# Novel Methods to Detect and Identify Fault and Open-Phase Conditions in Pole-Top Capacitor Banks

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# Novel Methods to Detect and Identify Fault and Open-Phase Conditions in Pole-Top Capacitor Banks

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***Abstract*—A common modern method for detecting fault and open-phase conditions in three-phase gang-operated pole-top capacitor banks is to use the measured neutral current. The neutral current is equal to the sum of the three phase currents that flow through the capacitor bank. If a fuse opens or if a switch fails to open or close on one or two phases, the neutral current increases from nearly zero to the bank's rated phase current. As a result, the capacitor bank controller detects the large, unbalanced currents and may alarm or even trip the capacitor bank. The neutral current can also be caused by system unbalance or by the presence of triplen harmonics, so any scheme attempting to identify open capacitor phases using neutral current must also take these into account. Also, a scheme based only on the neutral current cannot identify which phase is open.**

**This paper proposes using a quantity calculated from phase voltage and the neutral current to help identify which phase or phases are faulted or open. The paper describes two methods. The first method uses only one calculation using positive-sequence voltage and the neutral current; the second method uses three calculations based on per-phase voltage and the neutral current. The first method is applicable to single- and three-phase controlled capacitor banks, and the second method is applicable to only three-phase controlled capacitor banks.**

**This paper describes the use of these calculations to identify and indicate the phase or phases that are actually open or faulted. This paper also describes the advantages and robustness of these methods compared to the neutral-current-only method and how the proposed methods overcome unbalanced system and harmonic distortion issues. Identifying how many phases are open and which particular phases are open can be useful in resolving failures, maintaining and operating capacitor bank systems, and allocating single-phase load flow models.**

## I. Introduction

Electric power distribution systems make use of pole-top mounted capacitor banks to minimize reactive demand along a distribution feeder [1]. By minimizing reactive demand, voltage drop along the feeder is also minimized. Some distribution feeders require this reactive support to maintain acceptable voltage during peak demand or during abnormal switching. In other cases, the reactive support provided by pole-top capacitor banks reduces line losses. In all cases, the reactive support provided on distribution feeders also supports the reactive needs of the transmission system feeding the distribution system.

Pole-top capacitor banks have an important job to do in the power system. When they become less available due to an open-phase or element fault condition [2], the utility owning the capacitor banks is motivated to repair and restore the capacitor banks and their reactive support as soon as possible.

Many unbalanced bank conditions result from problems that make the bank's reactive support less available. These unbalanced bank conditions cause current to flow in the bank neutral of a grounded wye capacitor bank (see Fig. 1). Many modern pole-top capacitor bank controllers include a measurement channel for a current transducer installed directly on the neutral conductor between the wye point and the pole ground or rack ground. These controllers can alert system operators when a significant unbalance current is flowing in the bank neutral so that they can respond to repair the cause of the unbalance. However, these schemes cannot tell which phase or phases of the bank are contributing to the unbalance.

Fig. 1a

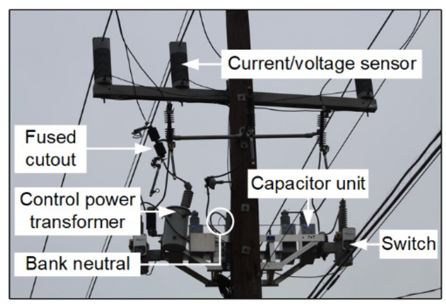


Fig. 1b

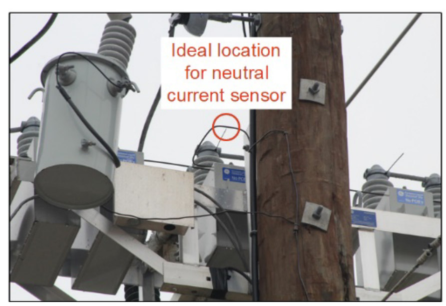


Fig. 1. Typical pole-top capacitor bank installation (a) and close-up of a neutral conductor from the wye point to the ground (b)

When a bank's unbalance condition persists, load flow models that assume three-phase reactive support present erroneous results. Even worse, if the metered peak load allocated to this load flow model is the result of bank unbalance but that unbalance is not accounted for, then there can be an incorrect allocation of reactive demand, which causes erroneous results for any subsequent load study. However, if system operators know when a bank unbalance occurs, which phase is involved, and when it is resolved, the model allocation can be confirmed and corrected if necessary.

