Revisiting Open-Phase Detection for Fuse-Protected Power Transformers

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Presented at the
78th Annual Conference for Protective Relay Engineers at Texas A&M
College Station, Texas
March 31–April 3, 2025

Previously presented at the
60th Annual Minnesota Power Systems Conference, November 2024

Originally presented at the
51st Annual Western Protective Relay Conference, October 2024

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***Abstract*—A blown fuse and open phase on the high side of distribution power transformers create unbalanced load conditions on the low side, which are detrimental to three-phase loads and can pose a fire hazard in the event of a permanent fault. The detection and isolation of this abnormal system condition are important for equipment protection and personnel safety.**

Open-phase detection techniques must be dependable and remain secure during loss of potential (LOP), faults, and balanced and unbalanced load conditions. In this paper, we analyze the impacts of the loss of a transformer high-side phase on low-side voltages for delta-wye transformers. Then, we review traditional open-phase detection techniques and present a new, reliable open-phase detection method using sequence voltages. This simple scheme has dependability improvements without a security compromise and is sensitive to open-phase events concurrent with permanent faults and balanced or unbalanced load conditions. These dependability improvements are demonstrated with a real-world open-phase event.

I. Introduction

An open-phase condition is a series fault in which one or two phases are disconnected or opened, causing an interruption of power flow through those phases, resulting in issues, such as unbalanced currents, fire hazards, and overvoltage. An unbalanced operating condition in the power system can be detrimental to three-phase electrical equipment. Open phases on a distribution transformer high side can be caused by transformer faults, the transmission line being single-phased due to a switching failure or broken conductor, and a high-side fuse operation due to a low-side fault.

Open-phase conditions are not always easy to detect. Several factors, such as a transformer load, winding connections, location of the open phase, and concurrent shunt faults, challenge the dependability of traditional detection techniques. The most common type of distribution power transformer is a delta-wye grounded Dyn transformer, which provides electrical isolation in the zero-sequence network. Therefore, this paper focuses on fuse-protected Dyn power transformers and radial feeders.

During healthy system conditions, open-phase detection techniques must remain secure during balanced and unbalanced load conditions and in the presence of loss of potential (LOP) and faults. Many traditional detection methods lack dependability during unbalanced conditions. In this paper, we examine traditional detection methods and introduce a new method, which utilizes positive- (V1), negative- (V2), and zero- (V0) sequence voltages. The proposed method offers enhanced dependability without sacrificing security and can detect open-phase events in the presence of permanent faults and various load conditions.

This paper provides an open-phase event example that challenges traditional open-phase detection methods, demonstrating the need for alternative methods. The event is evaluated against the sequence voltage method presented within this paper, demonstrating the effectiveness of this method's improvements.

II. Open-Phase Equivalent Circuit

Radial Dyn distribution power transformers are often protected by fuses on the transformer high side, particularly at small single-transformer sites. Protective relays are generally installed on the low side to protect distribution feeders or the secondary bus. These low-side relays can be programmed to initiate a trip if an open-phase condition is detected by monitoring the low-side voltages. To effectively implement open-phase detection logic within these relays, it is crucial to understand the voltage profiles occurring under various system conditions during an open-phase event.

We evaluate different system conditions to understand the voltage profile seen by the low-side relay during those conditions. In the example system used throughout this paper, as depicted in Fig. 1, the system phase rotation is ABC. For simplicity, the transformation ratio is 1:1. The transformation ratio is the ratio of the line-to-line (L-L) voltages on each side of the transformer to one another during healthy system conditions. The relay is measuring the line-to-neutral (L-N) voltage on the transformer low side. The low-side load impedances are represented as ZL_A, ZL_B, and ZL_C for each respective phase.

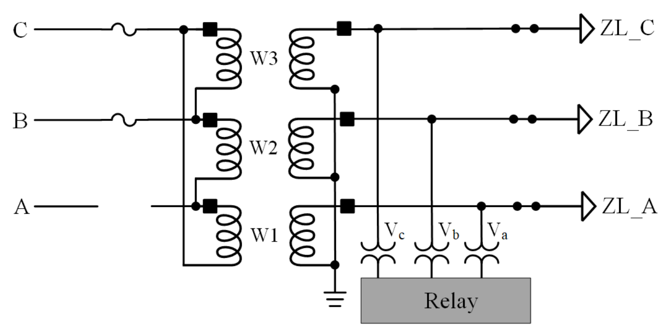


Fig. 1. System example with the A-phase high-side fuse open.

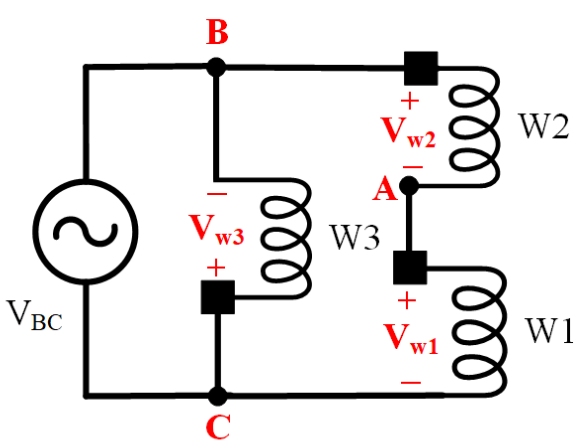
The circuits in Fig. 2 are used to represent an equivalent circuit of an ideal transformer during a high-side A-phase open condition. During this condition, one transformer high-voltage winding is connected between a power system source and the other two windings are connected in series to the same source. For example, when the A-phase is open, only the system V_{BC} voltage is intact, thus providing a source to the W3 transformer winding directly. The W1 and W2 windings are connected in series across the same source voltage. The delta connection in the transformer high-voltage windings creates a loop, and thus the sum of the V_{w1} and V_{w2} voltages on the W1 and W2 windings is opposite of that to the V_{BC} source voltage. This can be represented by solving Kirchhoff's voltage law (KVL) in one of the loops, as shown in (1). Fig. 2a provides a circuit representation of this condition.

$$V_{BC} = V_{W1} + V_{W2} \tag{1}$$

Because the transformer low-voltage windings are coupled to the high-side windings, the circuit can be represented with the low-side windings connected in place of the high-side windings. Because high-side L-L voltages are coupled with low-side L-N voltages on a Dyn transformer, to support a transformation ratio of 1:1, the transformer turns ratio must be $\sqrt{3}$:1. Therefore, the voltage source must be scaled down by this ratio when represented on the transformer low side, as represented in Fig. 2b. The respective low-side winding voltages are represented as V_a, V_b, and V_c.

With the high-side A-phase fuse open, the W1 and W2 windings are connected in series, requiring the low-side A- and B-phase currents to be the same. Furthermore, because the windings are series-connected, the addition of the ZL_A and ZL_B impedances reveals the total load impedance in this branch of the circuit. Therefore, the windings can be replaced with the phase load impedances, as represented in Fig. 2c. The observation of this equivalent circuit reveals that the V_a and V_b voltages follow the voltage divider principle. If the load impedances are equal, 50 percent of source voltage appears across each load and, therefore, each transformer winding. This equivalent circuit is explained further in the next two sections in which the impacts of different load between phases and fault conditions on the winding voltages are further analyzed.

a)



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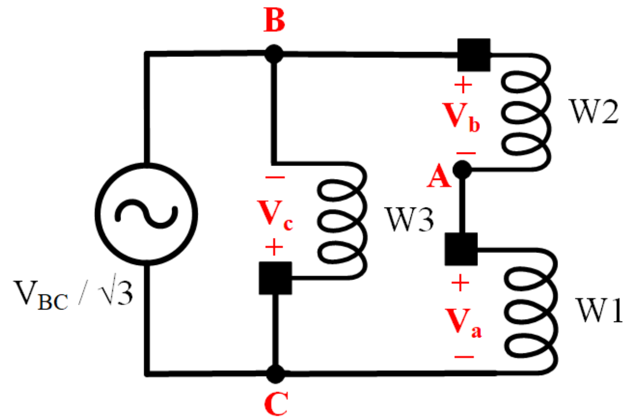

c)

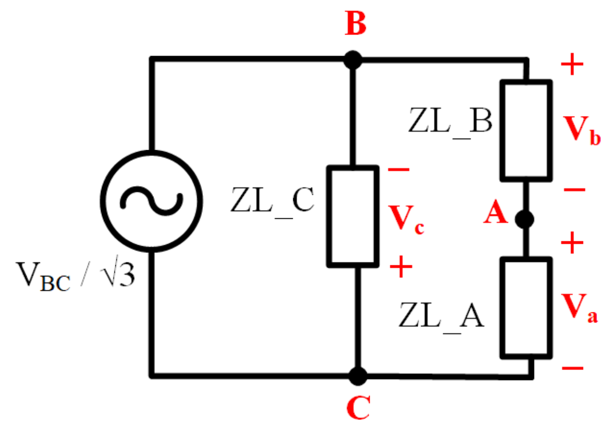

Fig. 2. Simplified circuit for the high-side open A-phase.

