Open-Phase Detection for Station Auxiliary Transformers

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***Abstract*—Open-phase conditions are not always self-evident on transformers. Several factors, such as transformer loading, winding connections, location of the open-phase, and the ground involvement, present challenges for traditional protection. Auxiliary transformers at generation stations feed critical loads. An open-phase condition that goes undetected will cause adverse operating conditions for electrical equipment, which could render redundant safety-related trains inoperable at nuclear power plants. An open-phase condition will eventually result in a protection trip, which can lead to a possible plant shut down.**

During the winter of 2012, an insulator on the dead-end structure of one of the phases of the transmission line servicing a station auxiliary transformer at the Byron Nuclear Plant failed, causing the conductor to drop to the ground. Neither the transmission operator nor the nuclear plant's protective relays detected the condition, resulting in the transformer being fed from two out of the three phases. This open-phase incident caused adverse effects on the plant operation and revealed a vulnerability in existing protection schemes at most generating plants. Key decision-makers in the U.S. nuclear industry agreed to proactively implement techniques to detect open-phase conditions to mitigate their impacts.

In this paper, we discuss some of the potential causes of open-phase conditions, their impacts on power system operation, the challenges in detecting them, and some novel methods developed to detect them. Finally, we discuss the implementation of these methods in microprocessor-based protective relays at several nuclear power generating stations. We also present field results of a successful open-phase detection in this paper.

I. Introduction

Power generation plants require power locally to run pumps and other critical auxiliary loads. A typical power generation plant layout is represented in Fig. 1. Most of the auxiliary loads are fed from the Unit Auxiliary Transformer (UAT). A Station Auxiliary Transformer (SAT), supplied from an offsite source, can supplement the UAT or serve as a hot stand-by. Diesel-fueled emergency generators can support black start operations when both the UAT and SAT are not available.

An open-phase condition is defined as a series power system fault where one or two phases are "opened," causing an interruption of power flow through those phases. A differentiating characteristic between a series fault and a shunt fault is the absence of high magnitudes of fault current in most cases. However, a series fault causes an unbalanced operating condition in the power system that can be detrimental to electrical equipment. Typical causes for open-phase conditions on the power system are the following:

- Broken conductors that fall on the transformer side
- Stuck breaker or circuit switcher mechanisms
- Blown fuses on one or two out of three phases

On Jan. 30, 2012, an insulator on the dead-end structure of one of the phases of the transmission line servicing the Unit 2 station auxiliary transformer at the Byron Nuclear Plant failed, causing the conductor to break and drop to the ground [1]. See Fig. 2.

Neither the transmission nor the nuclear plant's protective relaying detected the condition, resulting in the transformer being fed from two out of the three phases. This open-phase incident caused adverse effects on the plant operation and revealed a vulnerability in existing protection schemes at most generating plants.

Reference [2] identifies several other open-phase conditions since the Byron incident in 2012, illustrating the importance of identifying and protecting the power system against such conditions.

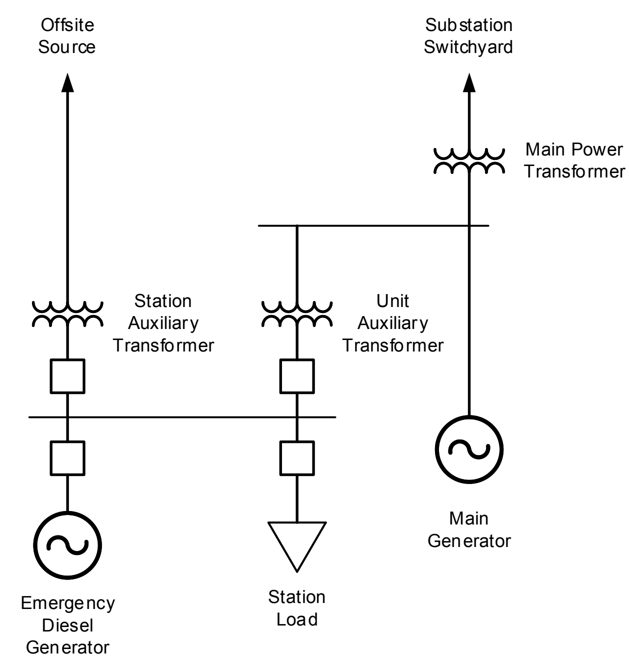

Fig. 1. Simplified Oneline of a Typical Power Generation Station

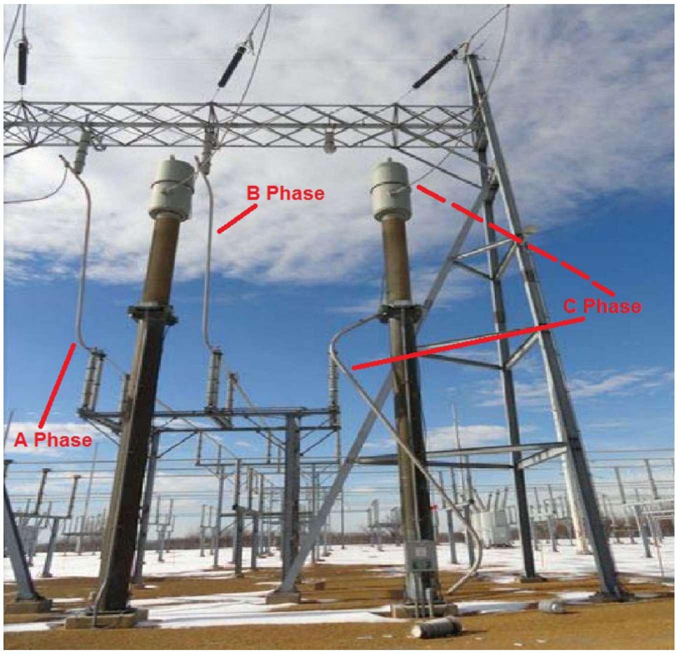

Fig. 2. Picture of Broken and Downed C-Phase Conductor at Byron Nuclear Plant (Courtesy of Exelon Generation LLC)

In this paper, we discuss the transformer currents and voltages response to various open-phase conditions. As we will see, several factors influence the response. These include transformer types and loading conditions. We developed open-phase detection algorithms to detect these conditions, and we explain their applicability to different types of transformers and loading conditions. Finally, we present project experience in implementing these algorithms in microprocessor-based relays and provide field results.

II. System Conditions in Response to Open-Phase Conditions

When an open-phase condition occurs on the high side of a three-phase transformer, currents and voltages are expected to become unbalanced. However, [3], [4], and [5] show that several factors influence the response to an open-phase condition. In this section, we discuss the factors that influence the response of a high-side open-phase condition on the currents and voltages that appear on the high and low side of the transformer. These factors include the following:

- Transformer winding connections
- Transformer core construction: core type (3- or 5-limb) or shell type
- Transformer loading
- Grounding of the open phase (on the non-source side)

We used a Real Time Digital Simulator (RTDS) to run electromagnetic transient simulations using the test system shown in Fig. 3 to study the transformer response to open-phase conditions, and recorded the high- and low-side transformer voltages and currents.