In this paper, a novel method is introduced for identifying unique unbalanced conditions, then identifying which phase or phases are contributing to the unbalance condition. This enables capacitor bank operators to not only respond immediately to restore the bank to full service, but this also points them to the phase of the bank that needs attention, thus, reducing downtime. Historical records of these failures also help system operators maintain load flow models with allocations accurate to the time of unbalance conditions.

## II. Causes of Neutral Current

### A. *Open-Phase Conditions*

The most obvious cause of an open-phase condition on a capacitor bank is a blown fuse. The purpose of the fuse is to provide short-circuit protection. As a result, blown fuses are typically caused by catastrophic failure of multiple element layers within a capacitor unit but can also be caused by large switching transients, lightning, or high steady-state harmonic currents. Regardless of the cause, the blown fuse isolates its phase so that the capacitor bank now offers unbalanced reactive support. This can allow for excessive voltage drop on the unsupported phase and can even allow excessive voltage unbalance on the feeder. Blown fuses are typically easy to identify visually, since the fuse barrel is designed to drop open when the fuse link blows. However, exposure to corrosive or contaminant environments can cause the fuse barrel to become stuck in the cutout, even when the fuse link blows, making it hard to identify the blown fuse visually.

An open-phase condition on a switched capacitor bank can also be caused by the failure of one of the switches to operate. For instance, the capacitor bank controller can attempt to close the bank, but if one switch fails to close, there is now an open-phase condition on that phase. This failure mode can also be hard to identify since the contacts are internal to the switch and not visible to the operator.

An open-phase condition can also be caused by a jumper that fails open. These can also be hard to identify, since the jumper terminations (the most likely point for a jumper to fail) are often hidden by animal guards (Fig. 2).

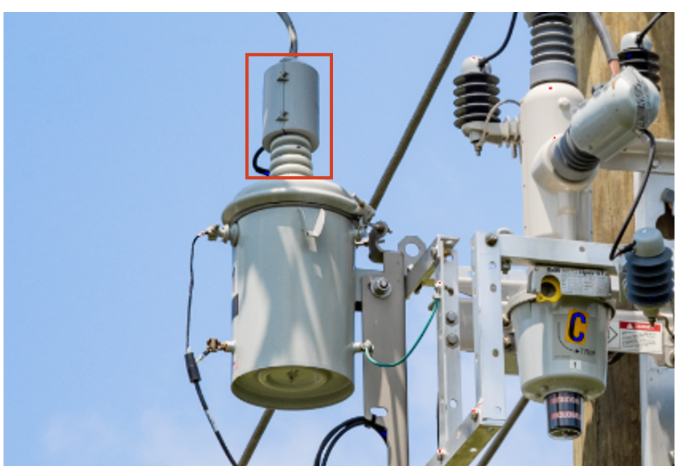

Fig. 2. Jumper termination hidden by animal guard.

In any of these cases, the neutral current flowing should be approximately equal to the rated current of the bank so it is easily detectable by measuring neutral current.

### B. *Capacitor Element Faults*

Reference [3] gives examples of typical capacitor bank construction. In a typical pole-top construction (see Fig. 1), there is only one series group of capacitor units, but there may be one to four units in parallel within the group. In some cases, each unit may be individually fused, but in most cases, one fuse protects the entire group on each phase. Although, within the capacitor unit, there are several capacitor elements arranged in parallel groups connected in series. Capacitor unit failures begin as capacitor element failures, in which case, the most typical failure is a short through one of the elements, which reduces the apparent impedance of the capacitor unit. If enough elements become shorted, the current demanded by the capacitor unit exceeds the minimum melt rating of the fuse and ultimately blows the fuse. Reference [2] states that typical fuse sizing accommodates continuous phase currents of 125 to 165 percent of capacitor bank rated current.