III. Impact of the Load During High-Side Open Phase

As explained previously, due to the presence of a voltage divider circuit, the load impedances impact the voltage profiles observed on the low side of the transformer. Depending on the load imbalance, the sequence and L-L voltages vary. Both load magnitudes and angles can impact the load balance of the system. These impacts are analyzed in this section.

A. No Load

The no-load condition during the high-side open A-phase is represented by open switches in Fig. 3. Because the B- and C-phases are intact, the V_{BC} voltage on the transformer high side remains at 1 pu; therefore, the low-side V_c voltage remains at 1 pu. Because transformer impedances are balanced, the voltage developed on the low-side V_a and V_b are 0.5 pu and 180 degrees out of phase with V_c. As a result, the V_{ab} voltage is zero and the magnitudes of V_{bc} and V_{ca} are reduced to 0.87 pu. During this open-phase condition, the magnitude of V1 reduces to 0.5 pu. Concurrently, the magnitude of V2 increases to 0.5 pu.

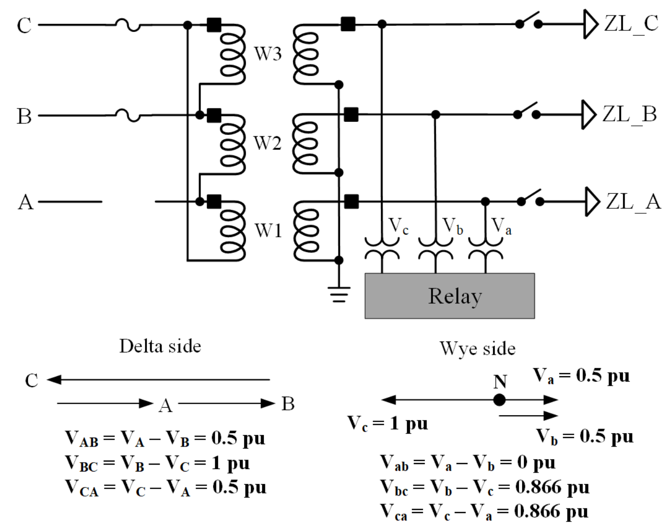

Fig. 3. Open A-phase on the transformer high side with no load.

B. *Balanced Load*

The balanced load condition presents a similar circuit to the no-load condition with a load impedance applied to the circuit, as represented in Fig. 1. Because load impedances are still balanced, the voltage profile for this case matches that of the no-load condition.

C. *Unbalanced Load*

The distribution circuit load impedances are often not balanced, and some loads are also not constant impedance loads. Some loads, such as constant power or current loads, present varying load impedance as system voltage characteristics change. A load impedance imbalance can be represented by either a magnitude difference, phase angle difference, or both. This simplified circuit is akin to the one presented in Fig. 2c.

Because load impedances differ, the resulting L-L and sequence voltages change, depending on the state of the unbalance. Assuming we have an ideal transformer, the voltage profiles observed by the low-side relay are shown in Fig. 4 through Fig. 7. For this analysis, the load impedance for B- and C-phases are held equal and constant, while the load impedance for the A-phase is varied to induce an unbalanced load condition. In Fig. 4 and Fig. 5, the A-phase load impedance angle is held constant, matching B- and C-phases, while the A-phase load impedance magnitude is decreased. With load impedances equal, the load impedance imbalance is 0 percent.

The L-L voltage shows substantial change in response to the percentage of load imbalance, whereas sequence voltages maintain a relatively consistent value. A typical setting threshold for the 27PP element, described in the phase-to-phase voltage open-phase detection scheme in Section VI, is represented by the dashed line labeled 27PP setting in Fig. 4, Fig. 6, and Fig. 10. This scheme is unreliable in conditions with severe load imbalance, as represented in Fig. 4, where the minimum L-L voltage exceeds the 27PP setting threshold.

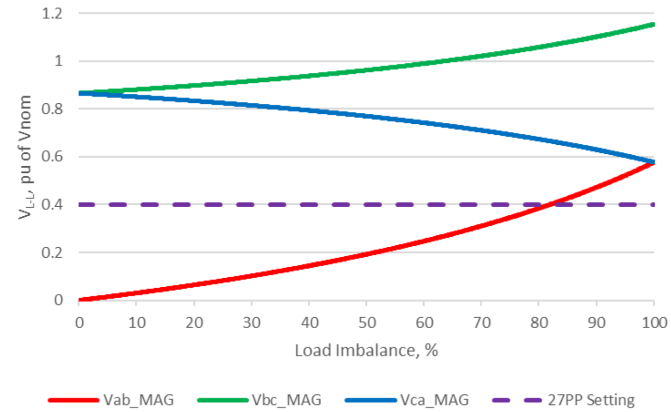

Fig. 4. Low-side L-L voltage with load magnitude imbalance during the open A-phase.

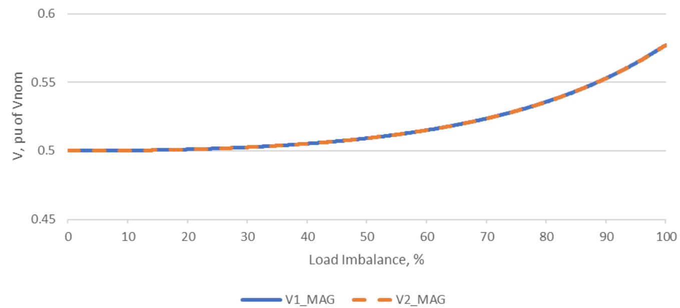

Fig. 5. Low-side sequence voltage with load magnitude imbalance during the open A-phase.

In Fig. 6 and Fig. 7, the A-phase load impedance angle is varied, while the A-phase load magnitude is held constant, matching the B- and C-phases. The angle variance represents a leading impedance and the difference of the A-phase load impedance angle to that of B- and C-phases.

In this scenario, V_{ab}, positive-sequence, and negative-sequence voltages show substantial movement in response to angle variance. As observed in Fig. 6, phase-to-phase voltage-based techniques are rendered unreliable during severe load angle separations between phase load impedances. Of all studied cases, the 90-degree phase variance presents the lowest measurement of positive-sequence voltages. This condition results in a minimum V1 measurement of 0.21 pu.

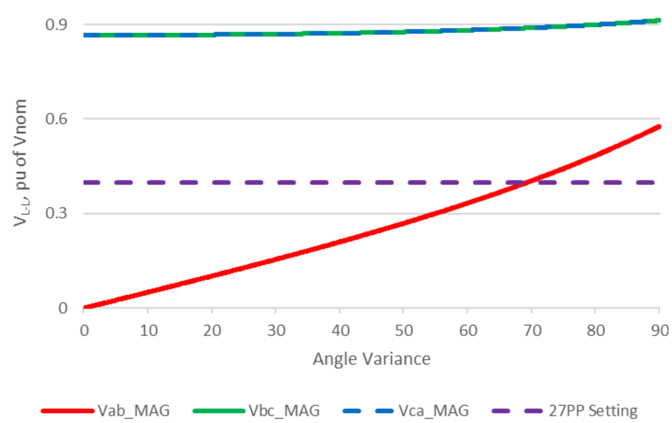

Fig. 6. Low-side L-L voltage with load angle imbalance during the open A-phase.

