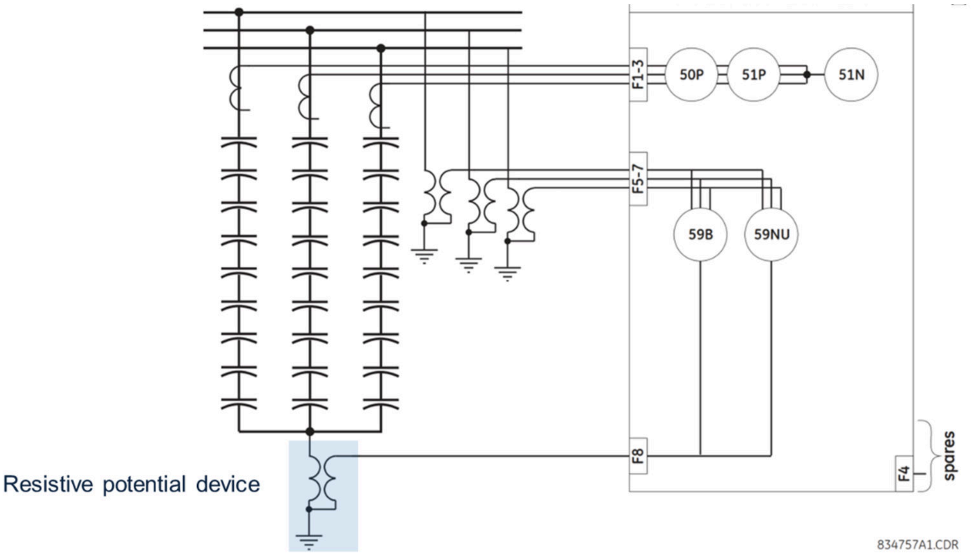
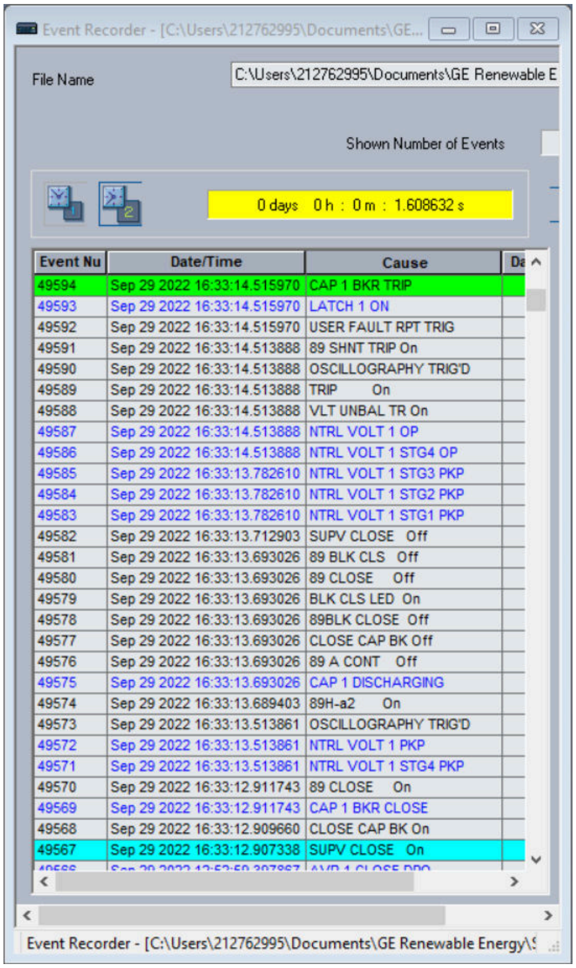


Figure 18. Ungrounded SCB and neutral voltage sensing

Upon closing the SCB a gross overvoltage occurred in the 59NU element, shown in the event record of Figure 19. This NTRL VOLT rise was in Stage 1 through Stage 4 (this application has these set to the same level and delay, as shown in Figure 20). The relay tripped the capacitor bank. After-event investigation revealed a mechanical problem in the circuit switch knife blades that did not make (connect) on Phase C.



Event Recorder - [C:\Users\212762995\Documents\GE...