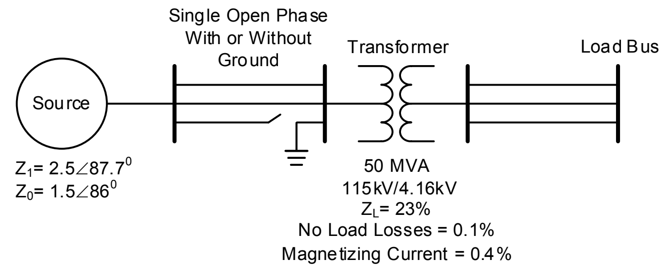

Fig. 3. Test System Modeled in RTDS Simulator

This test system uses the Unified Magnetic Equivalent Circuit (UMEC) transformer model [6], which accounts for the transformer core type and geometry. This is an important distinction because this model offers a more accurate representation of the magnetic coupling between the phases under normal operating conditions and during open-phase conditions.

Transformer winding connections, core construction, loading, and grounding are varied in each simulation and the results are presented in this section. The transformers modeled are typical of those that can be found in generation stations. The currents and voltages presented in the results are represented in per-unit (pu) quantities.

A. Y_g-Y_g Transformers

In Y_g-Y_g transformers, the core construction and loading affect the transformer's response to an open-phase condition. Depending on the core type, a Y_g-Y_g transformer may or may not regenerate the voltage on the opened phase, requiring a detailed analysis for developing adequate open-phase detection methods.

In a 3-limb core, the voltage on the open phase is regenerated because the magnetic flux of the two remaining phases flows through the limb associated with the opened phase because no alternate paths exist. The currents on the other two phases increase to carry the load on the open phase when the transformer is operated under load. Fig. 4 shows 100 percent voltage regeneration at no-load conditions. Fig. 5 shows an increase in load current on the two healthy phases when the loading is at 50 percent rated value. As the loading of the two healthy phases increases, less flux flows though the limb associated with the open phase and therefore the voltage on the open phase begins to decrease. These results can be seen in Fig. 5.

A 5-limb core or a shell-type core provides alternate paths for the flux to flow, so voltage regeneration will be minimal during an open-phase condition, as shown in Fig. 6 and Fig. 7.

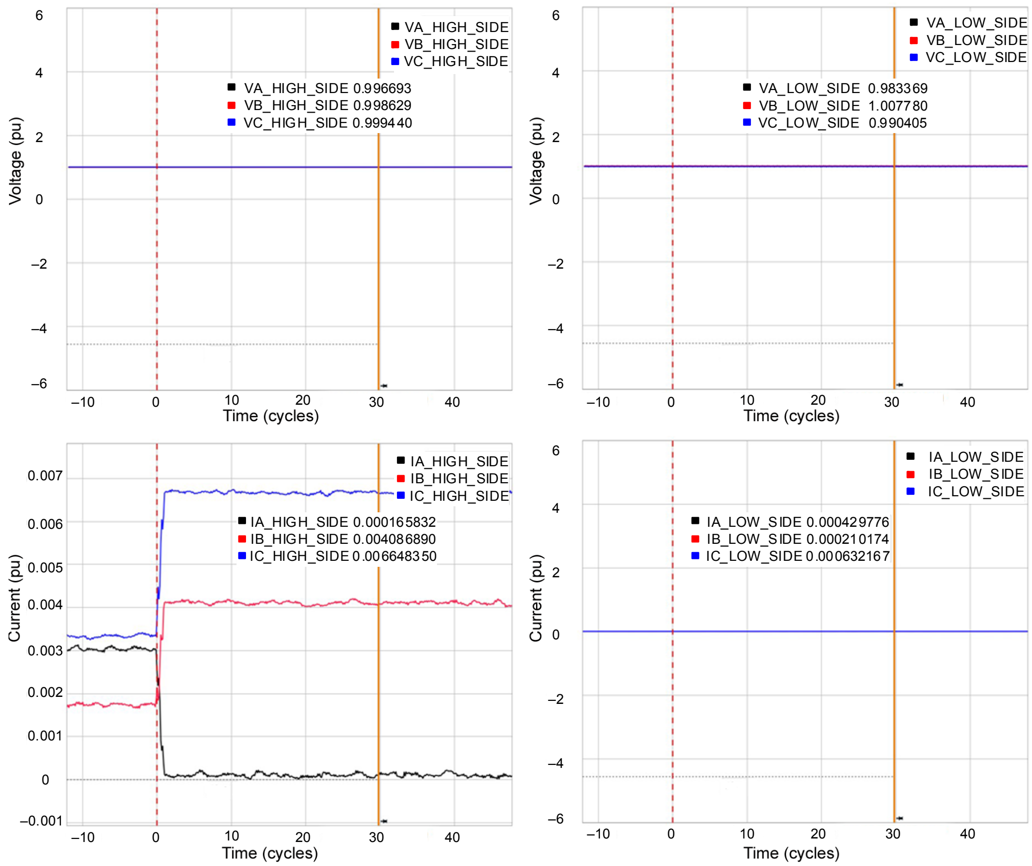

Fig. 4. Simulation Results: Ungrounded Phase A Open, No Load, 3-Limb Core Construction

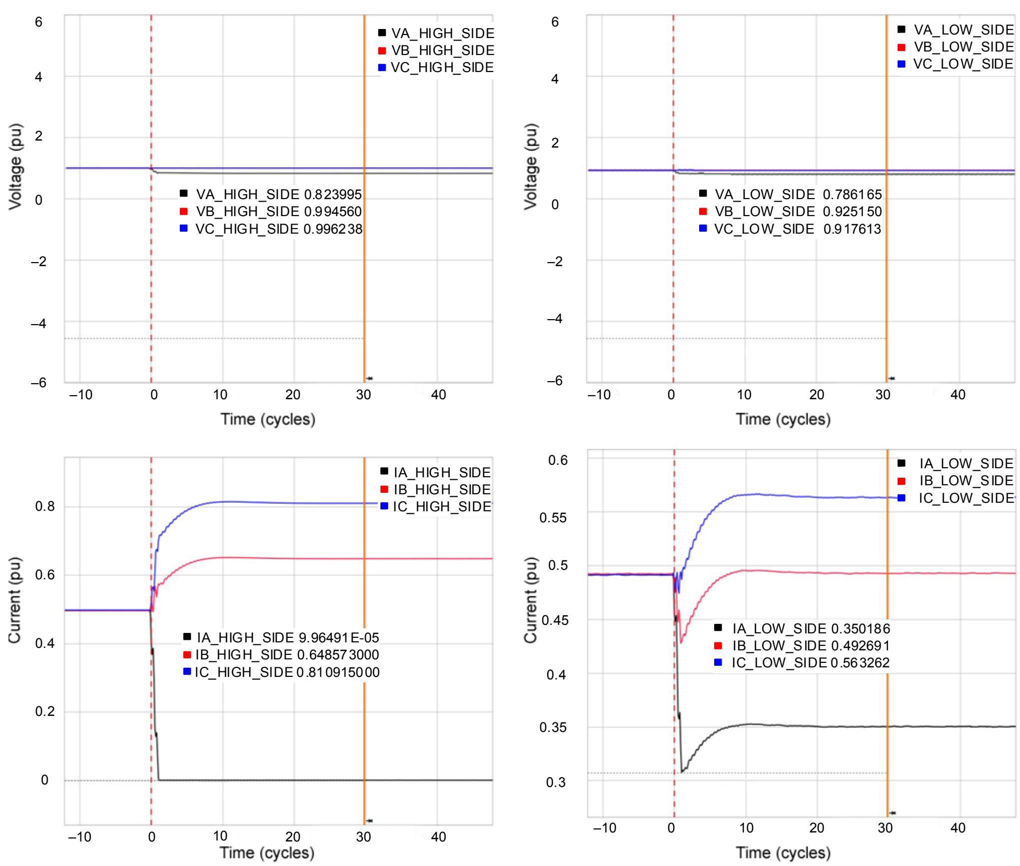

Fig. 5. Simulation Results: Ungrounded Phase A Open, 50% Load, 3-Limb Core Construction