Depending on the arrangement of elements within the unit, failure of one or two elements may not draw enough current to blow the fuse. This condition results in unbalanced current flowing through the bank, and therefore, through the neutral. The magnitude of the neutral current depends on how many elements are shorted and how many series groups are used in the construction of the unit, but realistically, it can be anywhere from 5 to 65 percent of the capacitor bank rated current. Fig. 3 illustrates a typical capacitor unit construction.

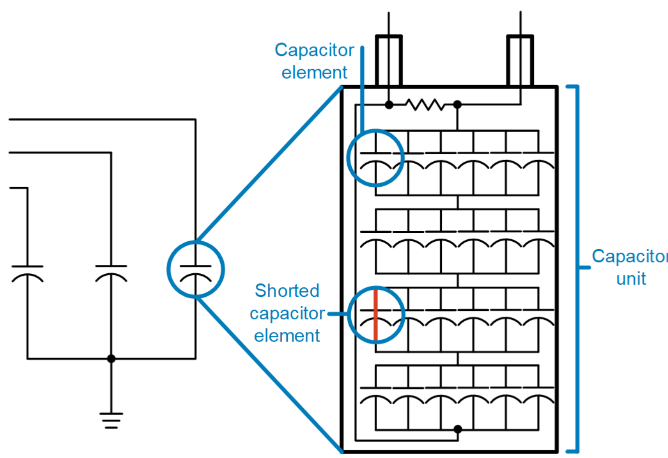


Fig. 3. Typical capacitor unit construction for pole-top applications.

### C. *System and Bank Unbalance*

A three-phase capacitor bank is nominally expected to have identical impedance on each phase. Because of manufacturing tolerances of capacitors, there is typically some mismatch between the phase impedances. Reference [2] recommends no more than 2-percent unbalance. If a balanced voltage is supplied to the unbalanced impedance, then unbalanced current flows through the bank, and therefore, through the bank neutral.

Even if the bank were perfectly balanced, the application of an unbalanced voltage to the balanced impedance results in unbalanced current flowing through the bank, and therefore, through the bank neutral. However, distribution system unbalance is typically limited to no more than 3 percent [4].

In either case, the resulting neutral current is still 2 to 3 percent of the bank rated current, which confirms that even a simple neutral current measurement can distinguish standing unbalance from fault and open-phase conditions. However, a single neutral current measurement still cannot identify the phase suffering the open or fault condition.

### D. Triplen Harmonics

If there are any triplen harmonics (third, sixth, ninth, etc.) present in the voltage supply on the feeder, then a resulting triplen harmonic current flows through the bank as well. Since triplen harmonics are known to have zero-sequence symmetry (i.e., the triplen harmonics on each phase are in-phase with each other), they also flow through the neutral [5]. The magnitude of neutral current caused by triplen harmonics are proportional to the magnitude of triplen harmonics present in the voltage supply.

Reference [6] allows for no more than 3 percent of any individual harmonic to be present in the distribution system voltage supply. Having 3 percent of third-harmonic voltage causes third-harmonic currents of 3 percent of the bank rated current (0.03 pu) to flow on each phase or 9 percent of bank rated current (0.09 pu) to flow through the neutral. A neutral current measurement that uses a wideband root-mean-square (rms) calculation can incorrectly identify this as a capacitor unit with an element fault. However, a neutral current measurement that filters to fundamental frequency measurements only ignores the triplen harmonic currents in the neutral.