File Name C:\Users\212762995\Documents\GE Renewable E

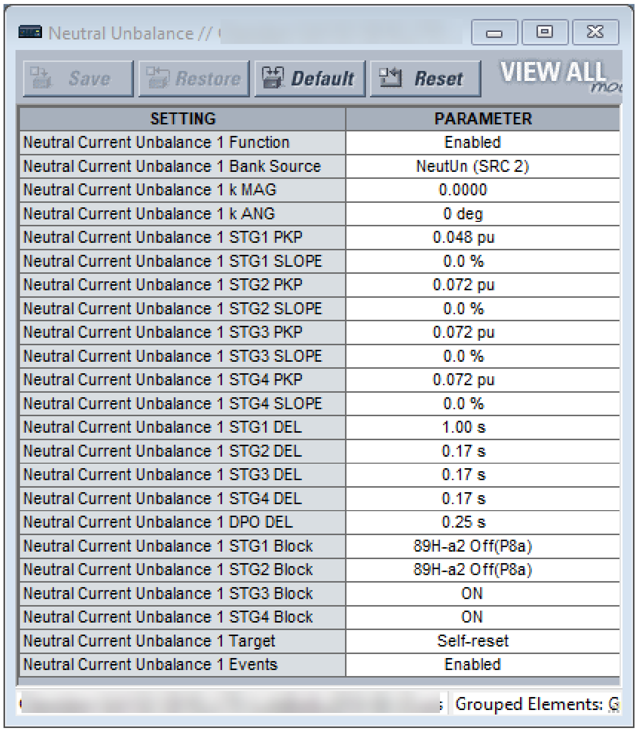
Shown Number of Events

0 days 0 h : 0 m : 1.608632 s

Event Nu	Date/Time	Cause	Da
49594	Sep 29 2022 16:33:14.515970	CAP 1 BKR TRIP	
49593	Sep 29 2022 16:33:14.515970	LATCH 1 ON	
49592	Sep 29 2022 16:33:14.515970	USER FAULT RPT TRIG	
49591	Sep 29 2022 16:33:14.513888	89 SHNT TRIP On	
49590	Sep 29 2022 16:33:14.513888	OSCILLOGRAPHY TRIG'D	
49589	Sep 29 2022 16:33:14.513888	TRIP On	
49588	Sep 29 2022 16:33:14.513888	VLT UNBAL TR On	
49587	Sep 29 2022 16:33:14.513888	NTRL VOLT 1 OP	
49586	Sep 29 2022 16:33:14.513888	NTRL VOLT 1 STG4 OP	
49585	Sep 29 2022 16:33:13.782610	NTRL VOLT 1 STG3 PKP	
49584	Sep 29 2022 16:33:13.782610	NTRL VOLT 1 STG2 PKP	
49583	Sep 29 2022 16:33:13.782610	NTRL VOLT 1 STG1 PKP	
49582	Sep 29 2022 16:33:13.712903	SUPV CLOSE Off	
49581	Sep 29 2022 16:33:13.693026	89 BLK CLS Off	
49580	Sep 29 2022 16:33:13.693026	89 CLOSE Off	
49579	Sep 29 2022 16:33:13.693026	BLK CLS LED On	
49578	Sep 29 2022 16:33:13.693026	89BLK CLOSE Off	
49577	Sep 29 2022 16:33:13.693026	CLOSE CAP BK Off	
49576	Sep 29 2022 16:33:13.693026	89 A CONT Off	
49575	Sep 29 2022 16:33:13.693026	CAP 1 DISCHARGING	
49574	Sep 29 2022 16:33:13.689403	89H-a2 On	
49573	Sep 29 2022 16:33:13.513861	OSCILLOGRAPHY TRIG'D	
49572	Sep 29 2022 16:33:13.513861	NTRL VOLT 1 PKP	
49571	Sep 29 2022 16:33:13.513861	NTRL VOLT 1 STG4 PKP	
49570	Sep 29 2022 16:33:12.911743	89 CLOSE On	
49569	Sep 29 2022 16:33:12.911743	CAP 1 BKR CLOSE	
49568	Sep 29 2022 16:33:12.909660	CLOSE CAP BK On	
49567	Sep 29 2022 16:33:12.907338	SUPV CLOSE On	