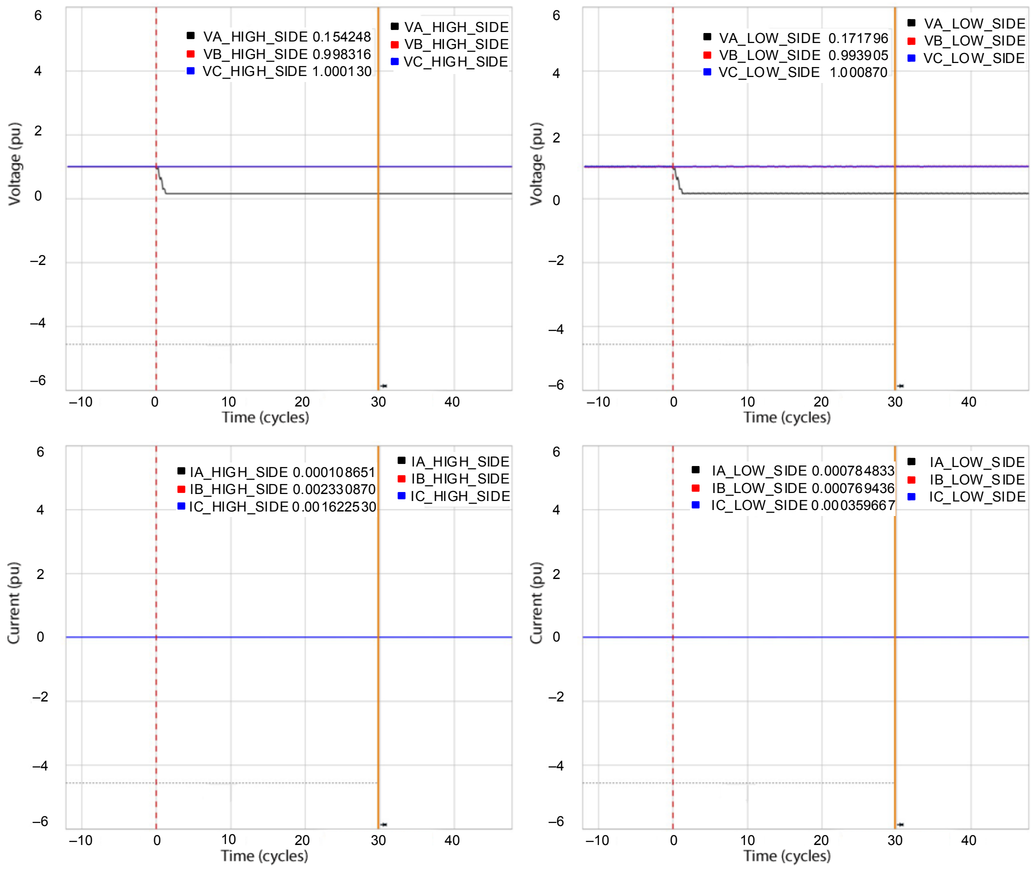

Fig. 6. Simulation Results: Ungrounded Phase A Open, No Load, 5-Limb Core Construction

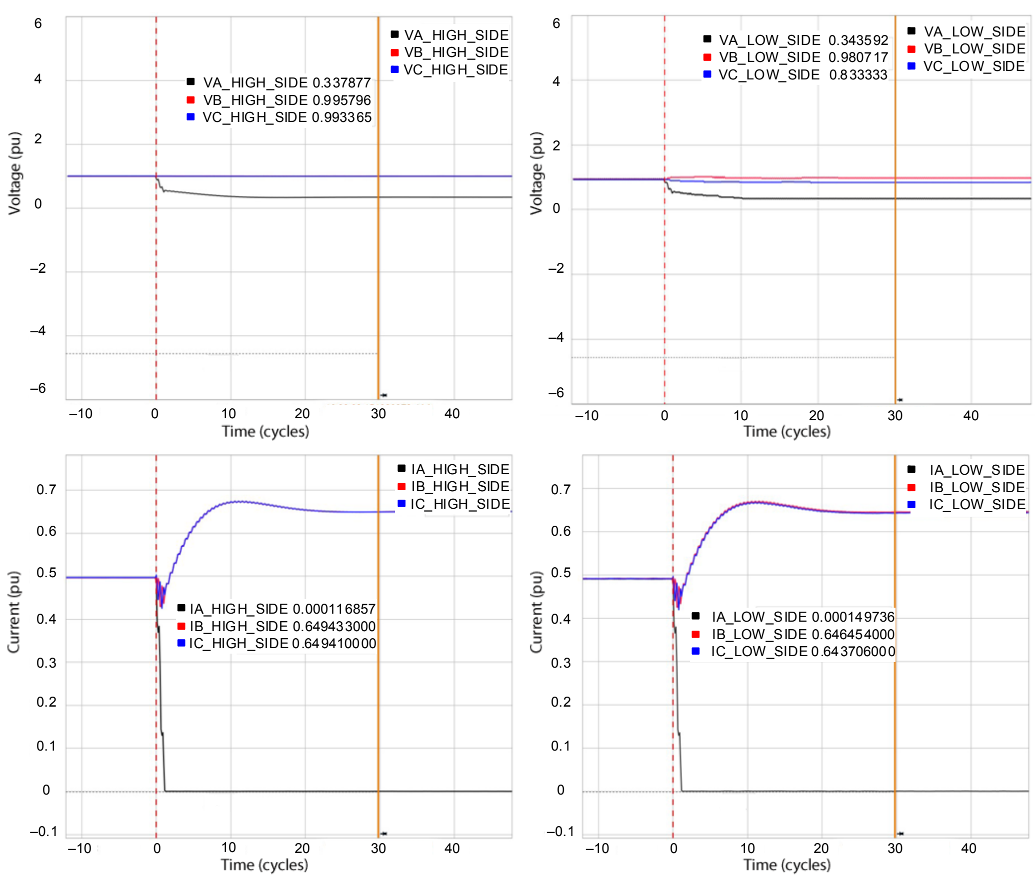

Fig. 7. Simulation Results: Ungrounded Phase A Open, 50% Load, 5-Limb Core Construction

B. *Δ-Y_g Transformer*

In this type of connection (ungrounded high-side), the response to an open phase on the high side of the transformer is not influenced significantly either by the loading levels or by core construction types [7]. The voltage on the winding not involved in the open phase retains its pre-fault value. The other two winding voltages will be half that of the pre-fault value. The voltage and current unbalance on both high- and low-side of the transformer will appear as mostly negative-sequence quantities. Fig. 8 and Fig. 9 show an ungrounded open phase at no load and 50 percent load, respectively.

C. *Y_g-Δ Transformer*

In an unloaded Y_g-Δ transformer, both the high- and low-side voltages corresponding to the open phase are regenerated such that effectively no change is observed in three-phase voltage magnitudes on the high and low side of the transformer. When the transformer loading increases, some unbalance will be introduced because of leakage flux and voltage drop. However, the unbalance is not significant enough to be able to develop a protection scheme based on symmetrical components. Transformer core construction is not an influencing factor in this type of transformer. Fig. 10 and Fig. 11 show an ungrounded open-phase condition at no load and 50 percent load, respectively.