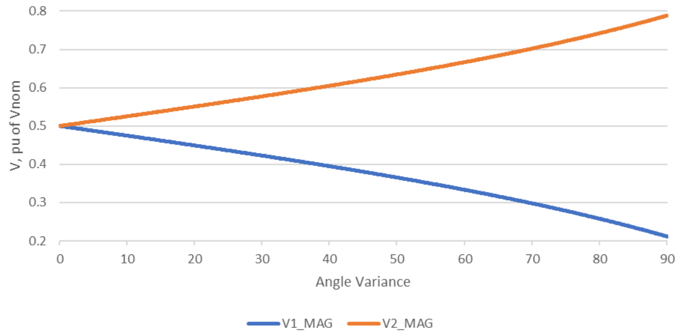

Fig. 7. Low-side sequence voltage with load angle imbalance during the open A-phase.

IV. Impact of Permanent Faults During High-Side Open Phase

Both single line-to-ground (SLG) and L-L faults on the transformer low side can result in a single-fuse operation on the transformer high side of a Dyn transformer. Three-phase and double line-to-ground faults both cause two high-side fuse operations at minimum, resulting in a no-voltage condition on the transformer low side. A no-voltage condition generally does not present a fire hazard or cause load damage; therefore, isolating these conditions is often not required in an open-phase detection scheme. If desired, this condition can be detected using either a positive-sequence or three-phase undervoltage scheme.

A. Permanent SLG Fault

An SLG fault on the low side of a Dyn transformer results in high-fault currents on two high-side phases equal in magnitude and out of phase with one another. Therefore, current on two fuses on the high side is above fuse operation levels. A single-fuse operation for low-side SLG faults can result when there is a fuse-racing condition or when one fuse operates prematurely due to fuse weakening. If one fuse operates before the other, current magnitudes are restricted to load levels, causing an open-phase condition. In this scenario, we assume the load is balanced during a permanent SLG fault. With all fuses intact, an AG permanent fault on the low side results in fault current on the high-side A- and C-phase fuses, only restricted by the fault resistance (R_F), source impedance, and transformer impedance. Fig. 8 represents a scenario in which the A-phase fuse blows prior to the C-phase fuse. In Fig. 8, IL_A, IL_B, and IL_C represent the pu currents on each respective low-side phase.

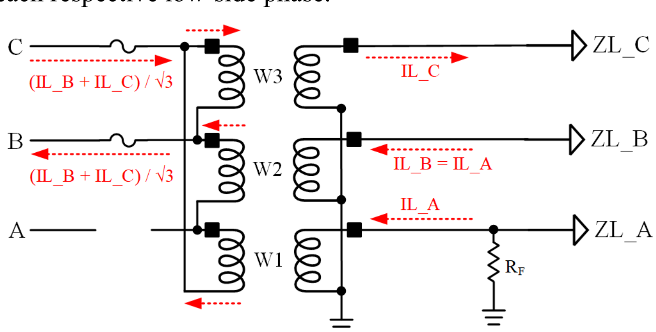

Fig. 8. Open phase with a balanced load and a permanent SLG fault.

Assuming we have an ideal transformer like the circuit in Fig. 2c, Fig. 9 illustrates the simplified circuit, where R_F represents the fault resistance. In this equivalent circuit, R_F is applied in parallel with the faulted phase load impedance. Despite the operation of the A-phase fuse on the high side, current continues to flow through the fault and A-phase on the low side due to the connected load on the B-phase, as influenced by the transformer high-voltage delta-winding connection. The magnitude of current varies, depending on the A- and B-phase load impedance and the fault resistance. This current magnitude is often much smaller than the transformer maximum load condition. A bolted fault presents the maximum current condition, because current is only restricted by the load impedance on the B-phase. During a bolted fault, if the load impedance is balanced, the low-side current magnitudes are all equal, and IL_C is directly out of phase with IL_A and IL_B. This results in current on the high side being equal to 115 percent of the low-side load current, as represented in Fig. 8. Because this current is restricted by load, this current is unlikely to operate the second fuse unless it was significantly damaged during the fault state.

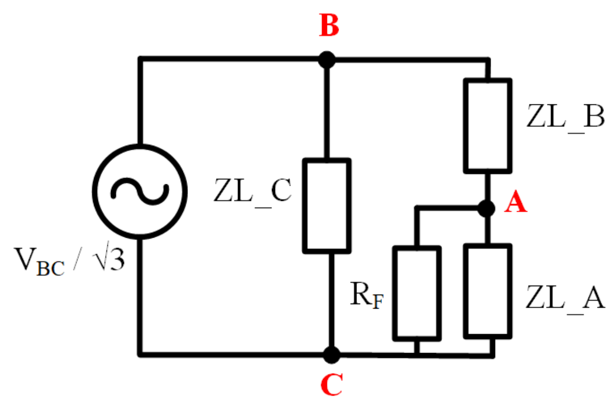

Fig. 9. Simplified circuit for an open A-phase with an SLG fault present on the low-side A-phase.

Similar to the unbalanced load condition, the voltage divider impedances vary in Fig. 9, depending on fault resistance and load impedances, causing the low-side L-L and sequence voltages to vary with fault resistance. Assuming we have an ideal transformer, the voltage profiles observed by the low-side relay during this condition are depicted in the plots of Fig. 10 and Fig. 11. The load impedance is fixed at 1 pu with an angle of 0 degrees, and R_F is increased in pu of load impedance to see its impact on the voltage profiles. Notably, the L-L voltages exhibit significant changes in response to variations in R_F, relative to Z_L. This challenges the use of phase-to-phase voltage-based techniques to detect this open-phase condition when R_F is low. In contrast, the sequence voltages remain stable, indicating that the values of R_F have minimal effect on these voltages.

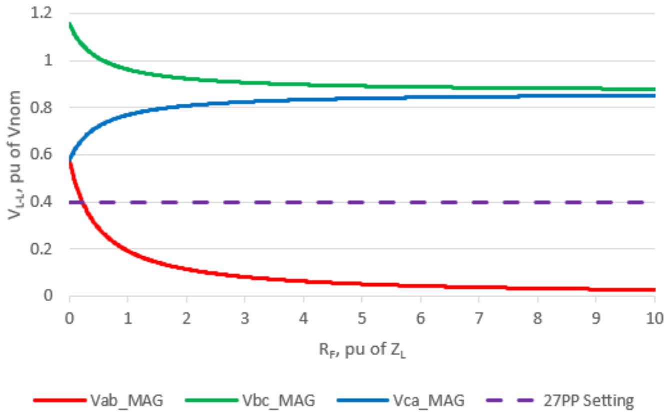

Fig. 10. Low-side L-L voltage with a balanced load, permanent SLG fault, and open A-phase.

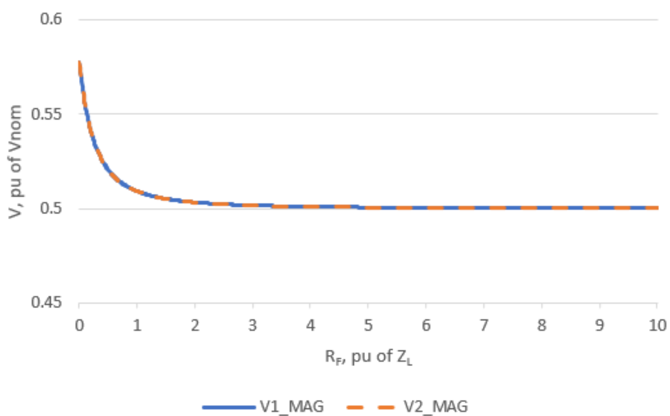

Fig. 11. Low-side sequence voltages with a balanced load, permanent SLG fault, and open A-phase.

