Minimizing Capacitor Bank Outage Time Through Fault Location

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***Abstract*—Capacitor banks are critical substation assets that play a vital role in providing reactive power support, thereby increasing the power system capacity. High-voltage capacitor banks are constructed as single-wye, double-wye, or H-bridge configurations and can be grounded or ungrounded. Capacitor banks consist of a number of single-phase capacitor units connected in series and parallel to achieve the desired voltage and VAR rating. The capacitor units can be externally or internally fused, fuseless, or unfused. When the unbalance resulting from unit or element failures becomes too high, the capacitor bank needs to be taken out of service by the protection system before the resulting unit overvoltages lead to a cascading failure and the faulty units must be replaced.**

If the bank is externally fused, then the unit with the blown fuse is usually the faulty unit, making identification obvious. If the bank is internally fused, fuseless, or unfused, then fault location is difficult because usually there is no visual indication of the problem. The result of a prolonged inspection is an extended outage of the capacitor bank. Although it might not be possible to identify the faulty unit in an internally fused, fuseless, or unfused bank, identifying the faulted phase and section narrows the search area and helps minimize the outage time.

This paper analyzes various capacitor bank configurations and proposes an economical method to help locate the faulty elements or units for each configuration. The paper also provides results that verify the proposed methods using a Real Time Digital Simulator (RTDS®).

I. INTRODUCTION

Shunt capacitor banks are essential in electrical power systems, playing a crucial part in providing reactive power support [1]. They provide voltage support and an improved system voltage profile at key points within the grid. In addition, they provide increased system capacity through the reduction of losses, and they provide a significant reduction and postponement of investments in transmission and generation capacity by relieving reactive power requirements. Because capacitor banks are relatively inexpensive, are quick to install, and can be deployed nearly anywhere on the grid, they are an ideal choice for reactive power support when compared with transmission or generation system upgrades.

A shunt capacitor bank, as shown in Fig. 1, consists of single-phase capacitor units connected in series and parallel combinations to achieve the desired voltage and VAR rating. Similarly, each capacitor unit consists of individual capacitor elements connected in series and parallel combinations. The capacitor units can be externally fused, internally fused, or fuseless.

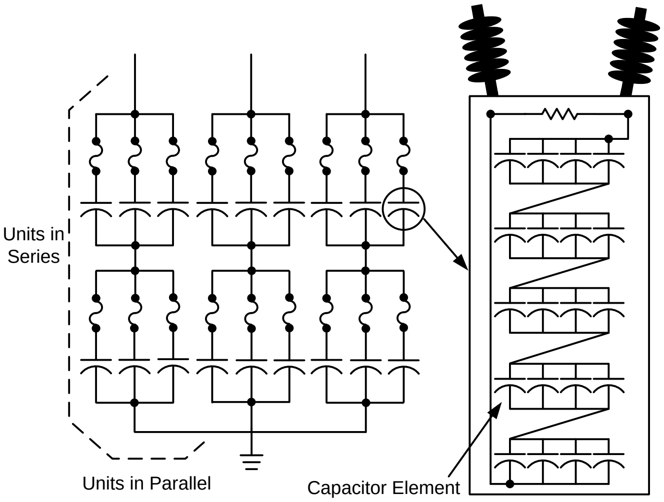

Fig. 1. Capacitor Bank Configuration

Although modern capacitor units are more reliable than earlier units, failures within the bank still occur, resulting in an unbalance condition within the in-service bank. If the unbalance is severe, a protective relay operates to take the bank out of service. In many cases, the unbalance only activates an alarm and does not trip the bank. If the bank remains in service because the unbalance condition is not severe enough to operate the relay protection, the remaining capacitor units are subjected to increased voltages, which can lead to cascading failures of the remaining units. When too many capacitor banks within an area are unavailable for service due to failures, the desired system benefits are not achieved. It is prudent to repair capacitor banks in a timely manner so that the proper system voltage profile can be maintained.

Typical steps to replace faulty units and put the bank back in service are as follows:

- Take the bank out of service.
- Isolate and ground the bank.
- Disconnect each unit.
- Identify the faulty unit by measuring the capacitance across each unit in the bank.
- Obtain the capacitances of the spare unit.
- Enter the capacitances in a spreadsheet.
- Balance the capacitances in the spreadsheet.
- Replace the faulty unit.
- Move other units within the bank (if required).
- Energize the bank.

The identification of the faulted unit is obvious in an externally fused bank (i.e., a blown fuse), but there is usually no physical evidence that a unit has failed for internally fused or fuseless banks. Modern banks are typically internally fused or fuseless, and therefore, the majority of the outage time is spent locating the faulty units.

Field operations personnel are faced with many challenges in a modern business environment. Cost-effective operation and maintenance programs are paramount to control departmental costs. A capacitor bank that has an unbalance alarm due to a unit or element failure may simply be left unattended for an extended period of time because the bank is still available for service. Whether a capacitor bank outage is planned in advance for repair or occurs suddenly due to an unbalance lockout event, the majority of the outage time is spent locating the faulty unit. The result is an extended outage of the capacitor bank while an electrical crew works to identify the failed capacitor units.

Narrowing the search by identifying the phase and section of the capacitor bank with the faulty unit or element significantly reduces operating and maintenance costs for utilities, allowing the bank to be returned to service quickly and thereby improving system reliability.

II. FAULT LOCATION TECHNIQUE

Unbalance protection methods provide primary protection against unit failures in capacitor banks. These methods detect unbalances within the bank due to element or unit failures. Unbalance protection asserts an alarm signal if the unbalance is small but trips the bank if the unbalance is high enough to cause a cascading failure.

There are four commonly used unbalance protection methods, as follows [2] [3]:

- Phase voltage unbalance.
- Neutral voltage unbalance.
- Phase current unbalance.
- Neutral current unbalance.

The choice of protection method depends on various factors such as bank configuration, availability of instrument transformers, sensitivity, and security. The unbalance protection methods use one or more of the measured quantities such as bus voltages, bank currents, neutral voltage, and neutral current to calculate the unbalance quantity.

The unbalance quantity is a phasor, and its magnitude measures the unbalance within the bank. The magnitude of the unbalance quantity directly indicates the number of failed elements or units.

This paper proposes a fault location technique that uses the phase angle of the unbalance quantity and compares it with a reference quantity phase angle [4] [5]. The reference quantity can be a phase voltage (bus), phase current (bank), positive-sequence bus voltage, positive-sequence bank current, and so on. If the bank is protected with the phase voltage or phase current unbalance protection method, then use phase voltage (bus) or phase current (bank) as the reference quantity. If the bank is protected with the neutral voltage or neutral current unbalance protection method, then use positive-sequence bus voltage or positive-sequence bank current as the reference quantity. The proposed fault location technique helps in identifying the phase and section of the bank that has the faulty element or unit. The fault location information can be included as part of the event report and can be used by the utility crew to perform planned maintenance.

For sensitivity, the fault location technique is supervised with an alarm or trip condition from unbalance protection. For security, a ±15-degree blinder is applied to exclude unbalances not resulting from capacitor failures, such as instrument transformer errors. The fault location technique is embedded as part of the unbalance protection, and hence, it is an economical solution.

The fault location technique is affected by the fusing method of the bank (i.e., whether it is fused or fuseless). Fig. 2, Fig. 3, and Fig. 4 illustrate an example that shows the impedance and voltage and current distribution of a fused or fuseless bank. Fig. 2, Fig. 3, and Fig. 4 show four series groups of ten capacitors in parallel to demonstrate the three stages of a fuse operation. A capacitor symbol represents either one row of an internally fused unit or a complete unit in an externally fused bank.