## III. Novel Method for Identifying the Open or Faulted Phase in Capacitor Banks Using One Power Quantity

The neutral current magnitude alone is still useful to determine if the detected issue is standing unbalance ($\overrightarrow{I_N} < 0.03$ pu), an element fault ($0.05 \text{ pu} < \overrightarrow{I_N} < 0.65$ pu), or an open phase ($\overrightarrow{I_N} \approx 1$ pu). By using a fundamental filtered measurement, triplen harmonic quantities can be ignored, leaving only the element fault and open-phase conditions as measurable causes of significant neutral current.

The faulted or open phase can also be determined by combining the neutral current measurement with available voltage measurements. This method is useful for capacitor banks that only have a single-phase voltage measurement available and for capacitor banks with three phase voltage measurements available. There are other methods that combine phase voltage and neutral current [7], but the method introduced in this paper can be generalized to any likely combination of connected voltages through the calculation of positive-sequence voltage ($V_1$). Fundamentally, the method computes a quantity $\overrightarrow{P_N} = \overrightarrow{V_1} \bullet \overrightarrow{I_N}$.

$\overrightarrow{I_N}$ is measured directly from the bank neutral. $\overrightarrow{V_1}$, which is the positive-sequence voltage, must be calculated from any voltage that is available. It is best to use all three phases, but when only a single-phase voltage is available (often the case with pole-top capacitor banks), $\overrightarrow{V_1}$ can be estimated with enough accuracy to support the identification of faulted or open phases. See Table I.

TABLE I
$\overrightarrow{V_1}$ CALCULATION DEPENDING ON AVAILABLE VOLTAGE MEASUREMENT

| **Available voltage** | $\overrightarrow{V_1}$ **(ABC rotation)** | $\overrightarrow{V_1}$ **(ACB rotation)** |
|---|---|---|
| $\overrightarrow{V_A}$ | $\overrightarrow{V_1} = \overrightarrow{V_A}$ | $\overrightarrow{V_1} = \overrightarrow{V_A}$ |
| $\overrightarrow{V_B}$ | $\overrightarrow{V_1} = \vec{a}\,\overrightarrow{V_B}$ | $\overrightarrow{V_1} = \vec{a}^2\,\overrightarrow{V_B}$ |
| $\overrightarrow{V_C}$ | $\overrightarrow{V_1} = \vec{a}^2\,\overrightarrow{V_C}$ | $\overrightarrow{V_1} = \vec{a}\,\overrightarrow{V_C}$ |
| $\overrightarrow{V_A}, \overrightarrow{V_B}, \overrightarrow{V_C}$ | $\overrightarrow{V_1} = \dfrac{\overrightarrow{V_A} + \vec{a}\,\overrightarrow{V_B} + \vec{a}^2\,\overrightarrow{V_C}}{3}$ | $\overrightarrow{V_1} = \dfrac{\overrightarrow{V_A} + \vec{a}^2\,\overrightarrow{V_B} + \vec{a}\,\overrightarrow{V_C}}{3}$ |

In this way, $\overrightarrow{V_1}$ serves as a reference for the angle $\overrightarrow{I_N}$, which can be compared to determine the faulted or open phase. The angle comparison is made by evaluating the angle of the resulting $\overrightarrow{P_N}$. This angle falls in a uniquely predictable range for any specific phase or phases being open. The angle of $\overrightarrow{P_N}$ is also unique for an element fault on each phase. The angle of $\overrightarrow{P_N}$ alone cannot uniquely identify whether a phase is open or faulted, though, so the algorithm must be applied only after an element fault or open-phase condition has been identified using the neutral current magnitude.