B. *Permanent L-L Fault*

L-L faults on the low side of a delta-wye grounded transformer are likely to cause a high-side single-fuse operation. When fuses are intact for this L-L fault condition, a single phase on the transformer high side carries 115 percent of the low-side fault current, while the remaining two phases carry 57 percent of the low-side current, as represented in Fig. 12. The current magnitude during this condition is restricted by fault resistance, source impedance, and transformer impedance. After the first fuse operation, current magnitudes in the remaining high-side fuses are restricted by the load impedance on the low-side. In this condition, a second fuse is unlikely to operate.

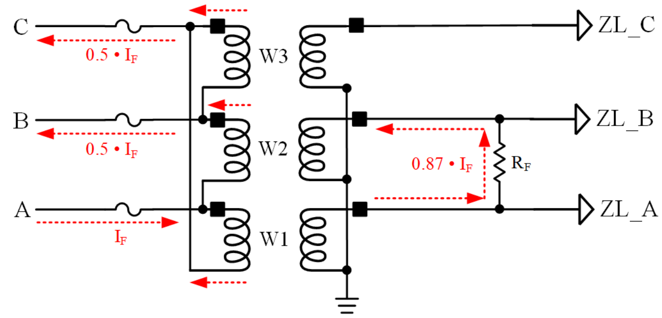

Fig. 12. Delta-wye transformer current distribution for a low-side AB fault with balanced loads.

1) *Open A-Phase*

If the A-phase fuse were to operate for the condition represented in Fig. 12, the result would be the condition represented in Fig. 13. With the high-side A-phase open, the low-side W1 and W2 windings are effectively connected in series, as reflected in the transformer high-side delta winding. The orientation of the high-side delta winding requires the low-side I_a and I_b currents to have equal magnitudes and the same phase orientation. For an AB fault, I_a must return from the fault to the transformer with equal magnitude and opposite phase orientation to I_b. Because the series W1 and W2 windings require I_a and I_b on the low side to have equal magnitudes and phase orientation, fault currents are restricted from flowing through the fault. Therefore, the only current flowing through the fault results from load sharing between the two faulted phases. Balanced resistive loads result in a current measurement on the high-side fuses of 87 percent of the C-phase load current (IL_C), as represented in Fig. 13. Because this current is restricted by the load on the faulted phases, a second fuse is unlikely to operate.

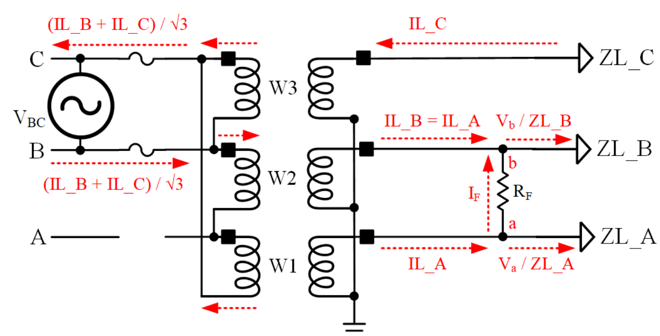

Fig. 13. Circuit characteristics with the A-phase open during an AB fault with balanced loads.

With an AB fault applied at the transformer low-side bushings, the low-side V_a and V_b only differ by the voltage drop across the fault resistance represented in Fig. 13. As mentioned previously, during balanced load conditions, no current flows through the fault, which results in no voltage across the fault resistance. This no-voltage condition is valid during balanced load conditions, regardless of the value of fault resistance. Therefore, the low-side V_a and V_b voltages have equal magnitudes and the same phase orientation during balanced load conditions, regardless of fault resistance. The low-side L-L and sequence voltages, therefore, match the no-load condition mentioned previously in this paper. This relationship is represented in Fig. 14 and Fig. 15, where R_F represents fault resistance in pu of the load impedance Z_L. All of the following open-phase detection techniques presented in this paper remain reliable during this condition.

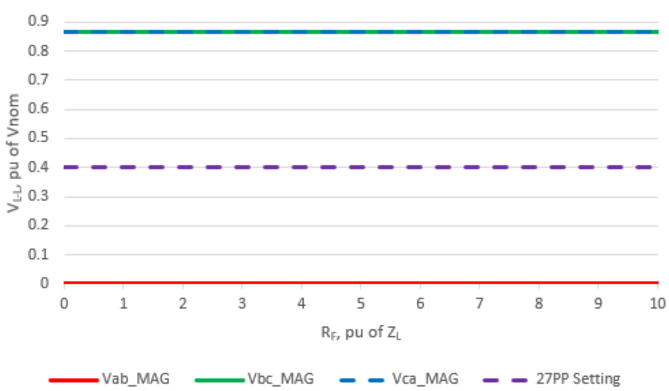

Fig. 14. Low-side L-L voltages with a balanced load, AB fault, and open A-phase with increasing R_F.

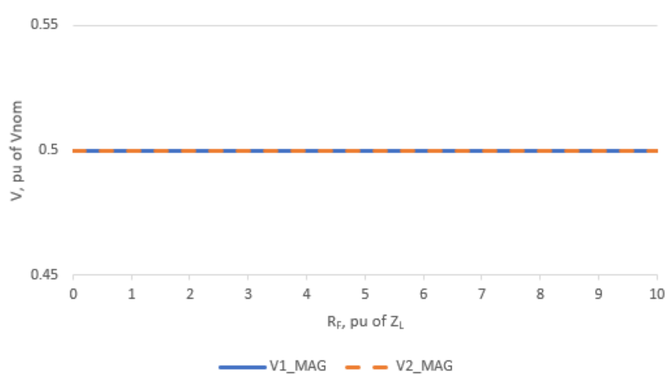

Fig. 15. Low-side sequence voltages with a balanced load, AB fault, and open A-phase with increasing R_F.

Unbalanced load conditions result in current flowing through the fault location and, thus, a voltage drop across the fault resistance. This results in a difference between the low-side V_a and V_b voltages. As load becomes increasingly imbalanced or the fault resistance increases during an imbalance, the voltage drop across the fault resistance increases, resulting in increasing differences in the V_a and V_b voltages. These differences are reflected into the L-L and sequence voltages, as represented in Fig. 16 and Fig. 17.

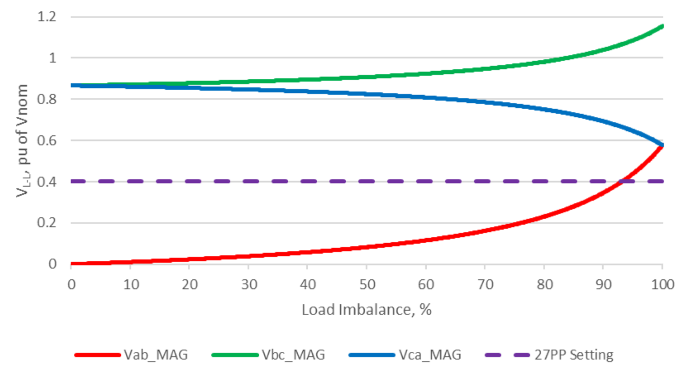

Fig. 16. Low-side L-L voltages during an imbalanced load, AB fault, and open A-phase with R_F = 1 pu of Z_L.

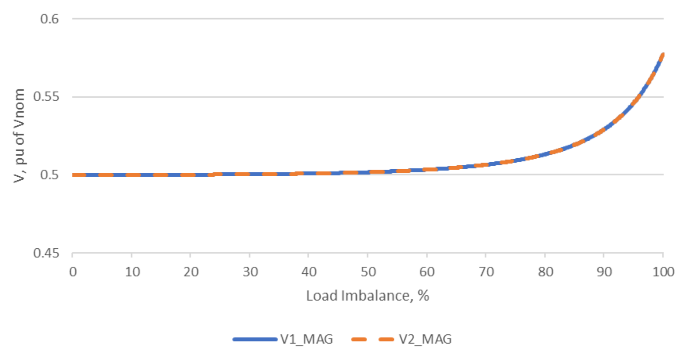

Fig. 17. Low-side sequence voltages during an imbalanced load, AB fault, and open A-phase with R_F = 1 pu of Z_L.

