Negative-Sequence Overcurrent Considerations for Induction Motor Loads

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Negative-Sequence Overcurrent Considerations for Induction Motor Loads

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***Abstract*—Negative-sequence overcurrent (51Q) elements can add sensitivity to transformer and feeder protection. Because these elements do not respond to balanced load current, they can be set below phase overcurrent elements. However, certain loads may cause higher than expected negative-sequence current to flow because their negative-sequence impedance is quite low when compared to their positive-sequence impedance. This paper describes an event in which a 51Q element operated for a fault on an adjacent feeder, discusses the impact of voltage unbalance on induction motors, and examines induction motor load modeling and sequence networks. The analysis is supported by a PSCAD model developed for this event. The paper also shares specific lessons learned to assist engineers to securely set 51Q elements in the presence of induction motor loads.**

I. Introduction

Traditional feeder and transformer protection schemes use a combination of phase and ground overcurrent elements to detect faults. For protection schemes with only phase and ground elements, phase-to-phase faults can pose a challenge. Phase elements can detect phase-to-phase faults; however, they are responsive to load current and can therefore be difficult to set securely and sensitively. Ground elements can be set more sensitively than phase elements because they are not responsive to balanced load. However, ground elements cannot detect phase-to-phase faults. Negative-sequence overcurrent (51Q) elements can address this issue of phase-to-phase fault sensitivity. Because 51Q elements are not responsive to load currents, they can typically be set both sensitively and securely to detect unbalanced faults.

Traditional approaches to setting 51Q elements have focused on providing sensitivity for phase-to-phase faults in distribution feeders [1]. This paper shows that the negative-sequence impedance of the load should also be considered to ensure correct operation of the 51Q element. When developing settings for a 51Q element in the vicinity of a large concentration of motors, load impedance must be taken into consideration for settings calculations; otherwise, sympathetic tripping may occur.

Reference [2] shows that out of zone unbalanced faults can cause increased negative- and zero-sequence currents to flow through unfaulted feeders because of the stalling of single-phase motors.

Reference [2] also discusses how the load on unfaulted feeders can provide a path for negative- and zero-sequence currents to flow in the reverse direction of the fault. This paper aims to expand on these observations by showing how three-phase motor loads can significantly affect the magnitude of this reverse negative-sequence current, and it provides a real-world event that resulted from the sympathetic tripping of 51Q elements.

II. Negative-Sequence Overcurrent

51Q elements are occasionally applied to provide the sensitivity necessary to detect phase-to-phase faults. This application is used in both feeder and transformer protection.

Traditional negative-sequence overcurrent settings are developed based on the downstream phase overcurrent protection elements. The slowest phase overcurrent device is selected for coordination with the upstream negative-sequence protection. The two settings are compared by deriving an equivalent phase overcurrent setting for the 51Q element [1].

51Q elements are also applied on the high side of delta-wye grounded transformers to detect low-side phase-to-ground faults [3]. Because the delta winding acts as a zero-sequence trap, ground overcurrent relays located on the delta winding side of the transformer are blind to low-side ground faults. Instead, these faults appear as phase-to-phase faults on the delta side of the transformer.

Negative-sequence overcurrent or current unbalance relays are also common for motor protection. These relays are required to provide thermal protection against excessive current induced on the rotor. As such, these elements are typically set with a relatively long delay.

III. Negative-Sequence and Induction Motors

Consider the equivalent circuit of an induction motor shown in Fig. 1.

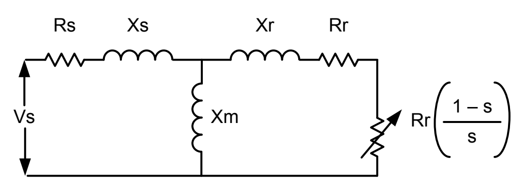

Fig. 1: Induction motor model [4]

where:

Vs is the terminal voltage.
Rs is the stator resistance.
Xs is the stator reactance.
Xm is the magnetizing reactance.
Xr is the rotor reactance.
Rr is the rotor resistance.
s is the slip frequency in per unit (pu).

Positive-sequence current circulating in the stator windings of a three-phase induction motor generates a rotating magnetic field that crosses the air gap. This magnetic field rotates at a synchronous speed that is dictated by the number of poles of the motor and the power system frequency. During normal operation, the rotor of the induction motor rotates at a slightly lower speed than the speed of the magnetic flux generated by the stator. The difference in speed, known as slip, causes low-frequency currents to flow in the rotor bars. The interaction between the flux generated by the stator and the currents circulating in the rotor bars produces mechanical torque. The slip is computed as follows [5]:

$$s = 1 - \left(\frac{Nr}{Ns}\right)$$

where:

s is the positive-sequence motor slip.