### A. Open-Phase Identification

To best explain the premise of this method, the nominal currents flowing through each phase of the capacitor bank can be considered as $\overrightarrow{I_{CA}}, \overrightarrow{I_{CB}}$, and $\overrightarrow{I_{CC}}$ and $\overrightarrow{I_N} = \overrightarrow{I_{CA}} + \overrightarrow{I_{CB}} + \overrightarrow{I_{CC}}$. If the bank rated current flows on Phases B and C while no current flows on Phase A due to an open fuse, then $\overrightarrow{I_N} = \overrightarrow{I_{CB}} + \overrightarrow{I_{CC}}$. Equation (1) illustrates $I_N$ if $\overrightarrow{V_A}$ ($\overrightarrow{V_1}$) is the phasor reference with an angle held to zero degrees and if currents through each phase of the capacitor bank lead their respective phase voltages by about 90 degrees.

$$\overrightarrow{I_N} \approx 1\angle -30 + 1\angle -150 = 1\angle -90 \text{ pu} \quad (1)$$

Equation (2) assumes phase voltages are at a nominal magnitude and phase angle.

$$\overrightarrow{P_N} \approx 1\angle 0 \bullet 1\angle -90 = 1\angle -90 \text{ pu} \quad (2)$$

The angle of $\overrightarrow{P_N}$ effectively represents the angle between $\overrightarrow{V_1}$ and $\overrightarrow{I_N}$. Alternatively, one can add the angle of the two phasors and achieve the same result. Either calculation is valid, but this paper calculates a single quantity with a magnitude that reflects $\overrightarrow{I_N}$ with an angle that identifies the open phase.

Following the same reasoning for the remaining open-phase conditions, the angle of $\overrightarrow{P_N}$ can be used to uniquely identify which phases are open, as shown in the nominal sectors of Fig. 4 and Fig. 5. The angle of $\overrightarrow{P_N}$ should fall near the center of any of these 60 degree sectors. A wide margin allows for measurement angle error, especially with the smaller signals present for a capacitor element fault discussed in the next section. However, some deadband between sectors is also needed to avoid chattering detection between sectors. A practical deadband between sectors may be in the range of 10 to 15 degrees.

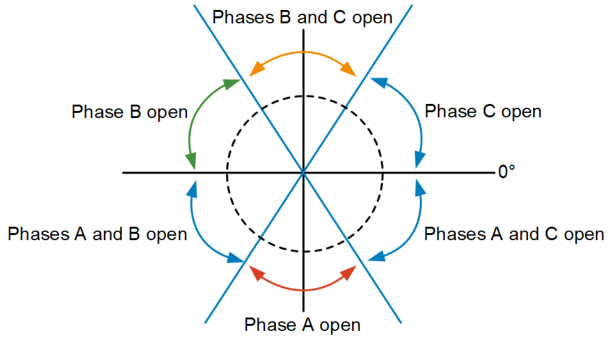


Fig. 4. Open phases indicated by the angle of $\overrightarrow{P_N}$ for ABC rotation.

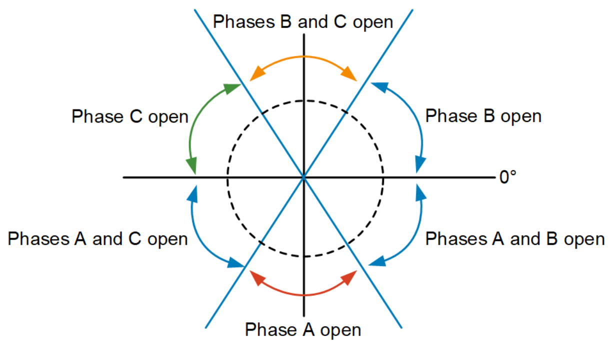


Fig. 5. Open phases indicated by the angle of $\overrightarrow{P_N}$ for ACB rotation.