Event Recorder - [C:\Users\212762995\Documents\GE Renewable Energy\

Figure 19. Events for neutral unbalance 59NU



Neutral Unbalance //

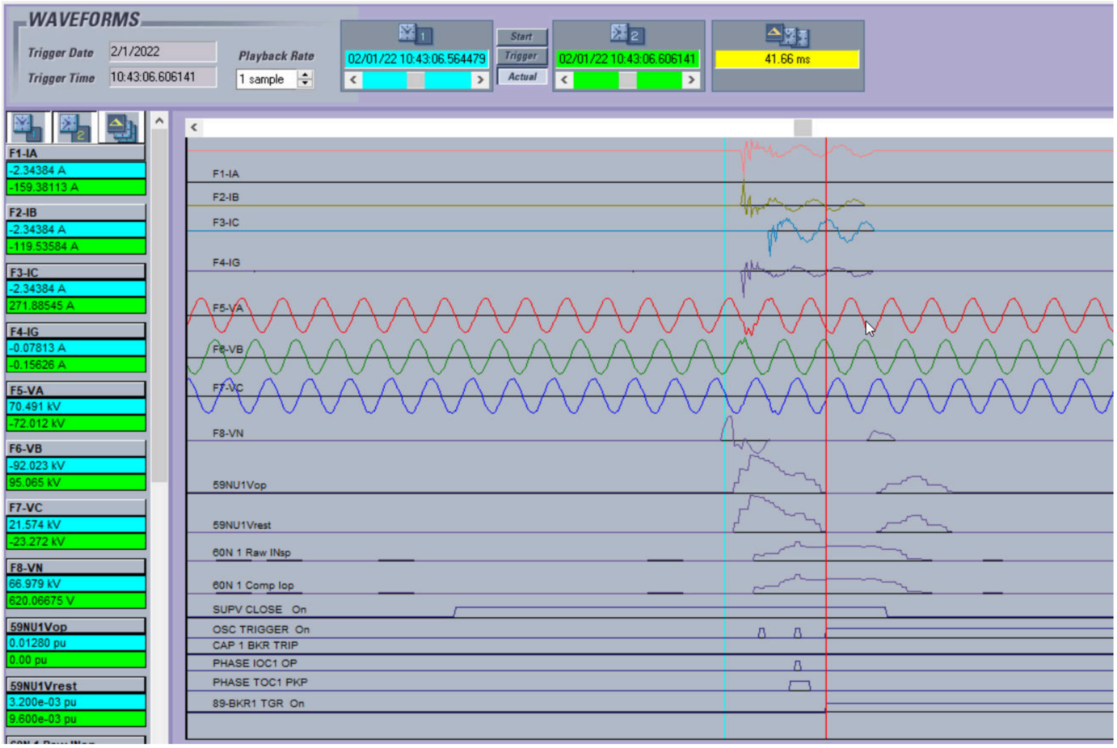
SETTING	PARAMETER
Neutral Current Unbalance 1 Function	Enabled
Neutral Current Unbalance 1 Bank Source	NeutUn (SRC 2)
Neutral Current Unbalance 1 k MAG	0.0000
Neutral Current Unbalance 1 k ANG	0 deg
Neutral Current Unbalance 1 STG1 PKP	0.048 pu
Neutral Current Unbalance 1 STG1 SLOPE	0.0 %
Neutral Current Unbalance 1 STG2 PKP	0.072 pu
Neutral Current Unbalance 1 STG2 SLOPE	0.0 %
Neutral Current Unbalance 1 STG3 PKP	0.072 pu
Neutral Current Unbalance 1 STG3 SLOPE	0.0 %
Neutral Current Unbalance 1 STG4 PKP	0.072 pu
Neutral Current Unbalance 1 STG4 SLOPE	0.0 %
Neutral Current Unbalance 1 STG1 DEL	1.00 s
Neutral Current Unbalance 1 STG2 DEL	0.17 s
Neutral Current Unbalance 1 STG3 DEL	0.17 s
Neutral Current Unbalance 1 STG4 DEL	0.17 s
Neutral Current Unbalance 1 DPO DEL	0.25 s
Neutral Current Unbalance 1 STG1 Block	89H-a2 Off(P8a)
Neutral Current Unbalance 1 STG2 Block	89H-a2 Off(P8a)
Neutral Current Unbalance 1 STG3 Block	ON
Neutral Current Unbalance 1 STG4 Block	ON
Neutral Current Unbalance 1 Target	Self-reset
Neutral Current Unbalance 1 Events	Enabled

Grouped Elements:

Figure 20. Neutral voltage unbalance 59NU settings

d) Bank overcurrent 60N

The modern capacitor-bank protection relay has many settings. Gathering bank data and running studies informs the settings values. Occasionally, errors occur when creating settings that make it past reviews and commissioning. This is the case with a bank trip, shown in the oscillograph in Figure 21.



WAVEFORMS

Trigger Date: 2/1/2022

Trigger Time: 10:43:06.606141

Playback Rate: 1 sample

Cursor 1: 02/01/22 10:43:06.564479

Cursor 2: 02/01/22 10:43:06.606141

41.66 ms

F1-IA	-2.34384 A	-159.38113 A
F2-IB	-2.34384 A	-119.53584 A
F3-IC	-2.34384 A	271.88545 A
F4-IG	-0.07813 A	-0.15626 A
F5-VA	70.491 kV	-72.012 kV
F6-VB	-92.023 kV	95.065 kV
F7-VC	21.574 kV	-23.272 kV
F8-VN	66.979 kV	620.06675 V
59NU1Vop	0.01280 pu	0.00 pu
59NU1Vrest	3.200e-03 pu	9.600e-03 pu

Figure 21. Closing SCB event

This capacitor bank is a split wye, ungrounded bank at 115 kV. The bank rating is 34 MVAr with 20 cans per phase. The bank arrangement is shown in Figure 22.