Nr is the rotor speed.

Ns is the synchronous speed.

When unbalanced sinusoidal voltages are applied to the stator of a three-phase induction motor, both positive- and negative-sequence currents flow in the stator windings. The negative-sequence current generates a magnetic field that crosses the air gap and rotates in the opposite direction with respect to the positive-sequence generated magnetic field and the rotor. The negative-sequence generated magnetic flux induces high-frequency currents in the rotor. The frequency of these currents is a function of the negative-sequence slip, which is computed as follows [5]:

$$s2 = 1 - \left(\frac{Nr}{-Ns}\right) = 2 - s$$

where:

s2 is the negative-sequence motor slip.

The model in Fig. 1 shows positive-sequence rotor resistance that varies with 1/s. The negative-sequence rotor resistance varies with 1/(2–s) [5]. Typically, positive-sequence motor impedance can be up to six times the negative-sequence motor impedance for small values of slip [6].

IV. Real-World Event

A. System Background

Fig. 2 shows a simplified single-line diagram of the system under consideration. The system is part of a steam turbine generating facility; however, only auxiliary loads are considered for the purpose of this analysis. A 45 MVA 138/34.5 kV delta-wye grounded main transformer supplies the 34.5 kV bus. A 12 MVA 34.5/4.16 kV delta-wye resistance-grounded auxiliary transformer is used to further reduce the voltage to supply the induction motor loads. The 34.5 kV bus supplies the auxiliary transformer and a number of overhead 34.5 kV distribution feeders. Radial feeders are connected to the 4.16 kV winding of the auxiliary transformer. The majority of the loads on these feeders are induction motors ranging from approximately 5 hp to 5000 hp with an aggregate total of approximately 7000 hp. Some lighting loads are also fed by this transformer; however, the size of these loads is negligible compared to the induction motor loads.

The 34.5 kV potential transformers (PTs) are located on the bus, whereas the Relay 2 current transformers (CTs) are located on the source side of the auxiliary transformer high-side breaker. The neutral CT from the auxiliary transformer is unavailable to connect to Relay 2.

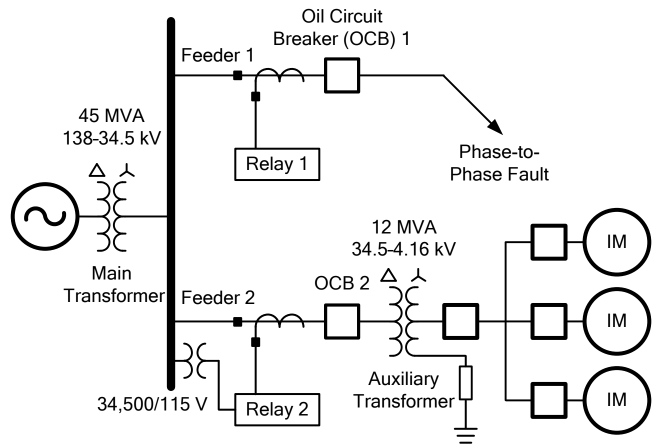

Fig. 2: Simplified single-line diagram

B. Protection Setup

Relay 1 is a microprocessor-based relay that protects Feeder 1 and is programmed with inverse-time overcurrent elements for both phase and ground fault protection. The main protection for the auxiliary transformer consists of a current differential relay (not shown). Relay 2 is another microprocessor-based relay that provides backup protection for transformer and low-side faults. Relay 2 uses an instantaneous phase overcurrent element, a phase inverse-time overcurrent (51P) element and a 51Q element. The 51Q element is set to protect the transformer in the event of a low-side single-phase-to-ground fault. The relay settings are summarized as follows.

- Relay 1 ground time-overcurrent settings
  - 51G pickup = 240 A
  - 51G time dial = 0.4
  - 51G curve = IEC very inverse (C2)
- Relay 1 phase time-overcurrent settings
  - 51P pickup = 640 A
  - 51P time dial = 0.25
  - 51P curve = IEC extremely inverse (C3)
- Relay 2 phase overcurrent settings
  - 51P pickup = 588 A
  - 51P time dial = 4.52
  - 51P curve = U.S. very inverse (U3)
  - 50P pickup = 2952 A
- Relay 2 negative-sequence time-overcurrent settings
  - 51Q pickup = 36 A
  - 51Q time dial = 1.26
  - 51Q curve = U.S. very inverse (U3)

Phase-to-ground fault currents at the 4.16 kV level are limited by the neutral impedance. As recommended by IEEE, a 51Q element was chosen to detect these low-magnitude, phase-to-ground faults [3].