*B. Faulted Phase Identification*

A similar approach can be taken to identify the unique angles of $\overrightarrow{P_N}$ for an element fault on any phase. If an element of the capacitor unit is shorted, then the entire parallel group of elements is shorted. If there are *S* groups of elements in the series inside the capacitor unit, the apparent impedance of the unit $X_C$ reduces to $X_C \cdot (S - 1) / S$, and the current will increase in that phase by a factor of S / (S – 1) but still leads the phase voltage by about 90 degrees. These and similar calculations can be found in [3]. Equation (3) shows an element fault on Phase A.

$$\begin{aligned} \vec{I}_N &= \vec{I}_{CA}\frac{S}{S-1} + \vec{I}_{CB} + \vec{I}_{CC} \\ &= \vec{I}_{CA}\frac{1}{S-1} + \vec{I}_{CA} + \vec{I}_{CB} + \vec{I}_{CC} \\ &= \vec{I}_{CA}\frac{1}{S-1} \\ &\approx \frac{1}{S-1} \cdot 1\angle 90 \text{ pu} \end{aligned} \quad (3)$$

Equation (4) assumes phase voltages are at nominal magnitude and phase angle, which means that when there is an element fault on Phase A, $\overrightarrow{P_N}$ leads $\overrightarrow{V_1}$ by 90 degrees.

$$\vec{P}_N \approx 1\angle 0 \cdot \frac{1}{S-1} \cdot 1\angle 90 = \frac{1}{S-1} \cdot 1\angle 90 \text{ pu} \quad (4)$$

Following the same reasoning for an element fault on Phases B or C instead, the angle of $\overrightarrow{P_N}$ can be used to uniquely identify which phase contains an element fault, as shown in Fig. 6 and Fig. 7.

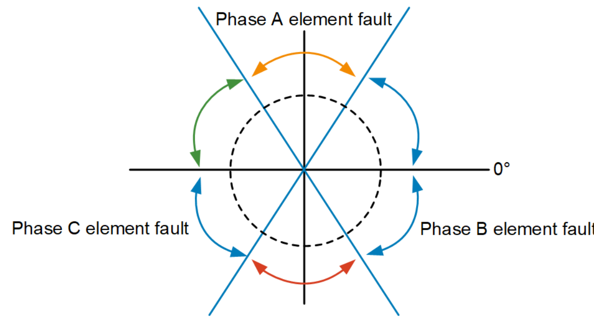


Fig. 6. Element fault phase indicated by the angle of $\overrightarrow{P_N}$ for ABC rotation.

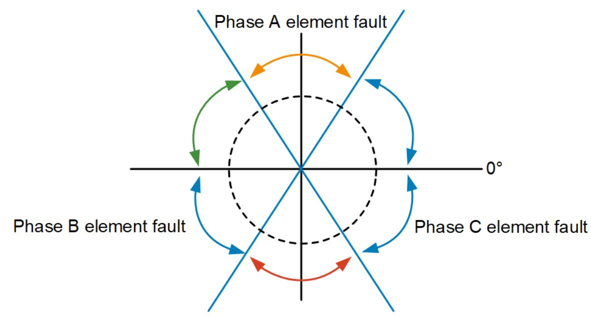


Fig. 7. Element fault phase indicated by the angle of $\overrightarrow{P_N}$ for ACB rotation.

## IV. Novel Method for Identifying the Open or Faulted Phase in Capacitor Banks Using Three Quantities

When three phase voltages are available, the same approach can be taken to identify an open or faulted phase by inspecting the angles of power quantities composed from all three phases. This is simply an alternative method and produces results equivalent to the previously demonstrated method (5).

$$\begin{aligned} \vec{P}_{NA} &= \vec{V}_A \cdot \vec{I}_N \\ \vec{P}_{NB} &= \vec{V}_B \cdot \vec{I}_N \\ \vec{P}_{NC} &= \vec{V}_C \cdot \vec{I}_N \end{aligned} \quad (5)$$

In this method, all three quantities can be evaluated to determine the open or faulted phase based on the angular relationships shown in Fig. 8, Fig. 9, Fig. 10, and Fig. 11. In these diagrams, $\overrightarrow{V_A}$ ($\overrightarrow{V_1}$) is the angular reference, held to 0 degrees.

For example, if Phase A is open, $\overrightarrow{I_N}$ is 1 / –90 degrees from the previous section. Therefore, one can expect $P_{NA}$ to plot at –90 degrees, $P_{NB}$ at 150 degrees, and $P_{NC}$ at 30 degrees, with respect to $\overrightarrow{V_1}$. If the three calculated quantities match what is expected, the method declares Phase A to be open.