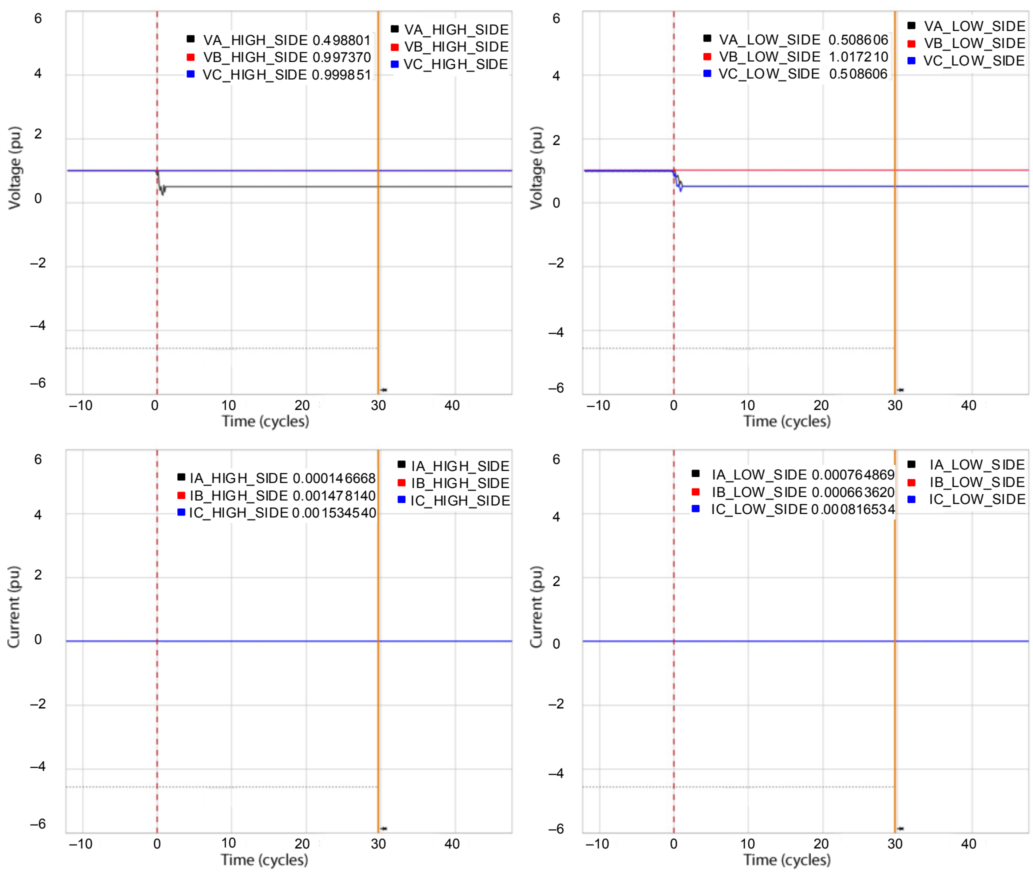

Fig. 8. Simulation Results: Ungrounded Phase A Open, No Load, 3-Limb Core Construction

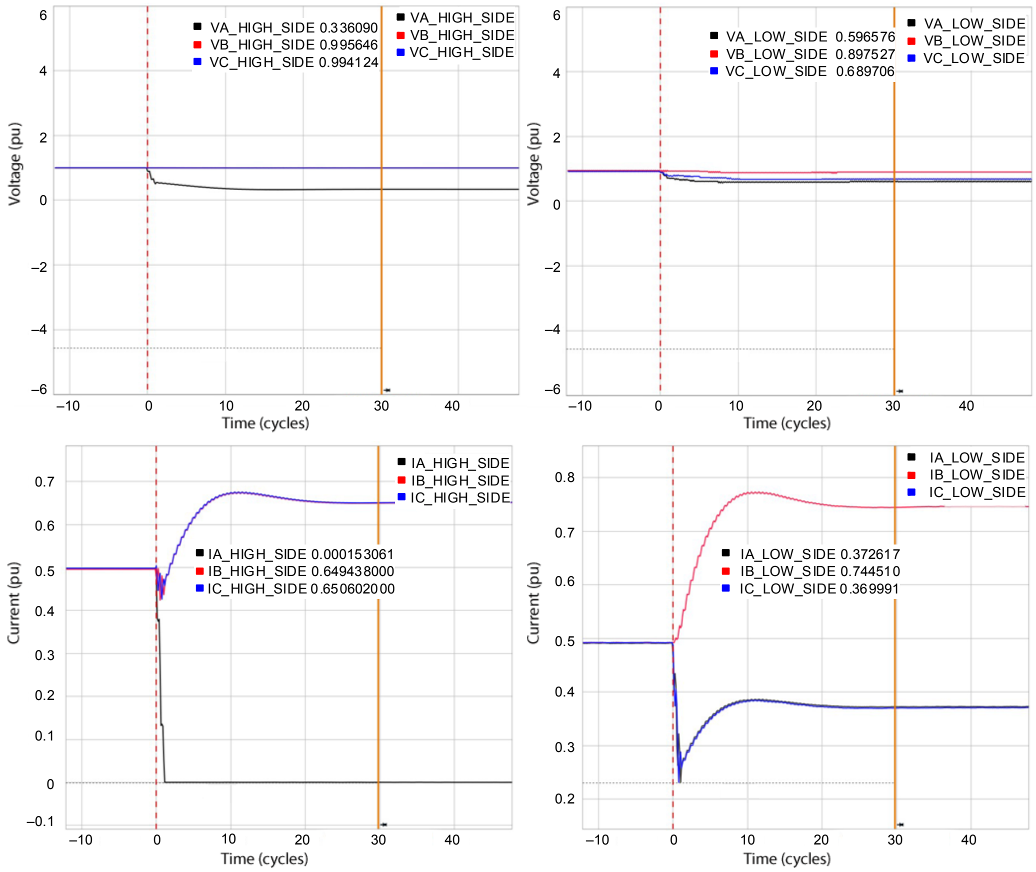

Fig. 9. Simulation Results: Ungrounded Phase A Open, 50% Load, 3-Limb Core Construction