Because the ground fault current is limited by the neutral resistor on the transformer, the 51Q element was set to pick up at 50 percent of the available transformer high-side current for a ground fault on the low side of the transformer. The time dial provided a 1-second clearing time for faults on the low side of the transformer. This delay was deemed acceptable because the differential scheme across the transformer was the primary protection, whereas the 51Q element provided backup.

C. Event Analysis

A phase-to-phase fault involving Phases A and B occurred on Feeder 1. Heavy winds knocked down the overhead feeder poles, causing the two phase conductors to short. Because the feeder is radial, the expected sequence of operation was for Relay 1 to isolate the fault that occurred within its zone of protection. As indicated by Fig. 3 and the sequence of relay element operation in Table I, Relay 1 operated as expected by detecting the increase in currents on Phases A and B and then began timing. Once the 51P element picked up, it timed out in 0.417 seconds (25 cycles) and tripped the feeder breaker. The event report that showed Relay 1 operating for the fault was not available. The Sequential Events Recorder report from Relay 1 was used to identify the time of operation of the protection elements and the relay.

This event was significant because the 51Q element in Relay 2 also picked up. The 51Q element was set sensitively to detect transformer low-side faults; however, it tripped the transformer in 0.13 seconds (8 cycles) for an out-of-zone fault (Fig. 4).

The auxiliary transformer is radially connected; therefore, Relay 2 was not expected to operate. Fig. 4 shows that the occurrence of the fault caused the phase currents through the auxiliary transformer to drastically increase. The fault on Feeder 1 increased only the Phase A and Phase B currents; however, the current through Feeder 2 indicates that Phases B and C were the highest in magnitude. This in turn caused the 51Q element in Relay 2 to time out and trip.

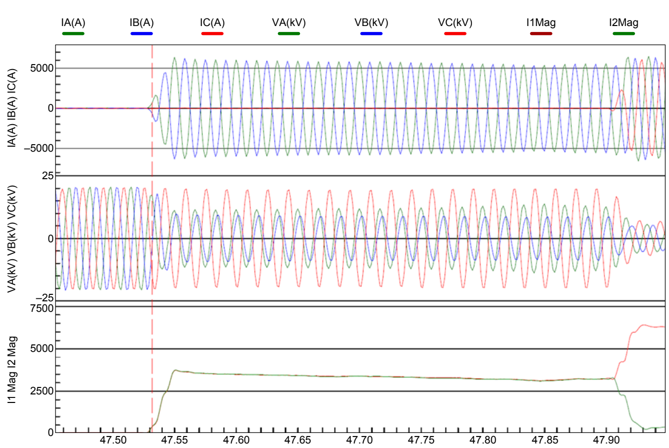

Fig. 3: 34.5 kV Relay 1 oscillography

TABLE I: RELAY 1 SEQUENCE OF EVENTS

Time (hr, min, s)	Element	State
20:39:47.532	51P	Asserted
20:39:47.949	Trip	Asserted
20:39:47.994	52A	Deasserted

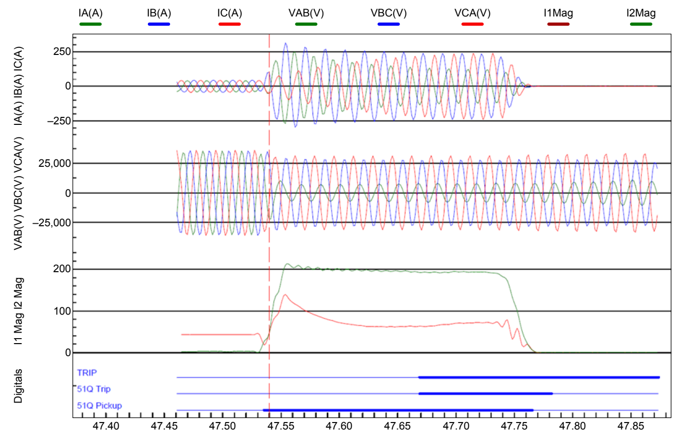

Fig. 4: 34.5/4.16 kV Relay 2 oscillography

For the radial system of transformer and induction motor loads, no appreciable current was expected for out-of-zone faults. Fig. 5 shows a phasor representation of the Relay 2 current measurements prior to the event. Note that prior to the event, the ABC phase sequence was such that Phase B lagged Phase A by 120 degrees for counter-clockwise phasor rotations. During the fault, Phase C lagged Phase A by approximately 100 degrees for counter-clockwise phasor rotations (Fig. 6).