Fig. 2 shows the normal state. Fig. 3 shows the circuit just after a short circuit occurs but before the fuse operates. Fig. 4 shows the final state of an externally or internally fused bank after the fuse operation. Impedance increases after the fuse operation. Fig. 3 represents the final state of a fuseless bank. Impedance decreases after a short circuit. This impedance variation affects the current and voltage distribution. Because the fault location technique is based on phase angle comparison, the current and voltage distribution affects the fault location.

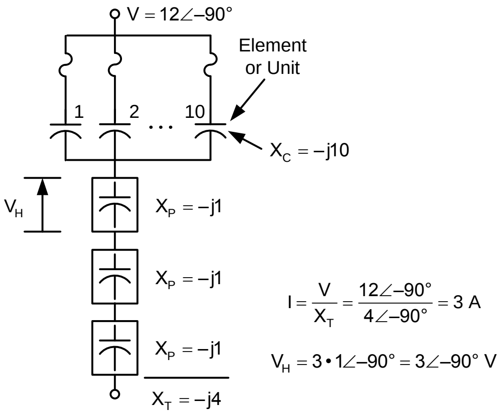

Fig. 2. Healthy System

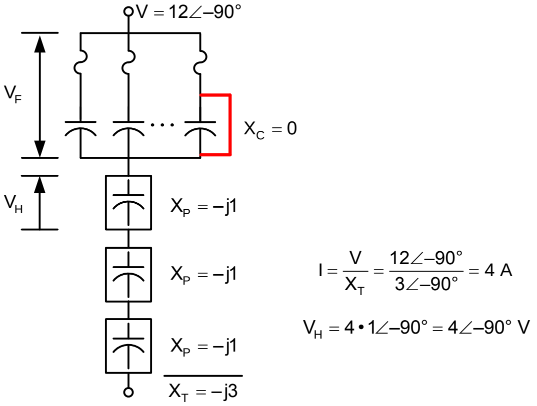

Fig. 3. System With Short Circuit

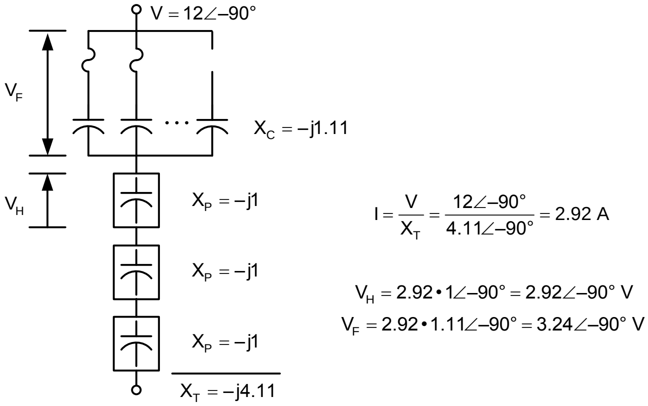

Fig. 4. System With Blown Fuse

The fault location technique is not affected by the inherent unbalance as long as the unbalance protection compensates for it. Unbalance protective relays are often provided with a manual command to reset the inherent unbalance. The inherent unbalance can be from the manufacturing intolerances in the bank, temperature changes, and so on. A bank with element or unit failures that cause acceptable overvoltage can be left in operation for some time awaiting scheduled or emergency maintenance. This can cause an unbalance alarm that needs to be reset by the protective relay so that subsequent failures are detected with maximum sensitivity. The fault location information needs to be saved before resetting the unbalance alarm. When a second failure happens, which results in an alarm or trip, the fault location technique is accurate for the second failure despite the preexisting failure. When the bank is taken out of service, personnel must search for two failures using the original and subsequent fault location information.

The following sections explain this fault location technique that can be used for various capacitor bank configurations, depending on the type of unbalance protection method used. The power system shown in Fig. 5 was modeled using a Real Time Digital Simulator (RTDS®) and used to validate the fault location technique for various capacitor bank configurations.

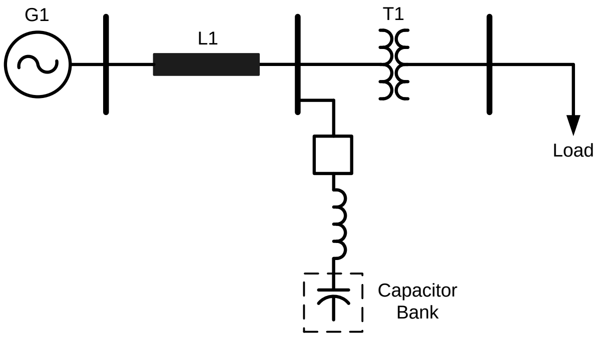

Fig. 5. Power System Modeled in RTDS

III. BANKS USING PHASE VOLTAGE UNBALANCE PROTECTION

A. Single-Wye Bank With Tapped Potential Transformer: Protection Theory and Fault Location Principle

Phase voltage unbalance or phase voltage differential protection is applied to a wye-connected capacitor bank with a potential transformer (PT) at the tap point, as shown in Fig. 6. The tap point can be at the midpoint of the bank or at a low-voltage capacitor just above the wye connection. The faulty element or unit can be in any of six locations in this bank—in any of the three phases and either above the tap point (top section) or below the tap point (bottom section) of each phase.

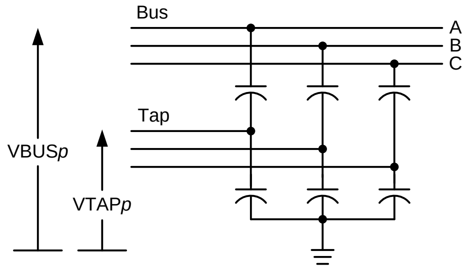

Fig. 6. Banks Using Tapped PT-Based Phase Voltage Unbalance Protection

The protection uses tapped voltage and bus voltage measurements to calculate the unbalance quantity as shown in (1).

$$DVp = VBUSp - Kp \cdot VTAPp \qquad (1)$$

where:

VBUS*p* is the Phase *p* bus voltage phasor.

VTAP*p* is the Phase *p* tap voltage phasor.

K*p* is the Phase *p* phasor setting based on relay measurements that reset DV*p*.

p is A, B, or C.

The unbalance quantity is per phase and so is the unbalance protection. The phase (A, B, or C) of the bank with the faulty unit or element is the phase for which the protection has operated (based on unbalance quantity magnitude). Comparing the phase angle of the unbalance quantity with the phase angle of the bus voltage allows the fault location to be further narrowed down by identifying the section (top or bottom from the tapped point) of the phase.

Fig. 7 shows the fault location technique for banks using voltage inputs from the tap point to provide per-phase voltage unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the respective bus voltage, and the referenced phase unbalance angle, DV*p*A, is then checked to determine if it is in Sector 1 (0° ± 15°) or Sector 2 (180° ± 15°).

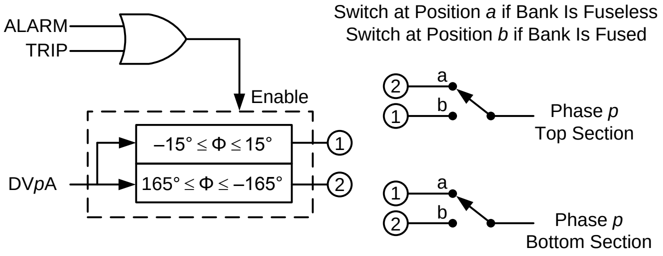

Fig. 7. Fault Location for Banks Using Phase Voltage Unbalance

For a fused bank, if DV*p*A is in Sector 1, then the faulty unit or element is in Phase *p* and the top section from the tap point. If DV*p*A is in Sector 2, then the faulty unit or element is in Phase *p* and the bottom section from the tap point. If the bank is fuseless, then the section identification is opposite (i.e., if DV*p*A is in Sector 1, then the fault is in the bottom section, and if DV*p*A is in Sector 2, then the fault is in the top section).