2) *Open B-Phase*

The fuse with higher currents is the most likely to operate during an L-L fault condition. However, it is possible for one of the other two fuses to operate first if it has already been weakened. If one of the fuses with lower current operates first, a 2 pu voltage can result on the unfaulted low-side phase, assuming we have an ideal transformer.

If the B-phase fuse were to operate for the condition represented in Fig. 12, the result would be the condition represented in Fig. 18. The current on the transformer high side is restricted by the load impedances, resulting in high-side current, 173 percent of IL_A, assuming load impedances are balanced. If the high-side B-phase fuse operates, current magnitudes on the two remaining fuses are greater than the currents during the A-phase fuse operation represented in Fig. 13. Assuming the load is resistive, the current in the remaining fuses in Fig. 18 is twice the current from Fig. 13 as a result of the increased voltage. Therefore, the remaining high-side fuses are more likely to operate for this condition compared to the A-phase open condition. However, current is still restricted by load, and a second fuse operation is still dependent on load levels during this condition.

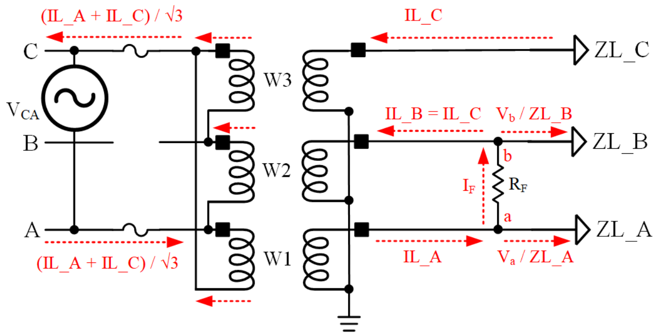

Fig. 18. Circuit characteristics with the B-phase open during an AB fault.

Fig. 19 represents a bolted AB fault on the transformer secondary bushings during the B-phase open event. V_{w1} is connected directly to the V_{AC} source on the high side, whereas the windings W2 and W3 are connected in series across that same source. During a low-side bushing AB bolted fault, the voltages V_a and V_b are directly connected on both the winding polarity and nonpolarity and are, therefore, equal. These voltages are magnetically coupled to the high-side V_{w1} and V_{w2} voltages, respectively.

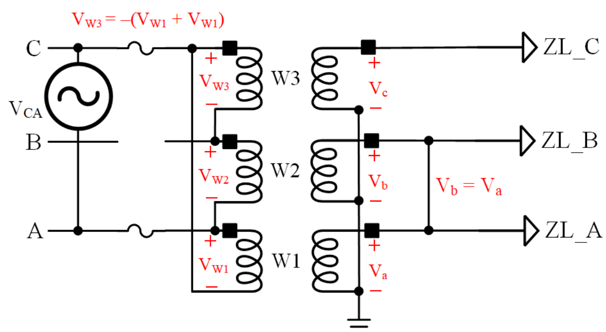

Fig. 19. Voltage profiles for the open B-phase with an AB fault.

Because the W3 winding is applied in a loop with the W1 and W2 windings, KVL can be applied. Solving for the W3 winding voltage V_{w3} reveals a 2 pu voltage with the opposite phase orientation from V_{w1} and V_{w2}. Due to the magnetic coupling of the winding W3, the low-side V_c voltage is also 2 pu. This voltage results in an ideal transformer. On an actual transformer, however, the transformer core is expected to saturate, resulting in lower voltage on the transformer low side. Likewise, as the fault moves away from the transformer or as load increases, V_{w3} decreases.

This voltage stress on the unfaulted phase can result in equipment and insulation failure, and it is, therefore, desirable to minimize tripping delays for this condition. The unfaulted phase voltage is dependent on fault resistance and load balance when the fault resistance is not zero. The unfaulted phase voltage decreases as the fault resistance increases, load increases, or load becomes increasingly imbalanced.

Due to the orientation of the delta winding during this condition, current is allowed to flow, for example, from the low-side W1 through the fault returning to W2. However, because W2 is connected in series with W3, this current is restricted by loading on W3. Due to current flowing through the fault, V_a and V_b voltages are only equal when the fault has no resistance or during a no-load condition, unlike the condition when the A-phase high-side fuse operated. Fig. 20 and Fig. 21 reflect the L-L and sequence voltages as R_F increases, with respect to Z_L during balanced load conditions. Fig. 22 and Fig. 23 reflect the L-L and sequence voltages as the load imbalance increases at a fixed R_F of 0.1 pu of Z_L.

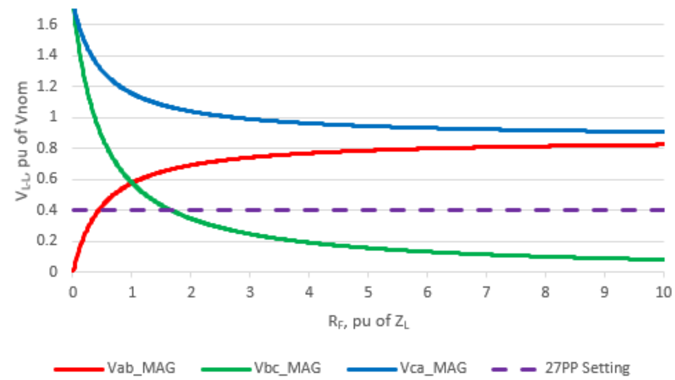

Fig. 20. Low-side L-L voltages with a balanced load, AB fault, and open B-phase with increasing R_F.

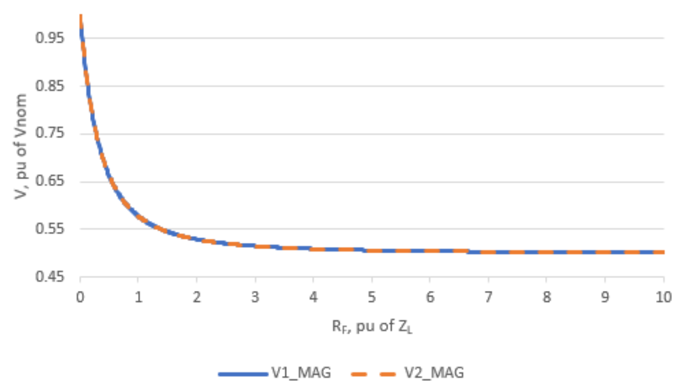

Fig. 21. Low-side sequence voltages with a balanced load, AB fault, and open B-phase with increasing R_F.

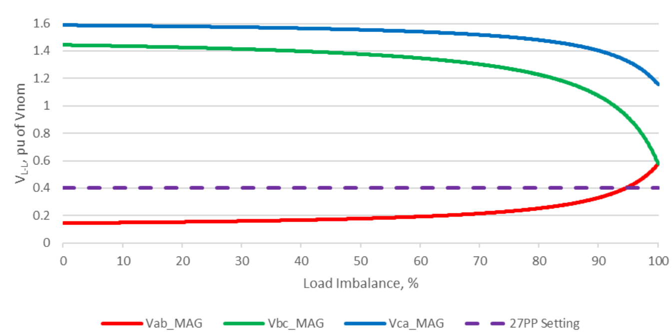

Fig. 22. Low-side L-L voltages during an imbalanced load, AB fault, and open B-phase with R_F = 1 pu of Z_L.

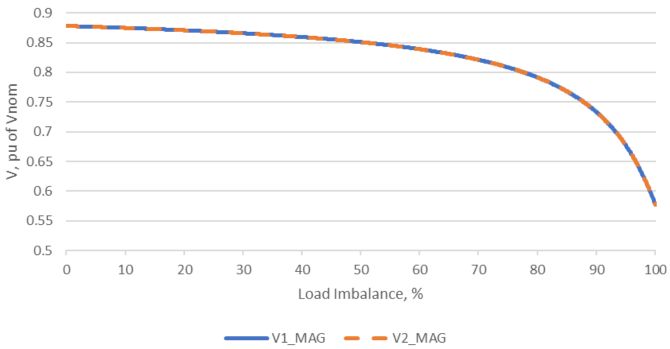

Fig. 23. Low-side sequence voltages during an imbalanced load, AB fault, and open B-phase with R_F = 1 pu of Z_L.