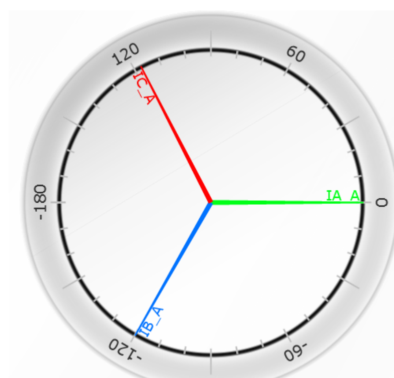

Fig. 5: Relay 2 phase sequence prior to event

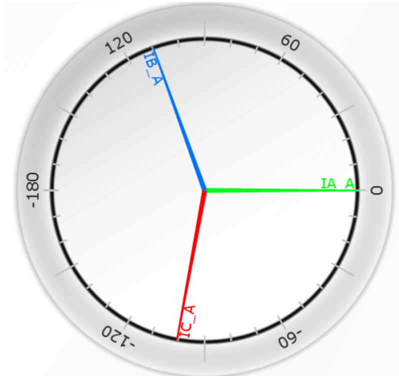

Fig. 6: Relay 2 phase sequence during event

This change in phase sequence indicates a high ratio of negative- to positive-sequence currents. As the amount of negative-sequence current increased relative to the positive-sequence current, the apparent phase sequence changed from ABC to ACB.

V. Sequence Components

The sequence component network for the event is shown in Fig. 7. For the purpose of this analysis, the fault is assumed to have occurred on the 34.5 kV bus. For a phase-to-phase fault, the positive- and negative-sequence networks are modeled as occurring in parallel at the point of the fault. The source impedance is combined with the main transformer impedance. The impedances shown in the figure are as follows:

- Positive-sequence source impedance = Z_{S1}
- Negative-sequence source impedance = Z_{S2}
- Positive-sequence Feeder 1 impedance = Z_{F1}
- Negative-sequence Feeder 1 impedance = Z_{F2}
- Positive-sequence transformer impedance = Z_{T1}
- Negative-sequence transformer impedance = Z_{T2}
- Positive-sequence load impedance = Z_{L1}
- Negative-sequence load impedance = Z_{L2}

In this network, the positive- and negative-sequence voltages for the 34.5 kV bus are equal for zero fault impedances. The positive- and negative-sequence impedances of the source are equal, the positive- and negative-sequence impedances of Feeder 1 are equal, and the positive- and negative-sequence impedance of the auxiliary transformer are equal.

During the event, Relay 2 observes that the magnitude of negative-sequence current is higher than positive-sequence current. The sequence impedances are estimated from the magnitude of positive-sequence voltage and current (V1 and I1) and negative-sequence voltage and current (V2 and I2) shown in the relay event report. The values are in pu and were calculated on a 100 MVA, 34.5 kV base. The positive- and negative-sequence transformer impedances were obtained from the transformer nameplate. Fig. 8 shows the behavior of V2, I2, and negative-sequence impedance (Z2) measured by Relay 2 as a function of time.