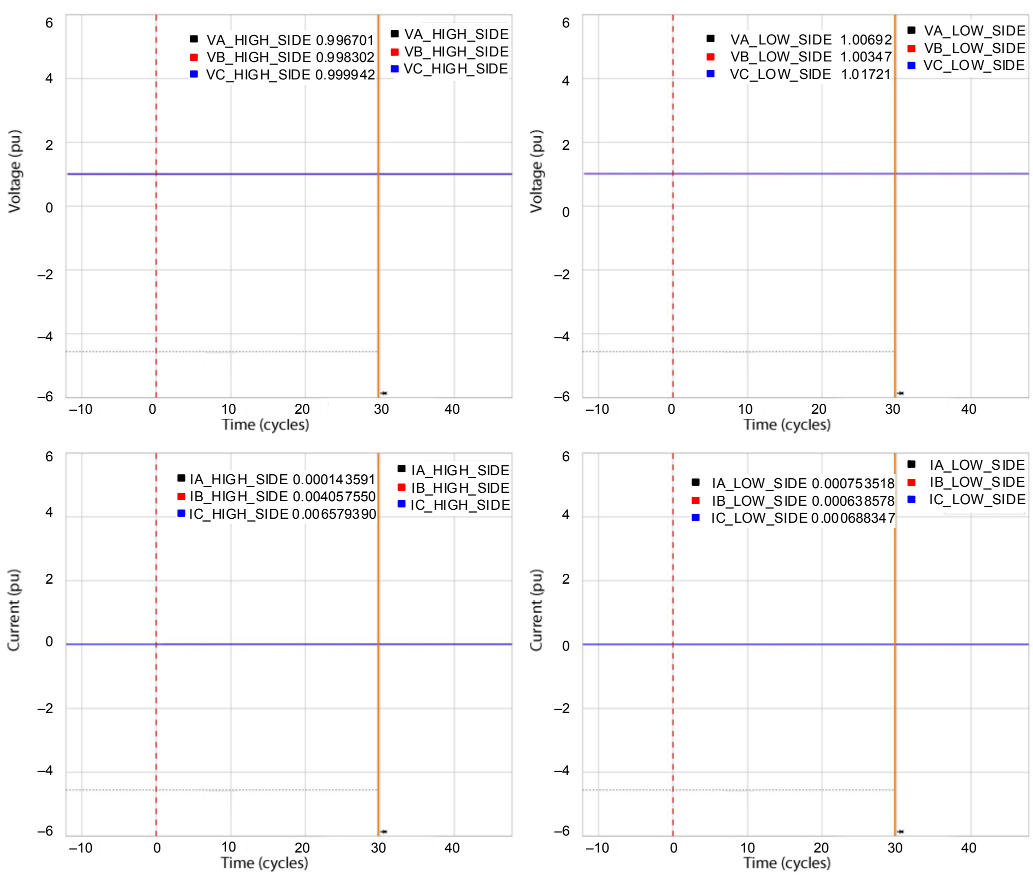

Fig. 10. Simulation Results: Ungrounded Phase A Open, No Load, 5-Limb Core Construction

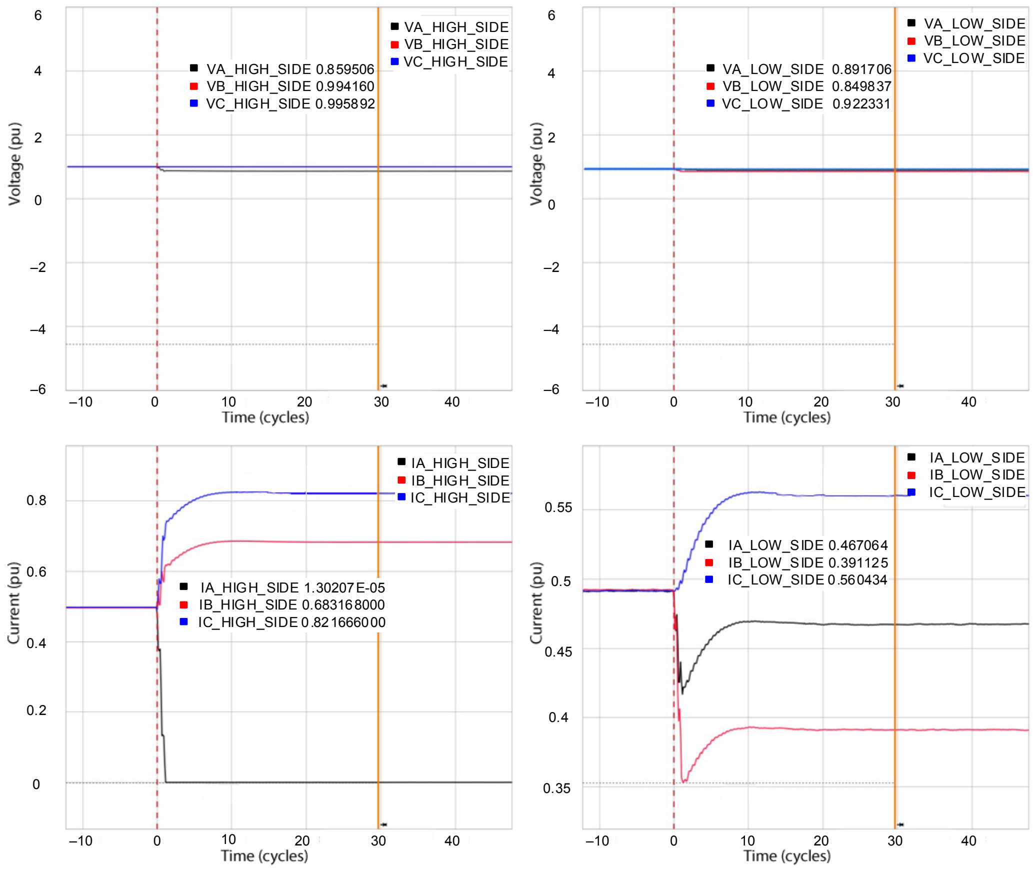

Fig. 11. Simulation Results: Ungrounded Phase A Open, 50% Load, 5-Limb Core Construction

III. Open-Phase Detection Algorithms

The analysis in the previous section demonstrates that voltage-based detection of open-phase conditions is not adequate for all transformer configurations. This section discusses current-based detection methods that can be implemented in microprocessor-based relays to complement and, in some applications, replace voltage-based detection. Under no-load conditions, the currents measured at the high side of the transformer are mainly transformer excitation currents that are inherent to the transformer. Each phase-excitation current can be different in magnitude, depending on the transformer connection and core design. Furthermore, these currents are not perfectly sinusoidal. Thus, the use of current symmetrical components is not a preferred approach for open-phase detection when the transformer is operated at no-load because of this current unbalance. As the transformer loading increases, the currents become more symmetrical and sinusoidal, allowing the use of symmetrical components shown in (1) as detection methods to the unbalance introduced by applicable open-phase conditions.

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (1)$$

ABC rotation

where:

α is 1∠120.

A. Averaging Algorithm (A1)

This algorithm uses the current transformers (CTs) at the high-side bushings of the transformer to average the measured excitation current on each phase over a specified period by using a microprocessor-based relay after the transformer is energized and left to soak. Once the current averaging duration expires, the average excitation current for each phase is determined and programmed as the per-phase excitation current baseline in the relay.

This approach accounts for the magnetic coupling between the phases that results in different excitation current magnitudes. This reduces challenges resulting from erroneous or insufficient data in the transformer test reports because the actual measured excitation currents for each transformer are used as the baseline.

If the current on any phase drops below a percentage of its recorded average value after a specified time delay, the relay declares an open-phase condition.

Fig. 12 shows an ungrounded open Phase A condition on a 3-limb Y_g-Y_g transformer operated at no load with the parameters shown in Fig. 3. The averaging algorithm (PH_A_A1) detects the current drop of Phase A below 50 percent of the programmed baseline after the specified 30-cycle time delay expires.

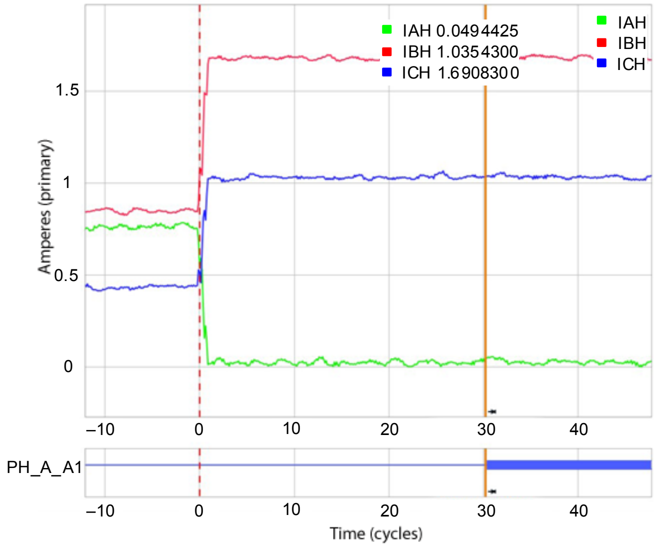

Fig. 12. Simulation Results: Ungrounded Phase A Open, No Load, 3-Limb Core Construction

The drop percentage must consider the farthest point electrically in the zone of detection to account for the worst-case scenario charging current. Fig. 4 shows that the voltage regenerates perfectly on the open phase; thus, if the transformer is fed from underground cables or long overhead transmission lines, the current may not drop to zero depending on the location of the open phase. If the charging current on the open phase is not lower than the excitation current by a sufficient margin, the zone of detection may need to be divided or a small minimum load may be required. This consideration also applies to the Digital Filters algorithm.