This economical fault location technique reduces the investigation time by 83.3 percent (one out of six possible fault locations) for a wye-connected grounded or ungrounded bank that uses phase voltage unbalance protection. Maximum gains in the search time are possible if the tap is at the midpoint. The worst-case reduction approaches 66 percent (only a faulted phase) if the tap is very close to the neutral point of the bank.

B. Single-Wye Bank With Tapped PT: Simulation Capture Using the RTDS

An 88 kV, 27.43 MVAR capacitor bank was modeled in the RTDS. The bank is a single-wye grounded configuration and has a tap point in each phase for phase unbalance protection. The bank is internally fused and consists of 96 capacitor units. Fig. 8 shows the per-phase representation of the bank. Each phase of the bank has eight parallel grouped units connected in series (i.e., 32 units per phase). Each parallel group consists of four units. There are four parallel groups in the top section and four in the bottom section, so the tap is at the midpoint of the bank. Each capacitor unit consists of three parallel grouped elements, and each parallel group consists of 12 elements. The capacitor unit is rated at 6.7 kV and 318 kVAR.

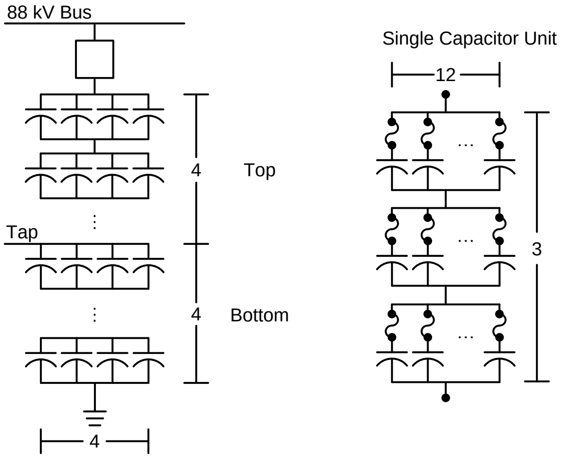

Fig. 8. Capacitor Bank Model for Phase Voltage Unbalance Fault Location

Fig. 9 shows the bus voltages and tap point voltages measured by the bus and tap point PTs. The secondary voltages are fed to a relay model that provides the unbalance protection. Fig. 9 also shows the Phase A voltage unbalance magnitude and the Phase A voltage unbalance angle referenced to the Phase A bus voltage from the relay model. An internal fault is simulated in the healthy bank by shorting four elements in a unit in Phase A and the top section of the bank. The fault is cleared by blowing appropriate fuses for the shorted elements, resulting in an unbalance voltage magnitude of 0.3 V secondary and an unbalance angle close to 0 degrees. The relay is set to assert an alarm above 0.2 V after a time delay. Fig. 9 shows that the relay correctly asserts ALARM A, PHASE A, and TOP A, indicating the faulty element or unit is in Phase A and the top section.

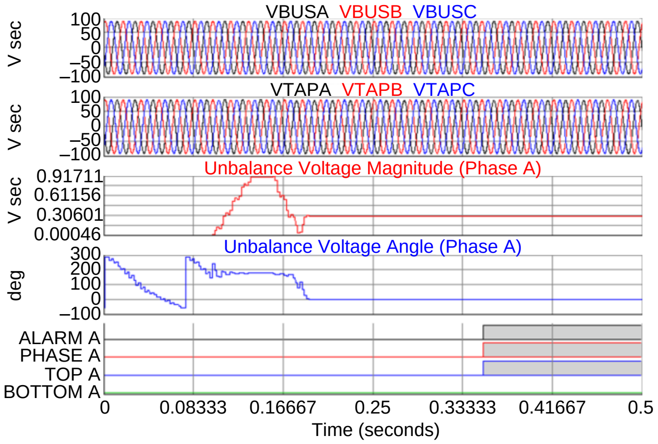

Fig. 9. Fault in Phase A and Top Section of a Bank Using Phase Voltage Unbalance Protection

An internal fault is simulated in the healthy bank by shorting four elements and blowing the respective fuses in a unit in Phase A and the bottom section of the bank. The fault results in an unbalance voltage magnitude of 0.3 V secondary and an angle close to 180 degrees. Fig. 10 shows the relay correctly asserts ALARM A, PHASE A, and BOTTOM A, indicating the faulty element or unit is in Phase A and the bottom section.

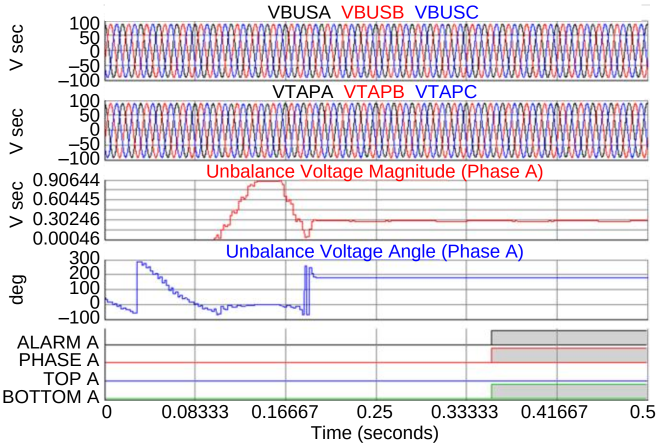

Fig. 10. Fault in Phase A and Bottom Section of a Bank Using Phase Voltage Unbalance Protection

IV. BANKS USING NEUTRAL VOLTAGE UNBALANCE PROTECTION

A. *Single- or Double-Wye Banks With Neutral-to-Ground PT*

1) *Protection Theory and Fault Location Principle*

Neutral voltage unbalance protection is applied to a wye-connected capacitor bank with a neutral PT, as shown in Fig. 11. The bank can be single or double wye. The faulty element or unit can be in any of three locations (three phases) for a single-wye bank and any of six locations (left or right section of each of the three phases) for a double-wye-connected bank.

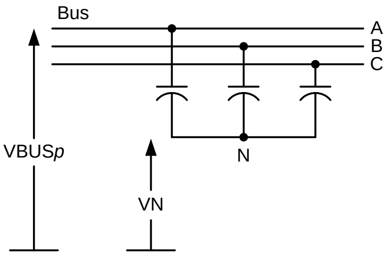

Fig. 11. Ungrounded Bank Using Neutral Voltage Unbalance Protection

The unbalance protection uses the neutral voltage and bus voltage measurements to calculate the unbalance quantity as shown in (2).

$$\begin{aligned}DVG &= VBUSA + VBUSB + VBUSC - 3 \bullet VN - \\ &\left(K1 \bullet (VBUSB - VN) + K2 \bullet (VBUSC - VN)\right)\end{aligned} \quad (2)$$

where:

VBUS*p* is the Phase *p* bus voltage phasor.

VN is the neutral voltage phasor.

K1 and K2 are the scale factor settings based on the relay measurements that reset DVG.

The unbalance quantity is not per phase, so the phase that has the faulty unit or element cannot be determined based on the unbalance protection operation. However, by comparing the phase angle of the unbalance quantity with the phase angle of the positive-sequence bus voltage, we can identify the phase that has the faulty unit or element.

Fig. 12 shows the fault location technique for ungrounded banks using neutral voltage unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bus voltage. The referenced phase unbalance angle, DVGA, is then checked to determine if it is in Sector 1 (0° ± 15°), Sector 2 (180° ± 15°), Sector 3 (–120° ± 15°), Sector 4 (60° ± 15°), Sector 5 (120° ± 15°), or Sector 6 (–60° ± 15°). For a fuseless bank, if DVGA is in Sector 1, then the faulty unit or element is in Phase A. If DVGA is in Sector 3, then the faulty unit or element is in Phase B. If DVGA is in Sector 5, then the faulty unit or element is in Phase C.