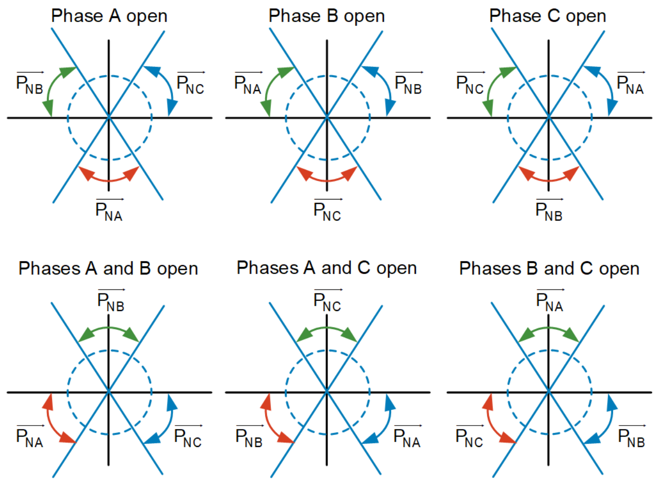


Fig. 8. Open phases indicated by the angle of $\overrightarrow{P_{NA}}, \overrightarrow{P_{NB}}, \overrightarrow{P_{NC}}$ for ABC rotation.

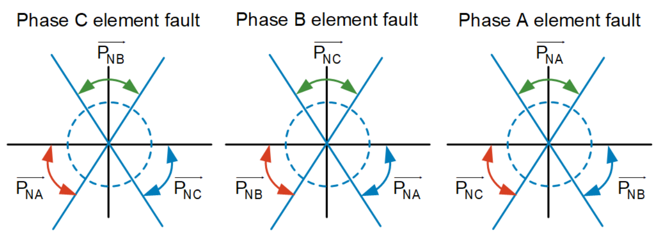


Fig. 9. Element fault phase indicated by the angle of $\overrightarrow{P_{NA}}, \overrightarrow{P_{NB}}, \overrightarrow{P_{NC}}$ for ABC rotation.

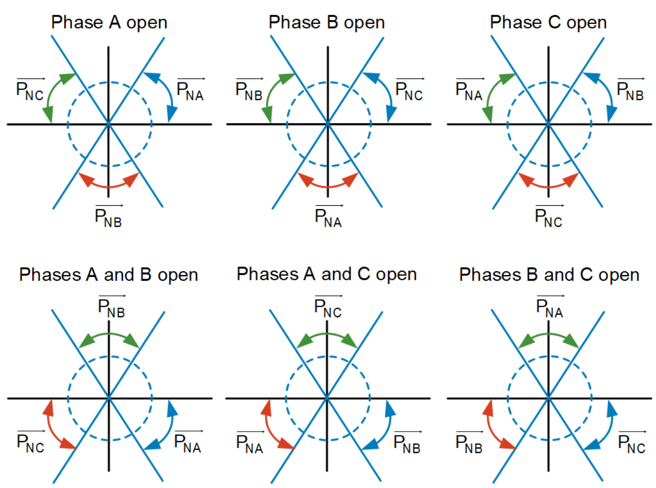


Fig. 10. Open phases indicated by the angle of $\overrightarrow{P_{NA}}, \overrightarrow{P_{NB}}, \overrightarrow{P_{NC}}$ for ACB rotation.

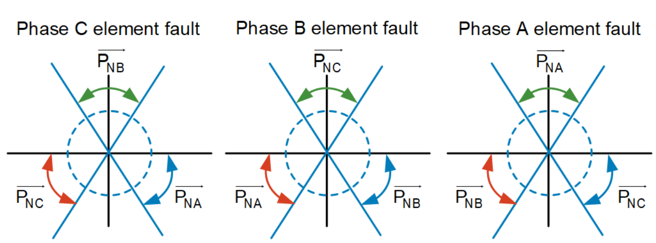


Fig. 11. Element fault phase indicated by the angle of $\overrightarrow{P_{NA}}, \overrightarrow{P_{NB}}, \overrightarrow{P_{NC}}$ for ACB rotation.