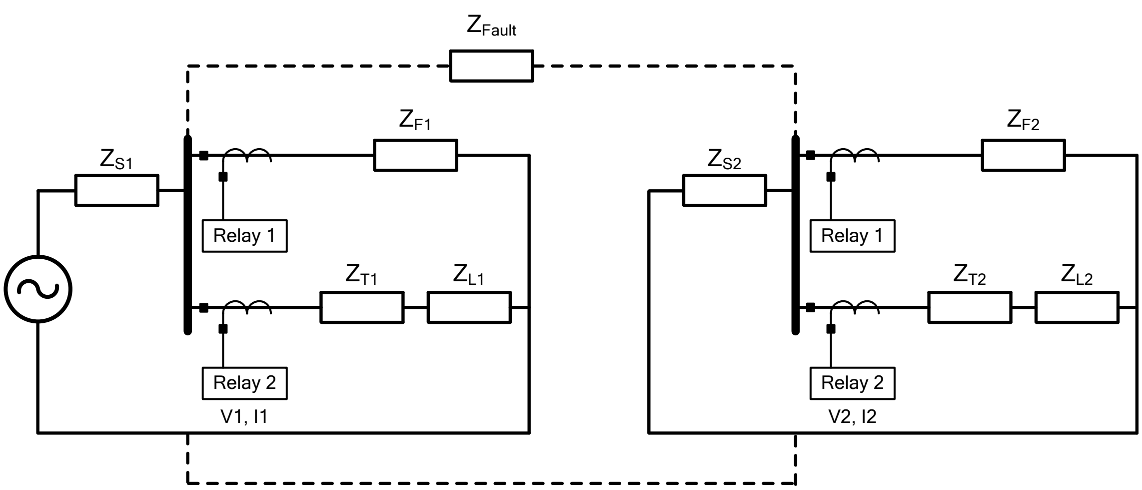

Fig. 7: Sequence component network during event

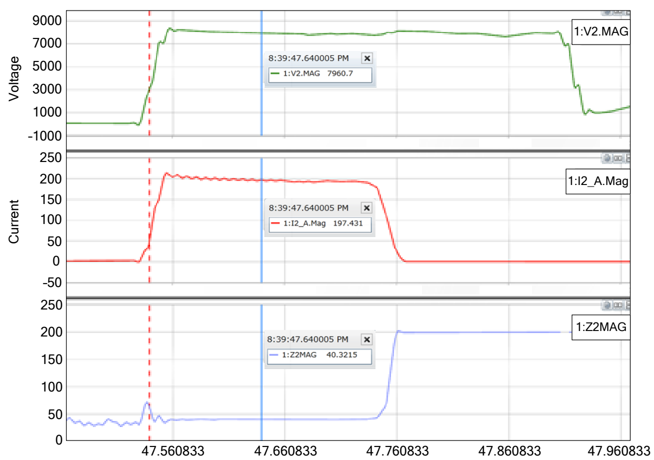

Fig. 8: Relay 2 impedance during fault

The following calculations were used to determine the sequence impedances at 47.640 seconds for the Relay 2 event.

$$\text{Zbase} = \frac{34.5 \text{ kV}^2}{100 \text{ MVA}} = 11.9\ \Omega$$

$$\frac{\text{V1}}{\text{I1}} = \frac{11{,}957.6\angle -155.18 \text{ V}}{61.57\angle -130.647 \text{ A}}$$

$$= 194.2\angle -24.53\ \Omega$$

In pu:

$$|\text{Z1}| = \frac{194.2\ \Omega}{11.9\ \Omega} = 16.31 \text{ pu}$$

where:

Z1 equals the sum of Z_{T1} and Z_{L1}.

Similarly:

$$\frac{\text{V2}}{\text{I2}} = \frac{7960.7\angle 34.33 \text{ V}}{197.431\angle 13.71 \text{ A}}$$

$$= 40.3\angle 20.62\ \Omega$$

In pu:

$$|\text{Z2}| = \frac{40.3\ \Omega}{11.9\ \Omega} = 3.38 \text{ pu}$$

where:

Z2 equals the sum of Z_{T2} and Z_{L2}.

The auxiliary transformer positive- and negative-sequence impedances are equal. Therefore:

$$Z_{T1} = Z_{T2} = 0.25\angle 90 \text{ pu}$$

Subtracting the transformer sequence impedance from the total impedance, we can calculate the load sequence impedances:

$$Z_{L1} = 16.31\angle -24.53 \text{ pu} - 0.25\angle 90 \text{ pu} = 16.41\angle -25.32 \text{ pu}$$

$$Z_{L2} = 3.38\angle 20.62 \text{ pu} - 0.25\angle 90 \text{ pu} = 3.3\angle 16.55 \text{ pu}$$

These calculations indicate that the load impedances are different for positive and negative sequences. For this event, the only possible difference is the induction motor loads.