B. Digital Filters Algorithm (A2)

Another approach to monitoring the transformer excitation currents is through the use of digital filters like an Infinite Impulse Response (IIR) filter. The output of an IIR filter reaches the input quantity asymptotically after a certain time constant. Fig. 13 shows the IIR filter output response when subjected to a step increase and a step decrease in Phase A current.

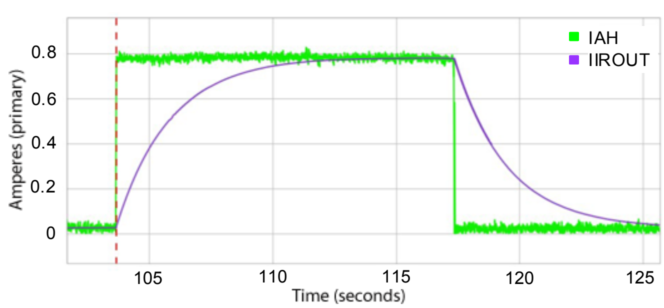

Fig. 13. IIR Filter Response to Step Changes in Phase A Current

This algorithm passes each of the phase currents through an IIR filter and compares each phase current to the output of its filter. For steady-state conditions, the IIR filter output and the input phase current magnitude will be almost identical. If the current drops below a percentage of the IIR filter output after a specified time delay, the relay declares an open-phase condition.

The main advantage of this algorithm over the averaging algorithm is that the undercurrent thresholds adjust dynamically to changes in the transformer excitation currents as a result of variations in the grid voltage. The main advantage of the averaging algorithm over this algorithm is that it can be qualified for longer durations since the IIR filter output is a decaying baseline during an open-phase condition. The time delay needed to qualify the IIR filter algorithm for an open-phase condition must be shorter than the filter time constant.

Fig. 14 shows the IIR Filter algorithm (PH_A_A2) response to the event simulated in Fig. 12. The algorithm detects the current decrease of Phase A below 50 percent of the IIR filter output after the specified 30-cycle time delay expired.

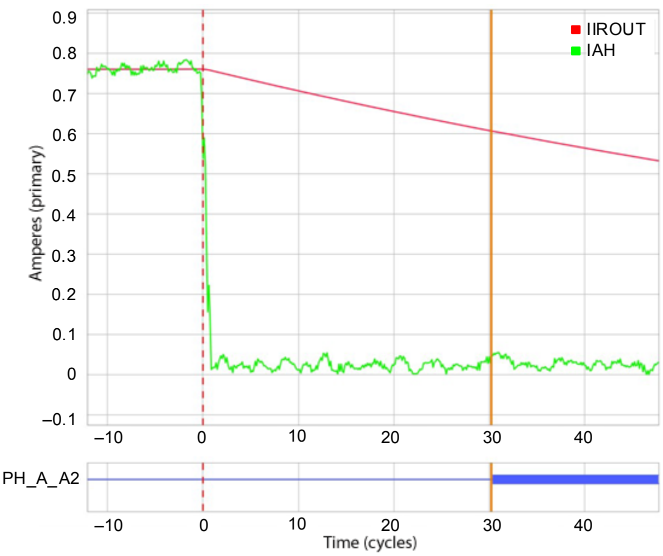

Fig. 14. Simulation Results: Ungrounded Phase A Open, No Load, 3-Limb Core Construction

C. Difference of the Ratio of the Second Harmonic to Fundamental Currents Algorithm (A3)

This algorithm uses the characteristics of analog-to-digital (A/D) converters to detect zero-current conditions. Microprocessor-based relays use A/D converters to sample analog quantities and convert them into digital bits. A/D converters exhibit errors that are significantly amplified when the input signal is absent and replaced by noise. During steady-state conditions, the transformer carries excitation currents that have a nondiscernible second-harmonic component as a percentage of the fundamental current. The ratio of the second harmonic to fundamental current remains minimal because the magnetizing currents do not change significantly over time. The difference of the ratio of the second harmonic to fundamental currents between two processing intervals should remain close to zero when the transformer is unloaded.

When an open-phase condition occurs, this difference becomes random as a result of the absence of the transformer excitation current on the open phase. Once the relay detects this randomness, a counter tallies how many times the difference exceeds a predetermined threshold during a specified time window. If the counter threshold is reached during this window, the relay declares an open-phase condition.

Fig. 15 shows the difference of the ratio of the second harmonic to fundamental algorithm (PH_A_A3) response to the event simulated in Fig. 11. The algorithm detects the randomness signature in the difference of the ratio of the second harmonic to fundamental currents and reaches the counter threshold within a specified time window (30 cycles).

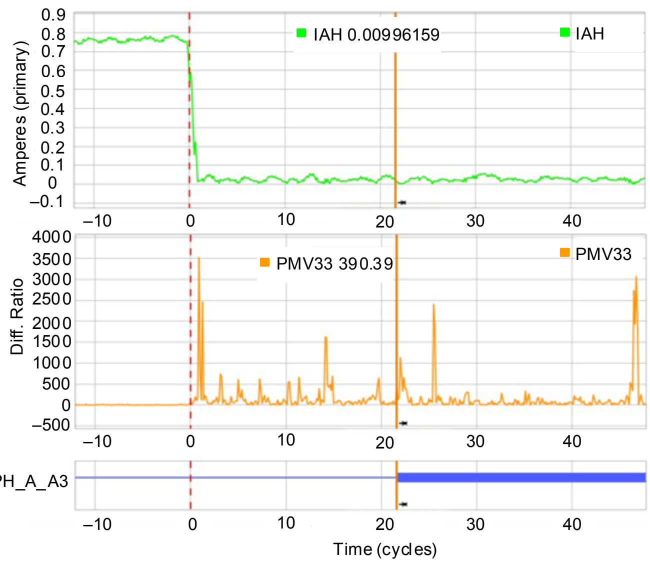

Fig. 15. Simulation Results: Ungrounded Phase A Open, No Load, 3-Limb Core Construction

The main advantage of this algorithm over the previous two algorithms is that it only requires confirmation that the steady-state excitation currents are above the A/D noise floor, requiring minimal configuration during implementation. The main disadvantage of this algorithm is in applications where sufficient charging current flows after the open phase occurs. In such applications, this randomness signature may not be detected if the charging current is above the A/D noise floor even if there is sufficient current drop margin between the transformer excitation current and the charging current flowing after the open-phase condition.

D. Waveform Zero-Crossings Based Algorithm (OP_LOAD)

Waveform Zero-Crossings Based Algorithm, designated as OP_LOAD, shown in Fig. 16 and described in [8], is used to detect ungrounded open-phase conditions when the transformer is operated at load. This logic analyzes the zero crossings and current magnitude on each phase to determine if a phase is open. If this logic does not detect a zero crossing within 1/2 of a power system cycle plus 1 relay processing interval, or if the current flowing through the open phase is below the 0.05 A secondary on one or two phases over a specified time delay, the relay declares an open-phase condition. This logic will be blocked from operation if no zero crossings are detected on all three phases.