For a fused bank, if DVGA is in Sector 2, then the faulty unit or element is in Phase A. If DVGA is in Sector 4, then the faulty unit or element is in Phase B. If DVGA is in Sector 6, then the faulty unit or element is in Phase C.

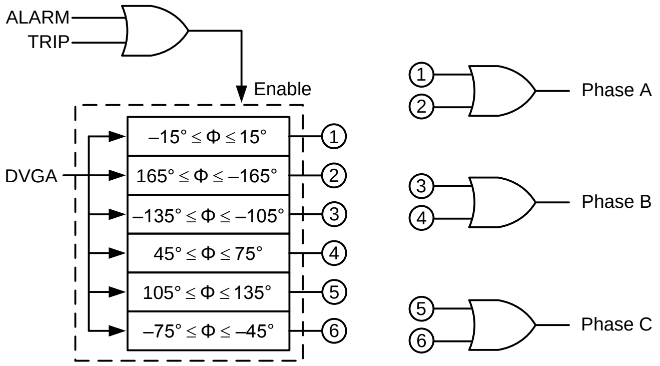

Fig. 12. Fault Location for Single-Wye Banks Using Neutral Voltage Unbalance Protection

This economical fault location technique reduces investigation time by 66.6 percent (one out of three possible faulted phases) for a single-wye ungrounded bank that uses neutral voltage unbalance protection.

This fault location technique can be applied to a double-wye ungrounded bank with a common neutral and a single neutral PT for neutral unbalance protection. In this case, however, the fault location technique cannot identify the section of the bank that has the fault. It can still identify the phase of the bank, resulting in a 66.6 percent (two out of six possible fault locations) reduction in investigation time.

2) Simulation Capture Using the RTDS

A 230 kV, 108.53 MVAR capacitor bank was modeled in the RTDS. The bank is a single-wye ungrounded configuration and has a neutral PT for neutral unbalance protection. The bank is fuseless and consists of 192 capacitor units. Fig. 13 shows a representation of the bank. Each phase of the bank has eight parallel strings with eight units connected in series, for a total of 64 units per phase. Each capacitor unit consists of a single string of eight elements in series. The capacitor unit is rated at 17.8 kV and 650 kVAR.

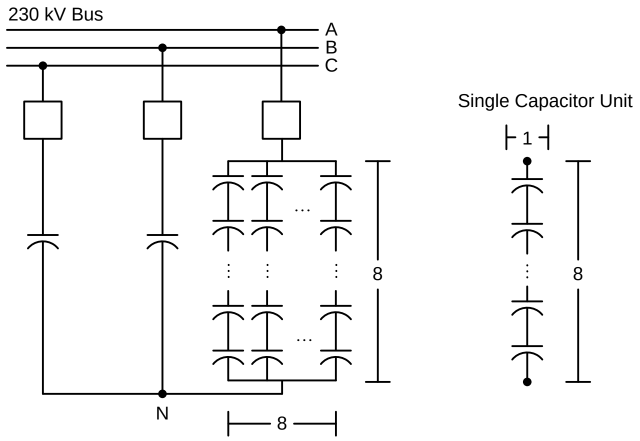

Fig. 13. Capacitor Bank Model for Neutral Voltage Unbalance Fault Location

Fig. 14 shows the bus voltages and neutral voltage measured by the bus and neutral PTs. The secondary voltages are fed to a relay model that provides the unbalance protection. Fig. 14 also shows the neutral voltage unbalance magnitude and the unbalance angle referenced to positive-sequence bus voltage from the relay model. An internal fault is simulated by shorting two elements in a unit in Phase A of the healthy bank, resulting in an unbalance voltage magnitude of 0.24 V secondary and an angle close to 0 degrees. The relay is set to assert an alarm above 0.2 V after a time delay. Fig. 14 shows the relay correctly asserts ALARM and PHASE A, indicating the faulty element or unit is in Phase A.

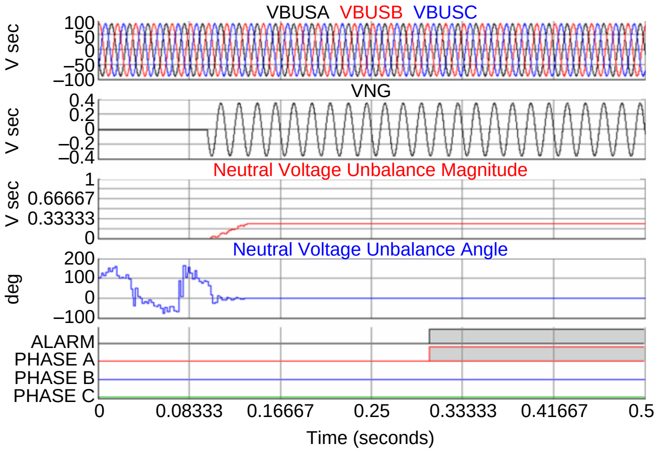

Fig. 14. Fault in Phase A of a Bank Using Neutral Voltage Unbalance Protection

An internal fault is simulated by shorting two elements in a unit in Phase C of the healthy bank. The fault results in an unbalance voltage magnitude of 0.24 V secondary and an angle close to 120 degrees. Fig. 15 shows the relay correctly asserts ALARM and PHASE C, indicating the faulty element or unit is in Phase C.

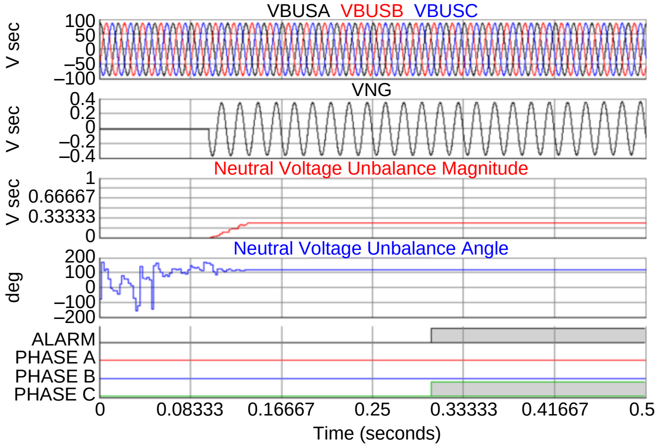

Fig. 15. Fault in Phase C of a Bank Using Neutral Voltage Unbalance Protection

B. Double-Wye Bank With PT Between Neutrals: Protection Theory and Fault Location Principle

Neutral voltage unbalance protection is applied to a double-wye-connected capacitor bank with a PT between the neutrals, as shown in Fig. 16. The faulty element or unit can be in any of six locations (three phases and the left or right section of each phase from the neutral PT).

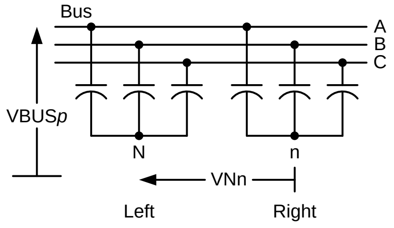

Fig. 16. Double-Wye Bank With a Neutral PT Using Neutral Voltage Unbalance Protection

The unbalance protection uses a neutral voltage (VNn) measurement to calculate the unbalance quantity as shown in (3).

$$\mathrm{DVG} = \mathrm{VNn} - \mathrm{Kn} \bullet \mathrm{V1BUS} \tag{3}$$

where:

VNn is the neutral voltage phasor.