## V. Conclusion

Pole-top capacitor banks play a critical role in maintaining acceptable voltage on the distribution system and optimizing the efficiency of the overall power system. When open-phase or element fault conditions occur, system operators need to be alerted so that they can respond quickly to restore the full function of the capacitor bank. Traditional capacitor bank controllers measure bank neutral current to identify these conditions but face the following challenges:

- System and bank impedance unbalance can cause current to flow in the bank neutral.
- Triplen harmonics in the voltage supply can also cause current to flow in the bank neutral.
- The faulted phase or open phase cannot be identified.

This paper establishes thresholds for distinguishing between standing unbalance, a faulted phase, and an open phase, and it introduces new methods for determining which phases are open or faulted.

A fundamental frequency neutral current measurement ignores triplen harmonics.

- $0.05 \text{ pu} < \overrightarrow{I_N} < 0.5$ pu identifies an element fault.
- $\overrightarrow{I_N} \approx 1$ pu identifies an open-phase condition.
- Voltage measurements can be combined with neutral current measurement to identify which phase is faulted or open.
- One method calculates $\overrightarrow{P_N} = \overrightarrow{V_1} \bullet \overrightarrow{I_N}$ and can derive $\overrightarrow{V_1}$ from all three voltage phases or from a single voltage; it is suitable for use with capacitor banks that have one potential transformer (PT) or three.
- Another method calculates $\overrightarrow{P_{NA}} = \overrightarrow{V_A} \bullet \overrightarrow{I_N}$, $\overrightarrow{P_{NB}} = \overrightarrow{V_B} \bullet \overrightarrow{I_N}$, $\overrightarrow{P_{NC}} = \overrightarrow{V_C} \bullet \overrightarrow{I_N}$ and is suitable for use only with banks containing three PTs.
- In both methods, the angle of the power quantity is used to determine which phase is open or faulted.

## VI. References

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## VII. Biographies

**Kei Hao**, **PE**, received his PhD in electrical engineering from the University of Wisconsin-Madison, his MSEE from the University of Wisconsin-Milwaukee, and his BSEE from La Universidad de la Republica, Uruguay. He earned his master's in business administration (MBA) from Washington State University. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2010 and worked as an automation and protection engineer in SEL Engineering Services, Inc. (SEL ES) for five years. In 2015, he joined the research and development division and served as a systems engineer and technical lead in the development of protection and control equipment and solutions for power systems. In 2021, he joined Google as a senior data center engineer, focusing on the designing of power system protection and control. He has experience in the fields of control and automation systems, wireless communications systems, and power system automation and protection. He is a member of IEEE and a registered PE in the state of California and holds six patents.

**Jeremy Blair**, **PE**, earned his BSEE from Louisiana Tech University and his MSECE from Georgia Institute of Technology. He joined Schweitzer Engineering Laboratories, Inc. (SEL) as an application engineer in 2013, authoring conference papers and application guides and assisting customers with relay and distribution automation solutions. Previously, he worked for Entergy Corporation as a distribution planning engineer with responsibilities in distribution system plans, protection, power quality, and automation. He also managed Entergy's Automatic Load Transfer and Sectionalization Program over its four-state territory. He is a licensed PE in Louisiana.

**Ben Rowland** received his BS in engineering management with an emphasis in electrical engineering from Gonzaga University in May 2014. After, he began working for Schweitzer Engineering Laboratories, Inc. (SEL) as an associate application engineer. Ben has worked in the fields of precise timing, wireless communications, distribution controls, and sensors. He currently holds the position of product line owner for capacitor bank controls and voltage regulator controls.


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