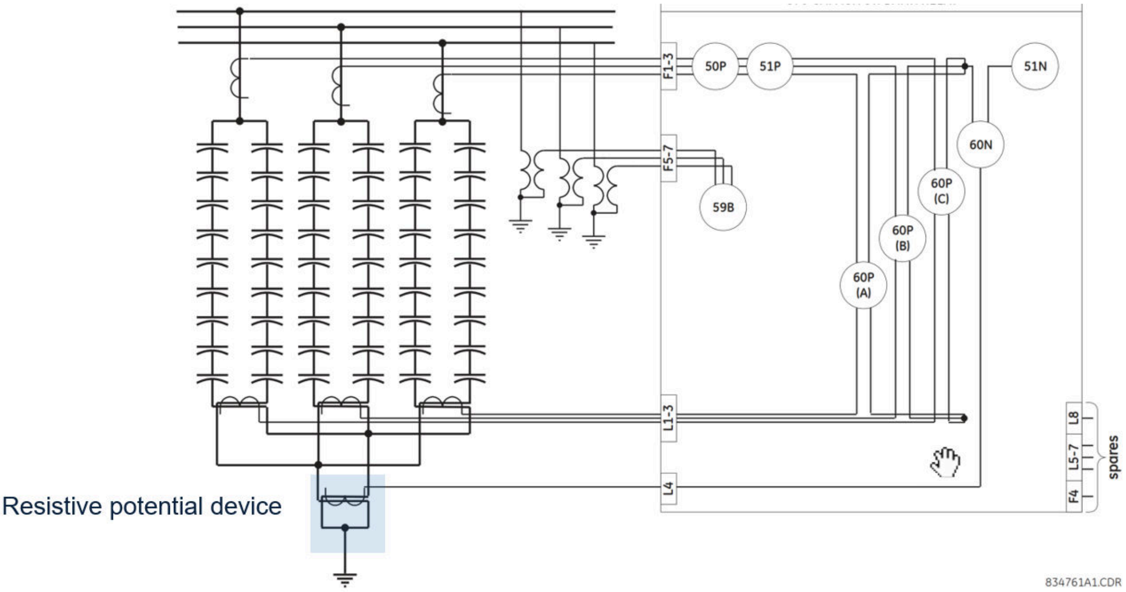


Figure 22. Current balance protection 60N and 60P

Operations closed the SCB, and surge charge current caused the bank to trip. Note that the neutral current unbalance 60N becomes active, and the bank opens as seen in the 89-BKR1 TGR On status. This was normal operation, not a trip. Settings were increased to ride through this event.

e) Bank phase overvoltage 59B settings

Abnormal system conditions can cause overvoltage stress to the capacitor bank. It is good practice to evaluate the capability of the bank to withstand transient overvoltages, according to the IEEE 1036-1992 standard or to manufacturer specifications. For example, consider the following manufacturer overvoltage tolerance limits to protect against overvoltage transients stressing the capacitor insulation:

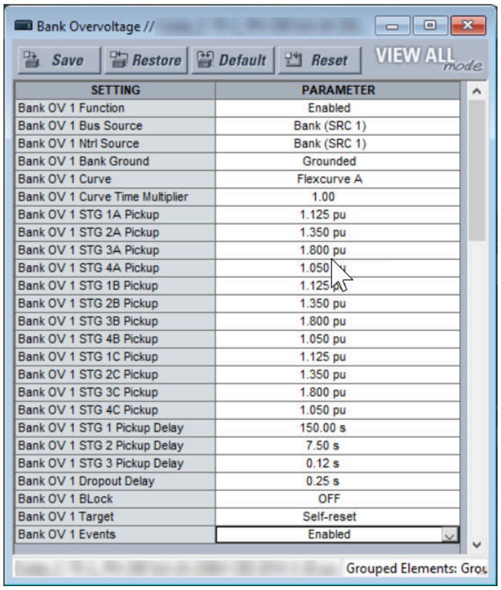
- 2 pu overvoltage for 0.25 second
- 1.5 pu overvoltage for 15 seconds
- 1.25 pu overvoltage for 5 minutes

Account for these tolerance limits conservatively when calculating the relay settings, approaching to within 10 percent of the limit (set to 90 percent) and at half the time. Three overvoltage trip stages are applied using a factor of 0.9 for the stage pickup overvoltage levels and half of the allowable time outlined (to prevent exceeding the lifetime limit).