In summary, permanent L-L faults during a high-side open phase result in varying L-L and sequence voltages on the transformer low side. Load imbalance and fault resistance can render the phase-to-phase voltage open-phase detection technique unreliable. To sense the open-phase event during these conditions, a different technique should be utilized to properly secure the detection during an LOP event and dependably operate during an open-phase condition.

V. Impacts of Blown Potential Transformer (PT) Fuse Conditions

With wye-connected PTs, when a single fuse blows in the PT circuit, the relay measures the affected phase line-to-neutral voltage to be zero. However, the line-to-neutral voltage of the other two phases remains unchanged, because the system voltage has not changed. As a result, two L-L voltage magnitudes reduce to 0.58 pu while the third L-L voltage remains unaffected [1]. V1 is reduced to 0.66 pu, and both V2 and V0 increase to 0.33 pu.

If two fuses blow, the relay measures the two phases' line-to-neutral voltages as zero. Consequently, the corresponding two L-L voltages are reduced to 0.58 pu, and the third voltage drops to zero. V1 decreases to 0.33 pu, and both V2 and V0 rise to 0.33 pu.

It is important to note these conditions do not constitute a primary system open-phase condition. Therefore, open-phase detection logic should not operate for PT blown fuse conditions. In Dyn transformer applications, an open-phase event on the transformer high side results in only small amounts of low-side V0 voltage. This V0 voltage is dependent on the ratio of transformer zero-sequence impedance to the load impedance. The highest V0 develops during an open phase, concurrent with an L-G fault when the transformer is operating at its top rating. Generally, there is significant separation between the V0 during this open-phase condition and the V0 for an LOP event. Therefore, a 59G element is a great fit to secure Dyn transformer open-phase detection logic.

VI. Traditional Detection Methods

For decades, methods have been widely used for detecting transformer high-side open-phase conditions. These methods vary in levels of complexity, dependability, and security performance. When designing a protection system, the goal is to maximize the dependability, security, and speed of the system while maintaining simplicity. Designing a transformer high-side open-phase detection algorithm is no different.

While detecting transformer open-phase conditions, it is imperative the system remains secure during LOP, fault, and unbalanced load conditions. The system should also dependably detect the open-phase condition during balanced loading, unbalanced loading, and permanent fault conditions. Existing detection techniques include detecting simple undervoltage, comparing system phase-to-phase voltage relationships, and using sequence current comparisons.

A. Shunt Fault Detection

All existing open-phase detection techniques operate on a time delay for selectivity during system fault conditions. This delay must be set longer than the maximum fault clearing time for a distribution fault. In most applications, a fast operation of open-phase detection logic is not a requirement. Therefore, a pickup timer of 5 seconds, as represented in Fig. 24 through Fig. 27, is often applied in this logic to coordinate with distribution faults.

Alternatively, logic can be applied to sense shunt faults to decrease the operation time delay of open-phase detection schemes. This operating philosophy might be advantageous during times with elevated fire risk to minimize energy dissipation into the fault location. A fault detector can be used to block the operation of open-phase detection logic when a fault is detected. Currents should be measured directly on the transformer low side for the fault detector to properly sense faults on all distribution feeders exiting the substation. Because this element is only able to sense downstream faults, a short pickup delay must be provided to maintain selectivity with transmission faults. This delay should be selected to coordinate with the longest clearing nearby transmission fault with a safety margin. Because the duration of the longest transmission fault is often much shorter than distribution fault durations, this delay can be much shorter than the 5-second delay mentioned previously. This fault detector is represented as 50F in the logic diagrams in Fig. 24 through Fig. 27.

B. Undervoltage

The simplest method for detecting a transformer high-side open-phase condition is the application of a simple undervoltage element, as represented in Fig. 24. This simplicity, however, comes with a significant penalty in security and dependability. This scheme requires LOP blocking logic to prevent tripping for an issue on the PT circuit. This requirement presents both security and dependability concerns, particularly during times of light loading. 3P27 blocks the logic from operating for scenarios, such as when multiple fuses are lost or the transmission source is lost, resulting in a no-voltage condition on the transformer low side. 27P operates the scheme for a single-phase L-N undervoltage event. The 27P setting is applied with a high set pickup threshold, biasing the element towards dependability.

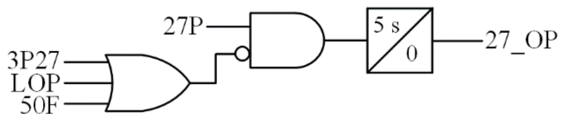

Fig. 24. Undervoltage open-phase detection logic.

C. Sequence Current Comparisons

Sequence current methods [2] use the ratio of negative-sequence and positive-sequence current (I2/I1), as represented in Fig. 25. The Dyn transformer delta winding presents a break in the zero-sequence network, resulting in the positive-sequence current being equal in magnitude with the negative-sequence current in high-side open-phase conditions.

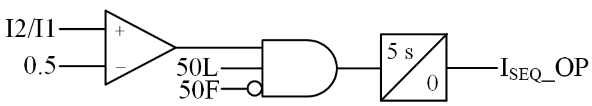

Fig. 25. Sequence current open-phase detection logic.

This method provides great security; however, it can lack dependability during light load conditions. Current methods need to be blocked during light loads, as represented as 50L in Fig. 25, to prevent relay operation due to measurement and instrument transformer errors or due to higher levels of system unbalance during light load conditions. To detect an open phase during these conditions, it is generally recommended to pair current-based detection techniques with voltage-based techniques. Current methods also provide some ability to detect open-phase conditions downstream of the current measurement location and in cases when sources exist on the distribution circuit.

Feeder reclosing techniques should also be considered when using current-based detection methods. Because these methods are sensitive to downstream open-phase events, care should be exercised when using this scheme on systems with single-pole reclosing applied. These schemes should not be applied on systems when single-pole lockout is implemented. On systems with single-pole tripping and three-pole lockout implemented, the open-phase detection scheme delay should be longer than the longest single-pole reclosing open interval.

D. Phase-to-Phase Voltage Relationships

L-L voltage relationships [1] can be used to identify a transformer high-side open-phase condition, as represented in Fig. 26. This method is more popular in modern use, due to its security benefits. This scheme can also be used in single-pole reclosing applications without a speed compromise, making it easy to deploy in distribution environments without worrying about single-pole reclosing coordination.

As explained previously, a transformer high-side open-phase condition results in one L-L voltage falling to zero and the other two falling to 0.87 pu, assuming the system load is balanced. The loss of a PT fuse causes two L-L voltages to fall to 0.58 pu while the third L-L voltage remains at 1 pu. By understanding this, logic can be built to securely detect a transformer high-side open phase by requiring one L-L voltage less than 0.4 pu (27PP) and another greater than 0.7 pu (59PP). Under balanced load conditions, this scheme dependably detects a transformer high-side open phase while remaining secure to LOP events.

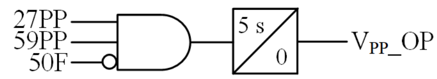

Fig. 26. Phase-to-phase voltage open-phase detection logic.

L-L voltage techniques provide the most robust traditional solution, particularly on distribution systems. This scheme remains secure during LOP, fault, and single-phase reclosing applications, and it remains dependable during balanced system loading conditions; however, it lacks dependability when the system load becomes unbalanced or when a fault is permanent during the open phase. As discussed in Sections III and IV, the low-side L-L voltage relationship from a high-side open phase changes during times of load imbalance or with a permanent fault applied. This scheme loses dependability when the smallest L-L voltage exceeds 0.4 pu during these conditions. These conditions are important to detect to prevent damage during an event.

VII. Sequence Voltage Detection Technique

Alternatively, detecting transformer high-side open-phase conditions can be done using sequence overvoltage elements, as represented in Fig. 27. This method dependably detects open-phase conditions during both balanced and unbalanced conditions without any penalty to security.