V1BUS is the positive-sequence bus voltage phasor.

Kn is the phasor setting based on relay measurements that reset DVG.

Fig. 17 shows the fault location technique for double-wye ungrounded banks with a PT between the neutrals and using neutral voltage unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bus voltage, and the referenced phase unbalance angle, DVGA, is then checked to determine if it is in Sector 1 (0° ± 15°), Sector 2 (180° ± 15°), Sector 3 (–120° ± 15°), Sector 4 (60° ± 15°), Sector 5 (120° ± 15°), or Sector 6 (–60° ± 15°).

For a fuseless bank, if DVGA is in Sector 1, then the faulty unit or element is in Phase A and the left section of the bank. If DVGA is in Sector 2, then the faulty unit or element is in Phase A and the right section of the bank. Similar logic applies to Phase B and Phase C.

For a fused bank, if DVGA is in Sector 2, then the faulty unit or element is in Phase A and the left section of the bank. If DVGA is in Sector 1, then the faulty unit or element is in Phase A and the right section of the bank. Similar logic applies to Phase B and Phase C.

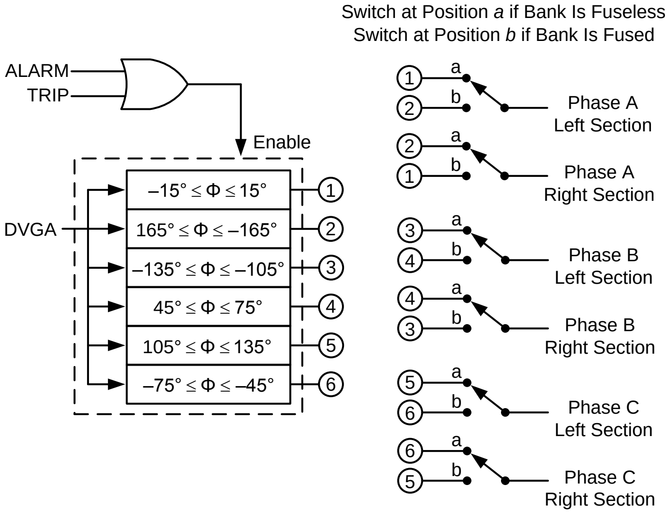

Fig. 17. Fault Location for Double-Wye Banks Using Neutral Voltage Unbalance Protection

This economical fault location technique reduces investigation time by 83.3 percent (one out of six possible fault locations) for a double-wye ungrounded bank with a PT between the neutrals that uses neutral voltage unbalance protection.

V. BANKS USING PHASE CURRENT UNBALANCE PROTECTION

A. H-Bridge Bank With Current Transformer (CT) in Each Phase

1) Protection Theory and Fault Location Principle

Phase current unbalance protection is applied to an H-bridge-connected capacitor bank, as shown in Fig. 18. The faulty element or unit can be in any of 12 locations (any of the three phases and the left, right, top, or bottom section of each phase from the bridge CT).

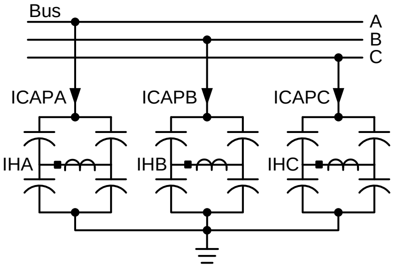

Fig. 18. H-Bridge Bank Using Phase Current Unbalance Protection

The protection uses balance or bridge current and bank current measurements to calculate the unbalance quantity as shown in (4).

$$60p = \mathrm{IH}p - \mathrm{K}p \bullet \mathrm{ICAP}p \tag{4}$$

where:

ICAP*p* is the Phase *p* bank current phasor.

IH*p* is the Phase *p* bridge current phasor.

K*p* is the Phase *p* phasor setting based on the relay measurements that reset 60*p*.

The unbalance quantity is per phase and so is the unbalance protection. The phase of the bank with the faulty unit or element is the phase for which the protection has operated (based on unbalance quantity magnitude). By comparing the phase angle of the unbalance quantity with the phase angle of the bank current, we can further narrow down the fault location by identifying the section.

Fig. 19 shows the fault location technique for H-bridge banks with phase current unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the respective bank current, and the referenced phase unbalance angle, 60*p*A, is then checked to determine if it is in Sector 1 (0° ± 15°) or Sector 2 (180° ± 15°).

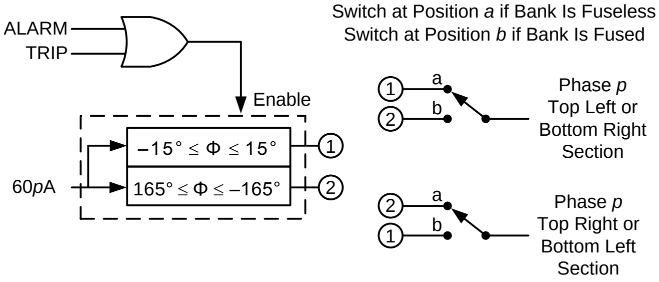

Fig. 19. Fault Location for H-Bridge Banks Using Phase Current Unbalance

For a fuseless bank, if 60*p*A is in Sector 1, then the faulty unit or element is in Phase *p* and either the top left or bottom right section. If 60*p*A is in Sector 2, then the faulty unit or element is in Phase *p* and either the top right or bottom left section. If the bank is fused, then the section identification is the opposite.

This economical fault location technique reduces the investigation time by 83.33 percent (2 out of 12 possible fault locations) for an H-bridge-connected grounded or ungrounded bank that uses phase current unbalance protection.

2) Simulation Capture Using the RTDS

A 345 kV, 130.9 MVAR capacitor bank was modeled in the RTDS. The bank is fuseless and consists of 264 capacitor units. Fig. 20 shows the Phase A representation of the bank. Each phase of the bank has eight parallel strings with 11 units connected in series, for a total of 88 units per phase. Each capacitor unit consists of a single string of six elements in series. The capacitor unit is rated at 9.96 kV and 600 kVAR.

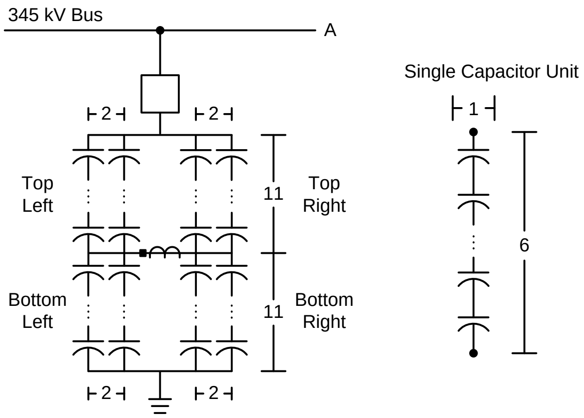

Fig. 20. Capacitor Bank Model for Phase Current Unbalance Fault Location

Fig. 21 shows the bank currents and bridge currents measured by the CTs. They are input to a relay model that provides the unbalance protection. Fig. 21 also shows Phase A current unbalance magnitude and Phase A current unbalance angle referenced to Phase A bank current from the relay model.

An internal fault is simulated by shorting five elements in a unit in Phase A and the top left section of the healthy bank. The fault results in an unbalance current magnitude of 2.2 A secondary and an angle close to 0 degrees. The relay is set to assert an alarm above 20 mA and after a time delay. Fig. 21 shows the relay correctly asserts 60ALARMA and LTRBA, indicating the faulty element or unit is in Phase A and in the top left or bottom right section.