This logic is used to detect single ungrounded open-phase conditions on all transformer configurations and double open-phase conditions on wye-connected primaries. This logic cannot be used to detect double ungrounded open-phase conditions on delta-connected primaries because this event results in a drop of all three phase currents.

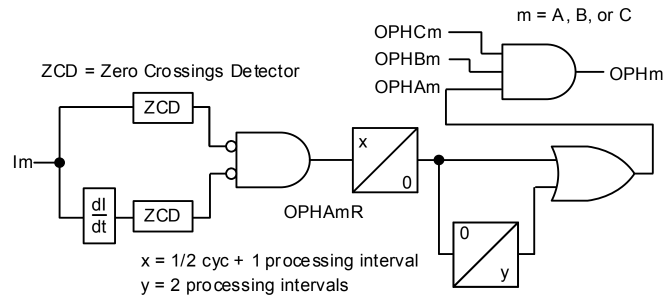

Fig. 16. Waveform Zero Crossings Detection Algorithm

Fig. 17 shows an ungrounded open Phase A condition on a 3-limb, Δ-Y_g transformer operated at 50 percent loading with the parameters shown in Fig. 3. The OP_LOAD algorithm operates because it does not detect zero crossings on Phase A over a 30-cycle time delay.

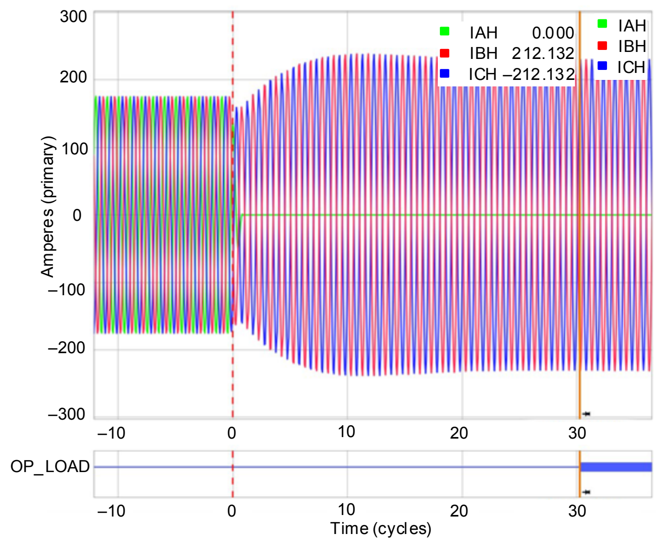

Fig. 17. Simulation Results: Ungrounded Phase A Open, 50% Load, 3 Limb Core Construction

E. Negative-Sequence Current-Based Detection Algorithm (OP_DEL)

The Negative-Sequence Current-Based Detection algorithm, designated as OP_DEL, uses the ratio of the negative-sequence to positive-sequence currents (3I2/I1) magnitudes measured at the transformer primary to detect single- and double-grounded open-phase conditions on delta-connected primaries. If the ratio of 3I2/I1 exceeds a set percentage over a specified period, the relay declares an open-phase condition.

Fig. 18 shows a grounded open Phase A condition on a 3-limb, Δ-Y_g transformer operated at 50 percent loading with the parameters shown in Fig. 3. The OP_DEL algorithm detects the increase in the 3I2/I1 ratio above 100 percent over a 30-cycle time delay.

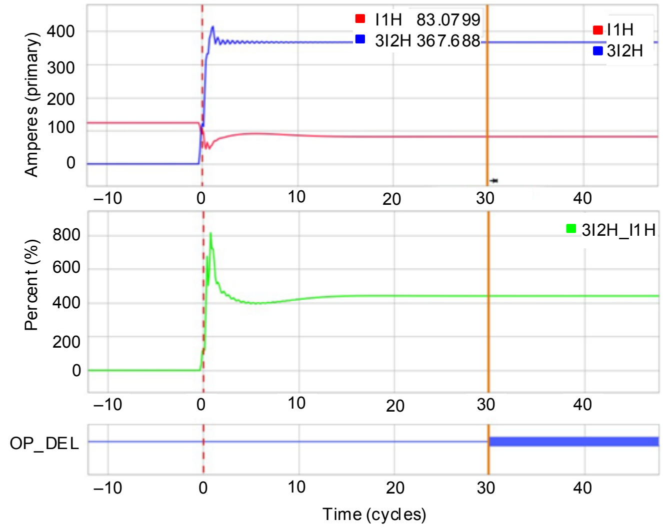

Fig. 18. Simulation Results: Grounded A-Phase Open, 50% Load, 3-Limb Core Construction

F. *Zero-Sequence Current-Based Detection Algorithm (OP_WYE)*

The Zero-Sequence Current-Based Detection algorithm, designated as OP_WYE, uses the ratio of the zero-sequence to positive-sequence currents (3I0/I1) magnitudes measured at the transformer primary to detect single- and double-grounded open-phase conditions on grounded wye-connected primaries. If the ratio of 3I0/I1 exceeds a set percentage over a specified time delay, the relay declares an open-phase condition.

Fig. 19 shows a grounded open Phase A condition on a 3-limb, Y_g-Y_g transformer operated at no load with the parameters shown in Fig. 3. The OP_WYE algorithm detects the increase in the 3I0/I1 ratio above 100 percent over a 30-cycle time delay.

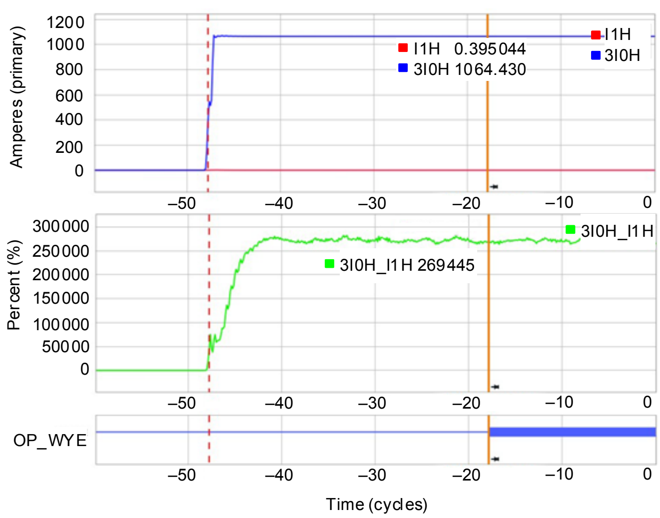

Fig. 19. Simulation Results: Grounded Phase A Open, No Load, 3-Limb Core Construction

If a grounded wye-connected primary transformer has low zero-sequence impedance, and consequently high zero-sequence current during a grounded open-phase condition, the OP_WYE algorithm can detect this condition throughout the transformer loading range. However, if the transformer has high zero-sequence impedance, and consequently low zero-sequence current during a grounded open-phase condition at higher loading levels, a combination of zero-sequence and negative-sequence current-based detection algorithms can be used to detected this condition. The OP_WYE algorithm can be used to detect grounded open-phase conditions at low loading levels, and the OP_DEL algorithm can be used to detect grounded open-phase conditions at higher loading levels.

G. *Negative-Sequence Voltage-Based Detection Algorithm (V2_OPEN)*

The Negative-Sequence Voltage-Based Detection algorithm, designated as V2_OPEN, uses the ratio of the negative-sequence to positive-sequence voltage (3V2/V1) magnitudes measured at the transformer low side to detect ungrounded and grounded open-phase conditions on the applicable transformers in Section II. If the ratio of 3V2/V1 exceeds a set percentage over a specified period, the relay declares an open-phase condition.