Table 1. Bank phase overvoltage 59B settings

59B	Amplitude calculation	Pickup setting	50 percent of maximum time (s)
Stage 1	0.9 • 1.25	1.125 pu	150
Stage 2	0.9 • 1.5	1.35 pu	7.5
Stage 3	0.9 • 2	1.80 pu	0.125

The resulting relay settings are these for the three stages (Figure 23):



SETTING	PARAMETER
Bank OV 1 Function	Enabled
Bank OV 1 Bus Source	Bank (SRC 1)
Bank OV 1 Ntrl Source	Bank (SRC 1)
Bank OV 1 Bank Ground	Grounded
Bank OV 1 Curve	Flexcurve A
Bank OV 1 Curve Time Multiplier	1.00
Bank OV 1 STG 1A Pickup	1.125 pu
Bank OV 1 STG 2A Pickup	1.350 pu
Bank OV 1 STG 3A Pickup	1.800 pu
Bank OV 1 STG 4A Pickup	1.050
Bank OV 1 STG 1B Pickup	1.125
Bank OV 1 STG 2B Pickup	1.350 pu
Bank OV 1 STG 3B Pickup	1.800 pu
Bank OV 1 STG 4B Pickup	1.050 pu
Bank OV 1 STG 1C Pickup	1.125 pu
Bank OV 1 STG 2C Pickup	1.350 pu
Bank OV 1 STG 3C Pickup	1.800 pu
Bank OV 1 STG 4C Pickup	1.050 pu
Bank OV 1 STG 1 Pickup Delay	150.00 s
Bank OV 1 STG 2 Pickup Delay	7.50 s
Bank OV 1 STG 3 Pickup Delay	0.12 s
Bank OV 1 Dropout Delay	0.25 s
Bank OV 1 BLock	OFF
Bank OV 1 Target	Self-reset
Bank OV 1 Events	Enabled

Figure 23. Bank phase overvoltage 59B stages settings

V. Conclusions

Protecting capacitor banks is a significant challenge. Effective protection methods include voltage differential (87V), neutral-voltage unbalance (59NU), phase-current unbalance (60P), neutral-current unbalance (60N) and bank phase overvoltage (59B). These methods are applied depending on the capacitor-bank arrangement and measuring points. The modern capacitor-bank protection relay compensates for unbalances among the power-system phase voltages through auto setting and self-tuning, increasing both sensitivity and security of protection. Real-world examples showed the applications of the protection methods.

VI. Bibliography

[1] IEEE Std 18-2012, IEEE Standard for Shunt Power Capacitors

[2] IEEE Std 1036-2020, Guide for the Application of Shunt Power Capacitors

[3] Fundamentals of Adaptive Protection of Large Capacitor Banks – Accurate Methods for Canceling Inherent Bank Unbalances; B. Kasztenny, J. Schaefer, E. Clark; Georgia Tech Protective Relay Conference, 2006

[4] Shunt Capacitor Bank Fundamentals and Protection; G. Brunello, B. Kasztenny, C. Wester; Conference for Protective Relay Engineers, Texas A&M University, 2003

[5] IEEE Std C37.99-2012, IEEE Guide for the Protection of Shunt Capacitors Banks

VII. Biographies

Ryan Bowersox received his BSEE degree from the University of Florida in 2006. He is a Senior Engineer in the Design and Applications group within Power Delivery at Florida Power and Light Company. He has 15 years of experience in protection and control, all at FPL. He is a licensed Professional Engineer in the state of Florida and is a Senior Member of the IEEE. Ryan is currently pursuing a PSM degree in Power Systems Engineering from Washington State University.

Daniel Ransom, PE is a Senior Technical Application Engineer at GE Grid Solutions, located in Tacoma, WA USA. Dan specializes in protection and automation development and applications support. He has a BSEE from Gonzaga University, Spokane, WA, and a degree from Washington State University, Pullman, WA. Dan is a Senior Member of the IEEE and participates in PES standards committees.

Joe Schaefer, PE, received his BSEE from the University of Florida. Joe has more than 30 years of experience in protection and control systems. In his current role, Joe is a principal engineer in the Design and Applications Group at Florida Power & Light. He is responsible for designing and testing relaying systems for transmission, distribution, and DER applications. Joe is a member of IEEE, PES, and IEEE 1547 WG.