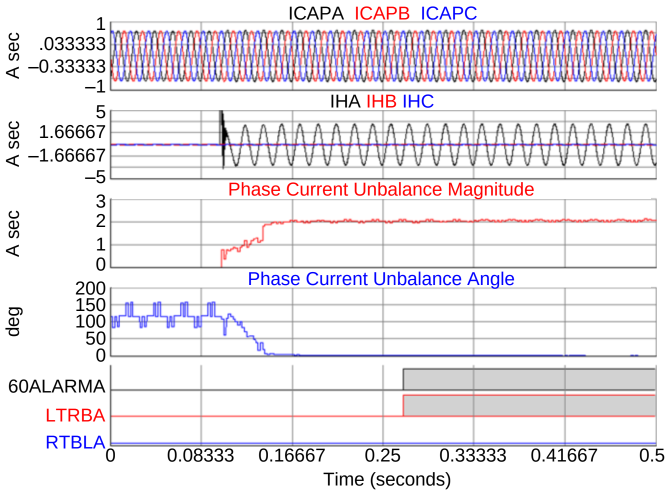

Fig. 21. Fault in Phase A Top Left Section of an H-Bridge Bank Using Phase Current Unbalance Protection

An internal fault is simulated by shorting five elements in a unit in Phase A and the bottom left section of the healthy bank. The fault results in an unbalance current magnitude of 2.2 A secondary and an angle close to 180 degrees. The relay is set to assert an alarm above 20 mA and after a time delay. Fig. 22 shows the relay correctly asserts 60ALARMA and RTBLA, indicating the faulty element or unit is in Phase A in the bottom left or top right section.

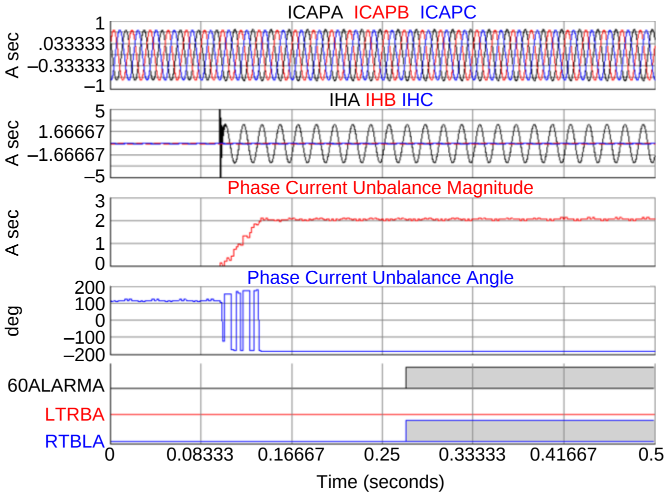

Fig. 22. Fault in Phase A Bottom Left Section of an H-Bridge Bank Using Phase Current Unbalance Protection

B. H-Bridge Bank With CT in Each Phase and PT at Tap Point

1) Protection Theory and Fault Location Principle

Modern protective relays can be configured to provide multiple unbalance protection schemes that are operative at the same time. This improves the reliability of the capacitor bank protection. If the H-bridge bank is provided with a PT at the tap point along with the bridge CTs, then both phase voltage and phase current unbalance protection can be applied at the same time. This scheme provides protection reliability, but most importantly, it can detect all 12 fault locations.

Fig. 23 shows the fault location technique for banks using tapped voltage-based phase voltage unbalance and bridge CT-based phase current unbalance protection. Recall that the phase current unbalance-based fault location can identify if the fault is in either the top left or bottom right sections and the top right or bottom left sections. Also, the phase voltage unbalance protection based on the voltage from the tap point can identify if the fault is in the top or bottom sections. Combining information from these two fault location techniques, we can identify any of the 12 fault locations in an H-bridge bank.

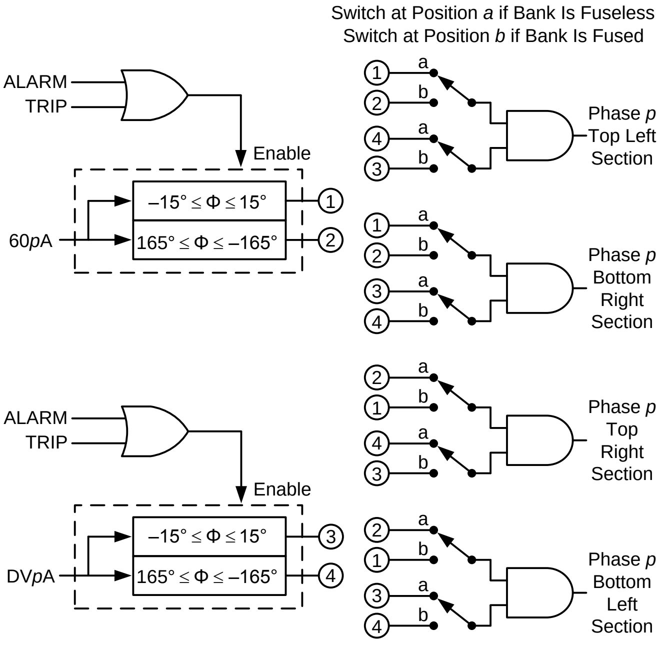

Fig. 23. Fault Location for H-Bridge Banks Using Phase Current and Phase Voltage Unbalance

This economical fault location technique reduces investigation time by 91.6 percent (1 out of 12 possible fault locations) for an H-bridge-connected grounded or ungrounded bank that uses phase current and phase voltage unbalance protection.

2) Simulation Capture Using the RTDS

Fig. 24 shows the Phase A voltage unbalance magnitude and the Phase A voltage unbalance angle referenced to the Phase A bus voltage angle, the Phase A current unbalance magnitude, and the Phase A current unbalance angle referenced to the Phase A bank current angle from the relay model. An internal fault is simulated by shorting five elements in a unit in Phase A and in the top left section of the bank. The fault results in an unbalance voltage magnitude of 1.25 V secondary and an angle close to 180 degrees. The relay is set to assert an alarm above 0.25 V after a time delay. Fig. 24 shows the relay correctly asserts 60ALARMA, 87ALARMA, LEFTA, and TOPA, indicating the faulty element or unit is in Phase A and the top left section.

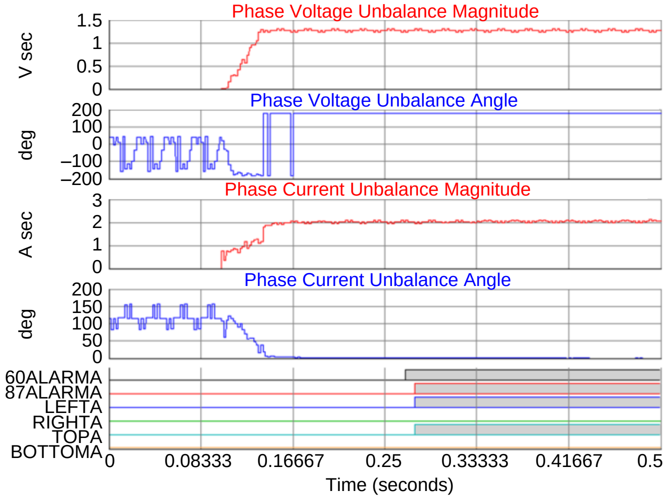

Fig. 24. Fault in Phase A Top Left Section of an H-Bridge Bank Using Phase Current and Phase Voltage Unbalance Protection

An internal fault is simulated by shorting five elements in a unit in Phase A in the bottom right section of the healthy bank. The fault results in an unbalance voltage magnitude of 1.25 V secondary and an angle close to 0 degrees. Fig. 25 shows the relay correctly asserts 60ALARMA, 87ALARMA, RIGHTA, and BOTTOMA, indicating the faulty element or unit is in Phase A in the bottom right section.