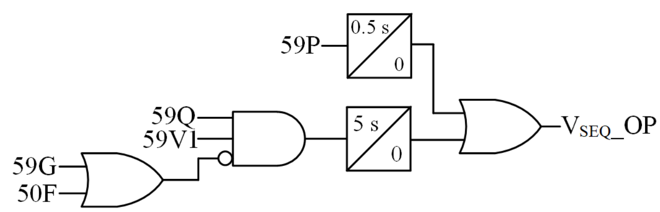

Fig. 27. Sequence voltage open-phase detection logic.

A. 59G

To properly secure the scheme during LOP conditions, zero-sequence overvoltage elements are applied. Due to the presence of a delta winding on a Dyn transformer, the zero-sequence network is broken at the transformer. In an ideal transformer, no zero-sequence voltage can be developed on the transformer low side for a transformer high side's open-phase condition. However, the presence of Z0T on a transformer results in a small amount of V0 on the transformer low side. This results during open-phase conditions, concurrent with unbalanced load or SLG conditions. This voltage is, however, small in magnitude compared to the 0.33 pu V0 expected during an LOP event. This makes it reliable to use zero-sequence voltage elements to secure the scheme for LOP events. In this scheme, a zero-sequence overvoltage element operating on V0 set at 0.2 pu is applied to block the open-phase detection logic operation for LOP conditions. This provides a 30 percent security margin during an LOP event, assuming the system voltages are 0.9 pu.

B. 59V1 and 59Q

Positive- and negative-sequence overvoltage elements are used to detect transformer open-phase conditions. Positive-sequence overvoltage elements are used to secure the scheme during a reverse phase orientation, known as negative-sequence rotation. During this condition, pure negative-sequence voltage quantities are seen without the presence of positive-sequence voltage quantities. These conditions can result from many reasons, but they are most often caused by improperly applied PT secondary wiring or relay settings. Some applications require protection against a primary system reverse phase rotation. The scheme represented in Fig. 27 can be changed to respond to this condition by removing 59V1 from the logic diagram to allow operation on the 59Q element without positive-sequence voltage supervision.

It is important to understand that V1 and V2 on the transformer low side for an open-phase condition are impacted by multiple conditions, such as the delta-winding phase orientation (i.e., Dyn1 or Dyn11), faulted phase, load imbalance characteristics, and which fuse operates. In this paper, our focus is on Dyn1 transformers with an A-phase open fuse. For a Dyn11 transformer with the A-phase open, V1 plots match the V2 plots of the Dyn1 transformer, and V2 plots match the V1 plots of the Dyn1 transformer. It is, therefore, important to set identical pickup thresholds for both the positive- and negative-sequence overvoltage elements.

Because the scheme is secured for the LOP condition using a zero-sequence overvoltage element, the positive- and negative-sequence overvoltage elements can be set sensitively to detect the transformer open phase. These elements should be set high enough to accommodate system steady-state unbalances and low enough to detect feasible open-phase conditions producing the lowest voltage. When a transformer open phase occurs during loading conditions with very high load angle separations among the phases, small levels of negative- and positive-sequence voltages may be produced. A pickup setting of 0.15 pu accommodates the worst-case load angle separation, as identified in Sections III and IV of this paper.

C. 59P

Depending on which high-side fuse operates for a low-side L-L fault, an overvoltage can result on the unfaulted phase. This condition should be isolated as quickly as possible to protect against voltage stress. Because a delta-wye grounded transformer acts to limit voltage rise during ground fault events when all phases are intact, a phase overvoltage element is used to distinguish this open-phase condition from other system conditions. This element is set at 1.3 pu to dependably detect this condition and remain secure against conditions that might result in a small phase voltage rise. A 0.5-second pickup delay is used to secure the operation during brief system transient conditions.

VIII. Real-World Open-Phase Event

On the morning of January 2, 2024, a utility in the United States had an event in which the C-phase transformer high-side fuse operated for a low-side CG fault. This event was later identified to be a failed C-phase bushing on the transformer low side. During this event, the utility had the phase-to-phase voltage-based open-phase detection method applied in low-side relaying at the site. This logic failed to identify the open-phase event, resulting in unbalanced voltage conditions on the distribution circuit until the transformer was isolated by line crews.

During the time of this event, the load on the system was light, causing current-based schemes to be rendered ineffective. The B-phase current had the maximum current magnitude of 13.8 A, as recorded by the relay with a current transformer ratio of 500, resulting in 27 mA of relay secondary current. A securely set load detector in current-based schemes would have blocked the operation of current-based open-phase detection schemes. Single-pole reclosing was also deployed in reclosers at the site, making current-based schemes less desirable.

The analysis of the event revealed the low-side V_c voltage to be zero and V_a and V_b at nominal voltage with opposite phase orientation. Furthermore, the phase-to-phase voltage magnitudes in the event are similar to that of a fault with zero resistance represented in Fig. 10. These relationships match those expected for a bushing failure, resulting in a permanent metallic fault. Fig. 28 shows the relay 27PP bit set at 0.4 pu remaining deasserted, resulting in the scheme's failure to operate.

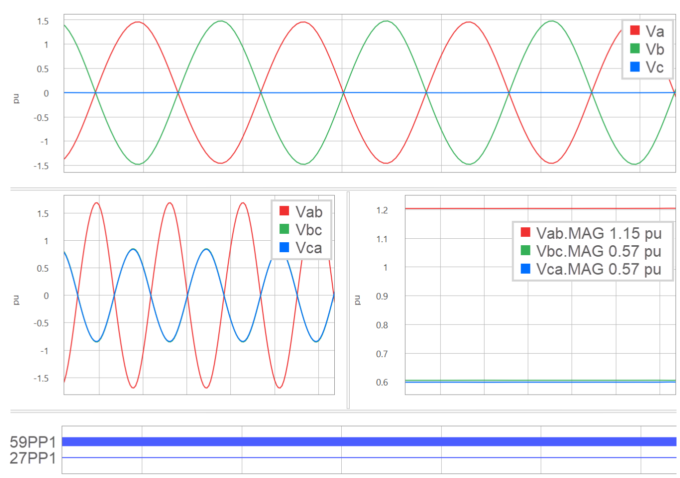

Fig. 28. Low-side pu voltages of the system during an open-phase event.

As part of the event analysis, we have recreated the sequence voltage element logic in this event to analyze its response. From Fig. 29, the positive- and negative-sequence voltages are 0.6 pu, whereas the V0 voltage is 0.0055 pu. This results in the assertion of the 59V1 and 59Q bits and no assertion of the 59G bit in the sequence voltage open-phase logic from Fig. 27. These conditions then qualify the logic to assert the tripping output VSEQ_OP.

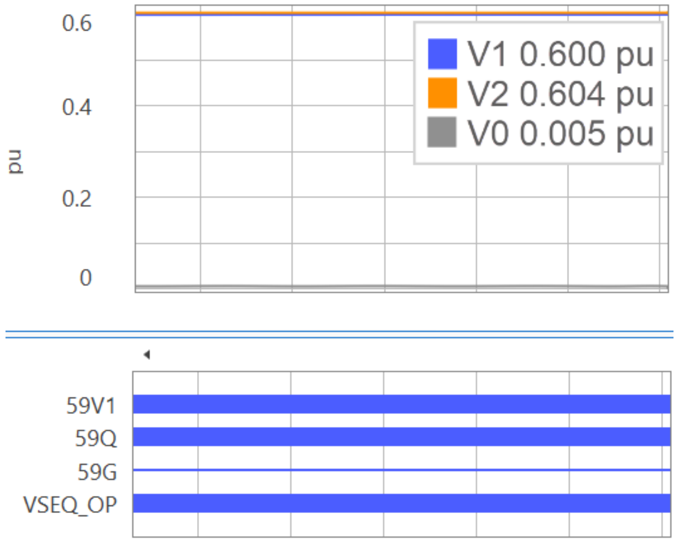

Fig. 29. Sequence voltage logic response to a system event.

IX. Conclusion

Transformer high-side open-phase detection is crucial in ensuring the safe and efficient operation of distribution power transformers. By reliably detecting open phases, equipment damage and fire risks can be minimized, ultimately leading to a safer and more reliable power system. Traditional open-phase detection methods lack dependability when the system is unbalanced or during light loading. Dependability and speed become more crucial in the case of an open phase caused by L-L faults on the low side of a Dyn transformer, which can result in high voltage on the unfaulted low-side phase.