Fig. 20 shows a grounded open Phase A condition on a 3-limb, Δ-Y_g transformer operated at no load with the parameters shown in Fig. 3. The V2_OPEN algorithm detects the increase in the 3V2/V1 ratio above 50 percent over a 30-cycle time delay.

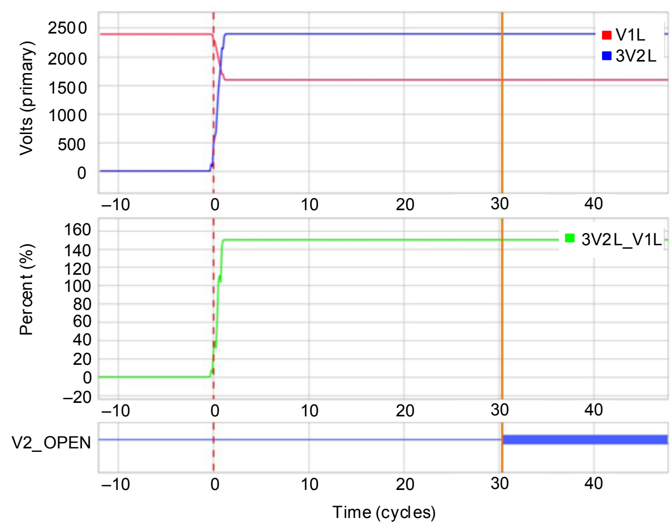

Fig. 20. Simulation Results: Grounded Phase A Open, No Load, 3-Limb Core Construction

TABLE I
APPLICABILITY OF ALGORITHMS TO DIFFERENT TRANSFORMER TYPES

	A1/A2/A3	**Zero Crossings**	**3I0/I1**	**3I2/I1**	**3V2/V1**
Y_g-Y_g (3-Limb)	Y	Y	Y	N*	N
Y_g-Y_g (5-Limb)	Y	Y	Y	N*	Y
Δ-Y_g	Y	Y	N	Y	Y
Y_g-Δ	Y	Y	Y	N*	N

* See the discussion in Section III, Subsection F.

IV. Project Implementation

A microprocessor-based relay with programmable logic features is a perfect environment to implement the algorithms discussed in Section III. Modern microprocessor protection relays have pre-calculated symmetrical components quantities in addition to three-phase currents and voltages that can be used in user-programmable logic. If a modern microprocessor-based relay protects the transformer, the high-side and low-side currents will be available, and probably low-side voltages, reducing the need for new instrument transformers or field connections in most applications.

The algorithms discussed in this paper have been implemented in microprocessor-based relays on SATs at several nuclear plants.

In implementing any of these algorithms, the first step is to identify the type of transformer, core construction, and typical loading. Based on these parameters, the algorithms to be implemented are determined. Thereafter, perform analysis to determine if the transformer requires a minimum loading. Two conditions determine this decision:

- The unloaded transformer magnetizing current is lower than the design limitation of the A/D converter of the protective relay.
- The maximum charging current on an open-phase condition is greater than the transformer magnetizing current.

Model the plant electrical network in an electromagnetic transient analysis program, then simulate different shunt and series fault and different operating conditions to verify the security and dependability of the algorithms and that you have selected the correct settings levels (thresholds) prior to field installation.

V. Field Results

On November 18, 2017, the offsite power source serving the SAT at a nuclear plant experienced an open-phase condition. The circuit switcher on the high-side of a remote transformer supplying the transmission line which fed the SAT had a faulty mechanism on one phase. This prevented the circuit switcher from closing completely, causing a high-resistance connection (series fault). Upon a subsequent reclosing operation, the mechanism failed completely. The SAT at this site was a grounded-wye primary transformer that employed the zero-sequence current-based algorithm. The open-phase condition resulted in a spike in 3I0 current. The algorithm asserted correctly, identified the event, and issued an alarm signal. Fig. 21 shows currents and digital signal corresponding to this event.

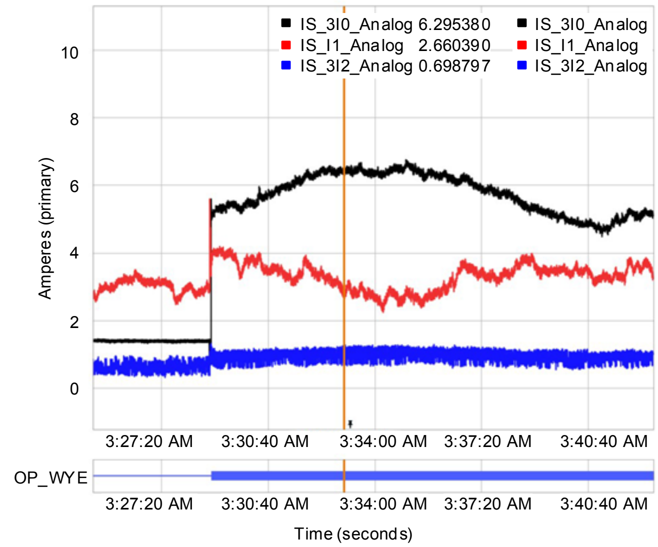

Fig. 21. PMU Data Showing an Open-Phase Condition

VI. Conclusion

Open-phase conditions on the high side of SATs at nuclear power plants can cause adverse operating conditions for safety-related loads such as reactor cooling pumps. Conventional protective elements using ground- or negative-sequence current or voltage elements cannot reliably detect these conditions for certain transformers because they are influenced by winding connections, core construction, and transformer loading. This paper discussed the challenges presented for conventional protection schemes and presented algorithms that can be applied to the different transformer types and work for a wide range of loading. These algorithms have been implemented in microprocessor-based relays on SATs at several nuclear plants and have been in an alarm-only mode for over two years with successful security and dependability record. One open-phase event that occurred during these two years was successfully identified.

VII. Acknowledgment

The authors of this paper are grateful to Dr. Normann Fischer for his contributions to the development of the open detection algorithms described in Section III, and his valuable feedback on this paper.

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IX. Biographies

Dwayne Cox received his Bachelor of Science in Electrical Engineering from the University of Maryland, College Park in 1993 and Master of Science in Computer Engineering from Johns Hopkins in 2009. He has over 20 years of experience in instrumentation and control systems. He is currently a Design Engineer with Exelon at Calvert Cliffs Nuclear Power Plant. He is a licensed professional engineer in Maryland.

Ahmed Abd-Elkader received his Bachelor of Science in Electrical Engineering, with honors, from Ain Shams University, Cairo, Egypt, in 2008 and an MBA, with honors, from Wake Forest University, Winston-Salem, NC, in 2015. He is currently pursuing a Ph.D. in Electrical Engineering from the University of North Carolina, Charlotte, NC. He is a lead protection engineer with Schweitzer Engineering Laboratories, Inc. with 10 years’ experience in power systems protection and control.

Harish Chaluvadi received his Bachelor of Technology (B.Tech) degree in Electrical and Electronics Engineering from National Institute of Technology, Tiruchirappalli, India in 2005 and MS in Electrical Engineering from Clemson University, SC in 2008. He has over 10 years of experience in power system engineering including analytical studies, design, field testing, and project management. He joined SEL Engineering Services Inc. in Lake Zurich, IL in 2012 as a Project Engineer. He is a licensed professional engineer in the states of California, Iowa, Wisconsin, and Minnesota.

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