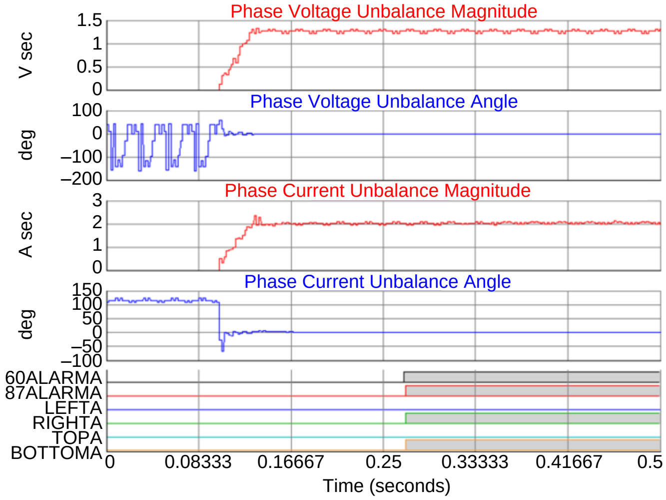

Fig. 25. Fault in Phase A Bottom Right Section of an H-Bridge Bank Using Phase Current and Phase Voltage Unbalance Protection

C. Double-Wye Bank With CT Measuring Each Phase Unbalance: Protection Theory and Fault Location Principle

Phase current unbalance protection is applied to a wye-connected capacitor bank with a CT measuring the phase unbalance, as shown in Fig. 26. The faulty element or unit can be in any of six locations (three phases and the left or right section of each phase CT).

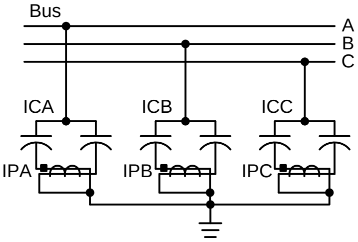

Fig. 26. Double-Wye Bank Using Phase Current Unbalance Protection

The unbalance protection and fault location technique are the same as for the H-bridge bank, but there are no top or bottom sections. Fig. 27 shows the fault location technique for this configuration.

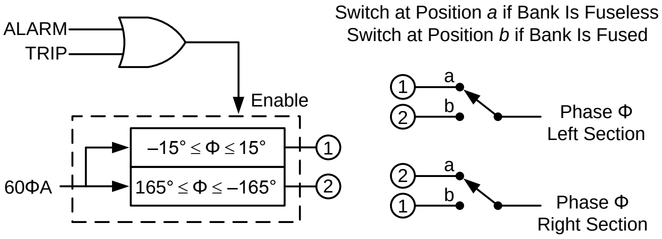

Fig. 27. Fault Location for Double-Wye Banks Using Phase Current Unbalance

This economical fault location technique reduces investigation time by 83.3 percent (one out of six possible fault locations) for double-wye-connected grounded or ungrounded banks that use phase current unbalance protection.

VI. BANKS USING NEUTRAL CURRENT UNBALANCE PROTECTION

A. Double-Wye Bank With a CT in the Common Neutral: Protection Theory and Fault Location Principle

Neutral current unbalance protection is applied to an double-wye-connected ungrounded capacitor bank with a CT in the common neutral, as shown in Fig. 28. The faulty element or unit can be in any of six locations (three phases and either the left or right section of each phase from the neutral CT).

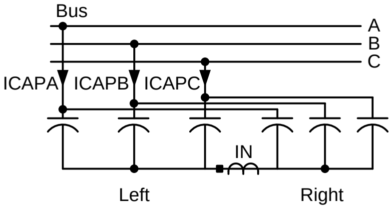

Fig. 28. Double-Wye Bank Using Neutral Current Unbalance Protection

The unbalance protection uses neutral current and bank current measurements to calculate the unbalance quantity as shown in (5).

$$60N = IN - \left(K1 \bullet ICAPB + K2 \bullet ICAPC\right) \qquad (5)$$

where:

ICAPp is the Phase p bank current phasor.

IN is the neutral current phasor.

K1 and K2 are the scale factor settings based on the relay measurements that reset 60N.

Fig. 29 shows the fault location technique for double-wye ungrounded banks with a CT in the common neutral and using neutral current unbalance protection. The phase angle of the unbalance quantity is referenced to the phase angle of the positive-sequence bank current (derived from ICAP*p*), and the referenced phase unbalance angle, 60NA, is then checked to determine if it is in Sector 1 (0° ± 15°), Sector 2 (180° ± 15°), Sector 3 (–120° ± 15°), Sector 4 (60° ± 15°), Sector 5 (120° ± 15°), or Sector 6 (–60° ± 15°). For sensitivity, the fault location technique is supervised with an alarm or trip condition from the unbalance protection. For security, a ±15-degree blinder is applied for unbalances not resulting from capacitor failures.

For a fuseless bank, if 60NA is in Sector 1, then the faulty unit or element is in Phase A in the left section of the bank. If 60NA is in Sector 2, then the faulty unit or element is in Phase A in the right section of the bank. Similar logic applies for Phase B and Phase C.

For a fused bank, if 60NA is in Sector 2, then the faulty unit or element is in Phase A in the left section of the bank. If 60NA is in Sector 1, then the faulty unit or element is in Phase A in the right section of the bank. Similar logic applies for Phase B and Phase C.

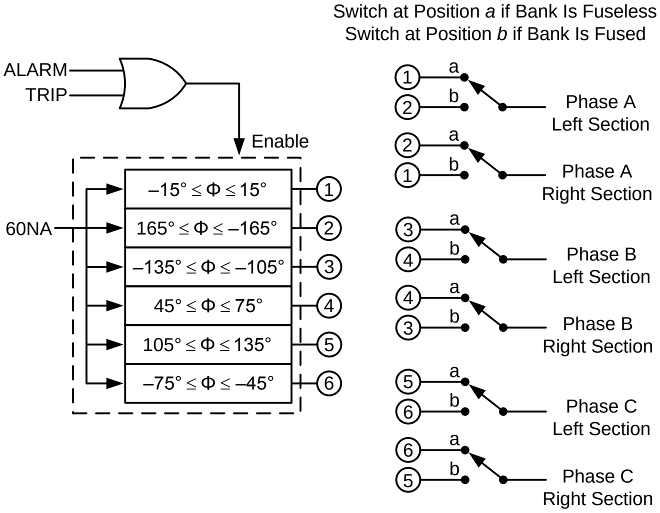

Fig. 29. Fault Location for Double-Wye Banks Using Neutral Current Unbalance Protection

This economical fault location technique reduces investigation time by 83.3 percent (one out of six possible fault locations) for a double-wye-connected ungrounded bank that uses neutral current unbalance protection.

B. Double-Wye Bank With a CT in the Common Neutral: Simulation Capture Using the RTDS

A 33 kV, 9.54 MVAR capacitor bank was modeled in the RTDS. The bank is a double-wye ungrounded configuration and has a CT between the neutrals for neutral current unbalance protection. The bank consists of 18 capacitor units and is internally fused. Fig. 30 shows the representation of the bank. Each capacitor unit consists of five series groups with each series group consisting of 15 elements connected in parallel. The capacitor unit is rated at 10.987 kV and 705 kVAR.