Using positive-, negative-, and zero-sequence overvoltage elements allows for a more comprehensive and dependable detection of open phases. A negative-sequence overvoltage element is used to dependably detect the open phase. Positive- and zero-sequence overvoltage elements are used to properly secure the logic, ensuring that only genuine open-phase conditions are detected and addressed promptly. This method improves the overall dependability of the system without compromising security and is sensitive to open-phase events with concurrent permanent faults and balanced or unbalanced load conditions. This not only enhances the safety of the system but also minimizes unnecessary downtime and maintenance costs.

X. Appendix: Derivations

Within this section, equation derivations used to produce the plots within this technical paper are detailed. Plots were derived assuming the transformer represented in Fig. 1 is an ideal transformer with an infinite source applied.

L-L voltages within the paper are represented using the respective L-L nominal voltage as the base. L-N and sequence voltages are represented using the respective L-N nominal voltage as the base. The L-L and L-N base voltages, therefore, have a difference of $\sqrt{3}$. In this appendix, the equations used to derive the L-N voltages are presented. The L-L and sequence voltages are then calculated using the derived L-N voltages.

A. *Loading With the A-Phase Open*

As discussed within Section III, the equivalent circuit in Fig. 2c can be used to represent the open-phase condition during a loading condition. The V_c voltage in this figure is directly connected to the V_{BC} source voltage. The V_a and V_b voltages are dependent on the voltage divider circuit created by the series connection of the ZL_A and ZL_B impedances. By using the voltage divider principle, V_b voltage can be represented by (2).

$$V_b = \frac{-V_c \bullet ZL\_B}{ZL\_A + ZL\_B} \tag{2}$$

With the application of an ideal transformer, V_a can then be derived by applying KVL around the delta winding of the transformer. Due to the magnetic coupling of the transformer low-side voltages with the delta-winding voltages, V_a can be represented using (3).

$$V_a = -(V_b + V_c) \tag{3}$$

These equations are used to produce the plots in Fig. 4 through Fig. 7 with different load impedance relationships.

B. *Low-Side SLG Fault With the A-Phase Open*

Like the loading condition, the SLG condition also creates a voltage divider circuit. The equivalent circuit for this condition is represented in Fig. 9. This circuit has one slight difference from that of Fig. 2c, that being fault resistance, R_F, is placed in parallel with the faulted A-phase loading impedance, ZL_A. The V_b voltage during an AG fault condition can be derived using the voltage divider principle to create (4), which can be rearranged and derived using (5).

$$V_b = \frac{-V_c \bullet ZL\_B}{\dfrac{ZL\_A \bullet R_F}{ZL\_A + R_F} + ZL\_B} \tag{4}$$

$$V_b = \frac{-V_c \bullet ZL\_B \bullet (ZL\_A + R_F)}{ZL\_A \bullet R_F + ZL\_A \bullet ZL\_B + ZL\_B \bullet R_F} \tag{5}$$

Like the loading condition, V_a can be derived using (3). These equations are used to produce the plots in Fig. 10 and Fig. 11.

C. *Low-Side L-L Fault With the A-Phase Open*

The circuit in Fig. 13 can be separated into five different segments during an L-L fault condition concurrent with a high-side open phase. The fault can be connected to the system A- and B-phases by two different nodes (a and b). By applying Kirchhoff's current law (KCL) at Node a, (6) can be derived. Likewise, by applying KCL at Node b, (7) can be derived.

$$IL\_A = \frac{V_a}{ZL\_A} + I_F \tag{6}$$

$$IL\_B = \frac{V_b}{ZL\_B} - I_F \tag{7}$$

As discussed in Section IV, during the AB fault condition concurrent with an A-phase open condition, the IL_A and IL_B currents must be equivalent due to the series connection of W1 and W2 in Fig. 13. Therefore, IL_B in (7) can be replaced with (6) and rearranged to solve for V_b, as represented in (8). V_a in (8) is then replaced with (3) and solved for V_b to reveal (9).

$$V_b = \frac{V_a \bullet (2 \bullet ZL\_A + R_F) \bullet ZL\_B}{ZL\_A \bullet (2 \bullet ZL\_B + R_F)} \tag{8}$$

$$V_b = \frac{-V_c \bullet (2 \bullet ZL\_A + R_F) \bullet ZL\_B}{ZL\_A \bullet (2 \bullet ZL\_B + R_F) + ZL\_B \bullet (2 \bullet ZL\_A + R_F)} \tag{9}$$

V_a is then solved using (3). These equations are used to produce the plots in Fig. 14 through Fig. 17.

D. Low-Side L-L Fault With the B-Phase Open

During the AB fault condition concurrent with a B-phase open condition, V_{CA} is instead the source voltage. This voltage is connected to the W1 winding and, therefore, coupled with V_a, as represented in Fig. 18. Also, during this condition the IL_A and IL_B currents are no longer equivalent. Therefore, different techniques must be used to solve for the L-N voltages. During this condition, as represented in Fig. 18, the IL_B and IL_C currents are equivalent due to the series application of the W2 and W3 windings. The IL_C current is represented by (10). The KCL principle is then applied at Node b and solved for I_F by replacing IL_C with (10) to reveal (11). Additionally, (3) can be solved for V_c and used to replace V_c in (11) to reveal (12).

$$IL\_C = \frac{-V_c}{ZL\_C} \tag{10}$$

$$I_F = \frac{V_b}{ZL\_B} - \frac{V_c}{ZL\_C} \tag{11}$$

$$I_F = \frac{V_b}{ZL\_B} + \frac{V_a + V_b}{ZL\_C} \tag{12}$$

Next, V_b is derived using voltage drop principles across the fault resistance from the V_a voltage, as represented by (13). I_F in (13) can be replaced with (12) and solved for V_b to reveal (14). Finally, (3) is used to derive V_c. These equations are used to produce the plots in Fig. 20 through Fig. 23.

$$V_b = V_a - I_F \bullet R_F \tag{13}$$

$$V_b = V_a \frac{ZL\_B \bullet ZL\_C - ZL\_B \bullet R_F}{ZL\_B \bullet ZL\_C + R_F \bullet (ZL\_B + ZL\_C)} \tag{14}$$

XI. References

[1] E.O. Schweitzer, III. and J. Kumm, "Detecting High-Side Fuse Operations Using an SEL-251 Relay," SEL Application Guide 1995-26, 1995.

[2] R. A. Wilson and V. Vadlamani, "Detecting Open Phase Conductors," proceedings of the 2015 68th Annual Conference for Protective Relay Engineers, College Station, TX, March 2015.

XII. Biographies

Josh LaBlanc received his BS in electrical engineering from the University of North Dakota in 2011. After graduation, Josh worked for an oil and gas pipeline company, Enbridge Energy, then an electric power utility, Minnesota Power. Josh has most recently spent 5.5 years working as an application engineer for Schweitzer Engineering Laboratories, Inc. (SEL). His primary roles are providing application and technical support and training on power system protection topics. Josh is a registered professional engineer in the state of Minnesota.

Yash Shah received his BS in electrical engineering from Maharaja Sayajirao University in 2017. In 2019, Yash received his MS in electrical engineering from Arizona State University. Yash worked at a mining company, Freeport-McMoRan, as an electrical engineer. He joined Schweitzer Engineering Laboratories, Inc. (SEL), in 2020 and is currently a field application engineer in the SEL office in Plymouth, Michigan. His responsibilities include providing application support and technical training for protective relay users.

John Aultman received his BS in electrical engineering from the University of North Dakota in 2009. He started his career as a field service engineer then application engineer for Rockwell Automation (Allen-Bradley) before working as a senior engineer and co-owner at a startup electrical engineering and consulting firm. He joined Schweitzer Engineering Laboratories, Inc. (SEL), in 2020 as an application engineer. His primary roles include providing application and technical support and training on power system protection topics to a variety of customers. John is currently a licensed professional engineer in the states of Minnesota and Wisconsin.

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