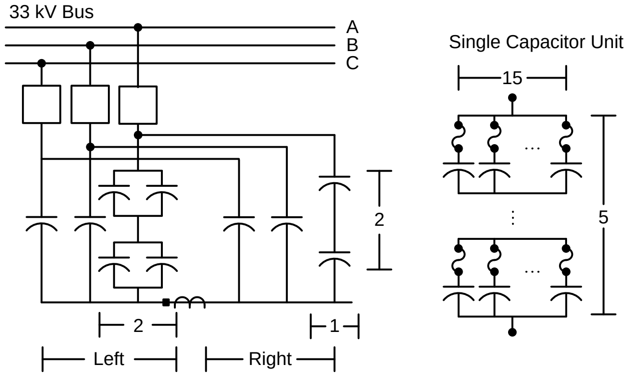

Fig. 30. Capacitor Bank Model for Neutral Current Unbalance Fault Location

Fig. 31 shows the bank and neutral currents measured by the bank and neutral CTs. They are input to a relay model that provides the unbalance protection. Fig. 31 also shows neutral current unbalance magnitude and neutral current unbalance angle referenced to the positive-sequence bank current from the relay model.

An internal fault is simulated by shorting two elements in a unit in Phase B and the left section of the healthy bank. The fault is cleared by blowing the appropriate fuses for the shorted elements, resulting in an unbalance current magnitude of 24 mA secondary and an angle close to 60 degrees. The relay is set to assert an alarm above 20 mA and after a time delay. Fig. 31 shows the relay correctly asserts 60ALARM, PHASE B, and LEFT, indicating the faulty element or unit is in Phase B in the left section.

Fig. 31 shows that the bank has some inherent unbalance (there is neutral current before the internal fault), which was compensated by the unbalance protective relay with new K1 and K2 factors. That is why the neutral current unbalance magnitude is reset before the internal fault. This demonstrates that the fault location technique is not affected by the inherent unbalance as long as it is compensated.

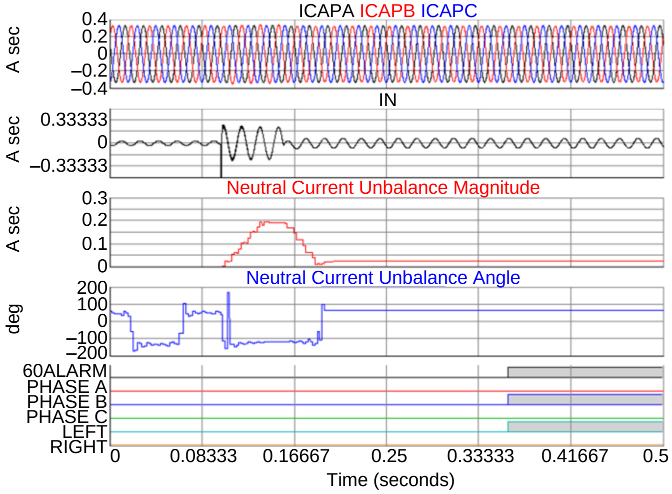

Fig. 31. Fault in Phase B and Left Section of a Bank Using Neutral Current Unbalance Protection

An internal fault is simulated by shorting two elements in a unit in Phase C and the right section of the healthy bank. The fault results in an unbalance current magnitude of 48 mA secondary and an angle close to 120 degrees, as shown in Fig. 32. Fig. 32 also shows the relay correctly asserts 60ALARM, PHASE C, and RIGHT, indicating the faulty element or unit is in Phase C and the right section.

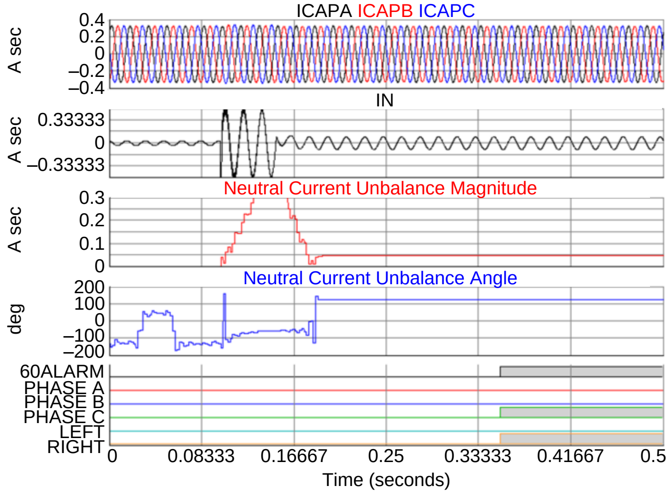

Fig. 32. Fault in Phase C and Right Section of a Bank Using Neutral Current Unbalance Protection

VII. CONCLUSION

Locating a faulty unit in a capacitor bank is a time-consuming process. The fault location technique proposed in this paper helps in identifying the phase and section of the bank with the faulty unit, thereby reducing the investigation time between 50 and 92 percent. The fault location technique is embedded as part of the unbalance protection, making it an economical solution. It can be applied to banks with various configurations and different fusing methods. The fault location technique is not affected by the inherent unbalance as long as the unbalance protection compensates it. The fault location technique helps in providing advance alarms for planned maintenance. It can be used to detect element failures in an externally fused bank before the fuse operates and therefore provide fuse savings and safety from case rupture. Using multiple unbalance protection methods helps to improve the reliability of protection and fault location.

VIII. REFERENCES

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[4] S. Samineni, C. Labuschagne, and J. Pope, “Principles of Shunt Capacitor Bank Application and Protection,” proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

[5] S. Samineni and C. Labuschagne, “Apparatus and Method for Identifying a Faulted Phase in a Shunt Capacitor Bank,” U.S. Patent 8 575 941, November 5, 2013.

IX. BIOGRAPHIES

Joseph Schaefer is a Principal Engineer at Florida Power & Light Company. He is responsible for developing and testing protective relay systems related to transmission, distribution, and distributed generation applications. Some of his designs include relay protection for grounded and ungrounded transmission capacitor banks up to 500 kV. Previously, Joe was employed as a protection field engineer responsible for relay equipment from 480 V to 500 kV applications. Joe received his BSEE from the University of Florida and joined Florida Power & Light Company in 1987. He is a member of IEEE.

Satish Samineni received his bachelor of engineering degree in electrical and electronics engineering from Andhra University, Visakhapatnam, India, in 2000. He received his master’s degree in electrical engineering from the University of Idaho in 2003. Since 2003, he has been with Schweitzer Engineering Laboratories, Inc. in Pullman, Washington, where he is a senior power engineer in the research and development division. He has authored or coauthored several technical papers and holds a United States patent. His research interests include power electronics and drives, power system protection, synchrophasor-based control applications, and power system stability. He is a registered professional engineer in the state of Washington and a senior member of IEEE.

Casper Labuschagne earned his diploma (1981) and master’s diploma (1991) in electrical engineering from Vaal University of Technology, South Africa, and is registered as a Professional Technologist with ECSA, the Engineering Council of South Africa. After gaining 20 years of experience with the South African utility Eskom, where he served as senior advisor in the protection design department, he began work at Schweitzer Engineering Laboratories, Inc. in 1999 as a product engineer. He transferred in 2003 to the research and development division, where he held the position of senior power engineer. In 2009, he was promoted to transmission engineering development manager. His responsibilities include the specification, design, testing, and support of transmission protection and control devices. Casper holds eight United States patents and has authored and coauthored several technical papers in the areas of protection and control.

Steven Chase received his bachelor of science degree in electrical engineering from Arizona State University in 2008 and his master of science in electrical engineering degree in 2009. He worked for two years as a substation design intern at Salt River Project, an Arizona water and power utility. He joined Schweitzer Engineering Laboratories, Inc. in 2010, where he works as a power engineer in the research and development division. He is currently an Engineer in Training.

Dereje Jada Hawaz received his bachelor of science degree in electronics engineering technology from DeVry University in 1999 and his master of engineering in electrical engineering from the University of Idaho in 2013. He joined Schweitzer Engineering Laboratories, Inc. in 1999 and has been involved in designing, developing, and validating protective relays. He is currently a power engineer in the research and development division. He is an IEEE member.

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