The sequence impedance ratio of the load is calculated as follows:

$$\text{Zratio} = \frac{|Z_{L1}|}{|Z_{L2}|} = \frac{16.41 \text{ pu}}{3.3 \text{ pu}} = 4.97$$

VI. PSCAD Simulation

A PSCAD simulation further demonstrates the effect of voltage unbalance on induction motors (Fig. 9). For the purpose of the simulation, the 4.16 kV feeders were replaced by a single squirrel-cage induction machine. The motor was sized to match the 2.8 MW load measured at the feeder transformer immediately prior to the fault. The additional simulation parameters were as follows:

- Source
  - Magnitude: 34.5 kV
  - Frequency: 60 Hz
  - Ramp-up time: 0.001 s
  - Inductance: 0.5 H
- Transformer
  - Rating: 12.5 MVA 34.5/4.16 kV
  - Connection: delta-wye grounded
  - Neutral resistance: 6.0 ohms
- Induction machine
  - Rated voltage: 4.16 kV
  - Rated current: 400 A
  - Control mode: Speed control
  - Speed: 0.99 pu

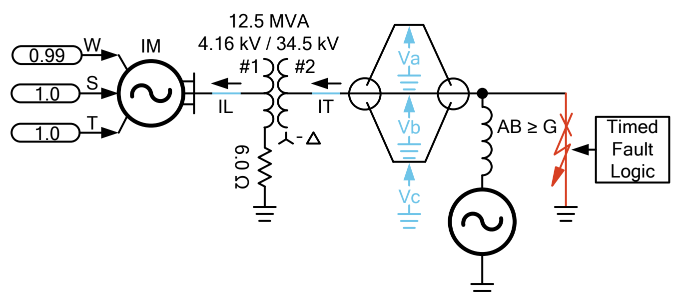

Fig. 9: PSCAD single-line diagram

Fig. 10 through Fig. 13 show the 34.5 kV transformer bushing current waveforms during the application of various 34.5 kV bus faults. Each simulation begins at 0 seconds and concludes at 1 second. Faults are applied at 0.5 seconds in each case.

The three-phase fault results in currents temporarily increasing after the fault occurs before decaying to near zero. In contrast, for each of the three remaining unbalanced fault types, currents increase beyond the prefault values for the remainder of the simulation. The negative-sequence network is involved in each unbalanced fault.

This result is counterintuitive given the radial nature of the transformer and induction motor load. Because the fault is upstream of the transformer and the only change imparted on the remaining system during these faults is an unbalanced voltage, the change in current can be attributed to this change in voltage. Reference [2] provides a similar example in which a transmission fault depressed the distribution feeder voltages, resulting in higher than expected phase currents on the feeders.

As presented earlier, the unbalanced voltage results in an increased negative-sequence voltage. That voltage, when impressed on the negative-sequence network consisting of the transformer and induction motor, causes increased negative-sequence current to flow.

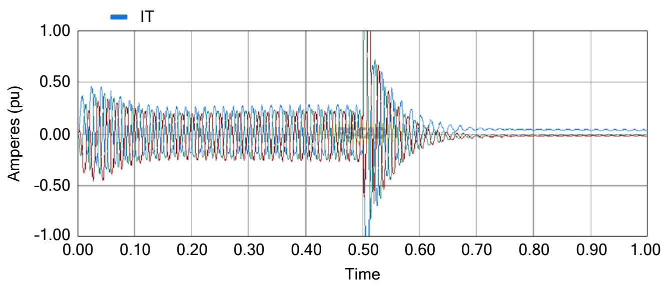

Fig. 10: Simulated 34.5 kV bus three-phase fault

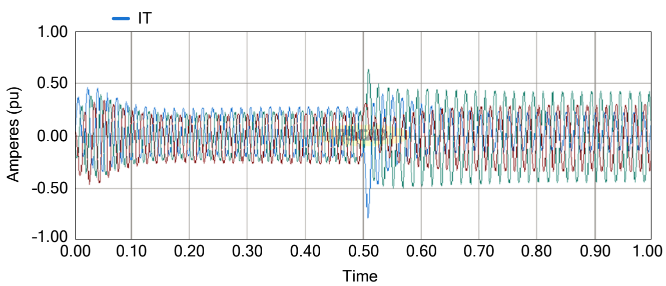

Fig. 11: Simulated 34.5 kV bus phase-to-ground fault

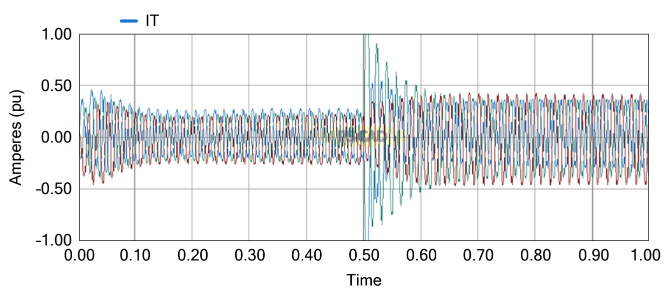

Fig. 12: Simulated 34.5 kV bus phase-to-phase-to-ground fault

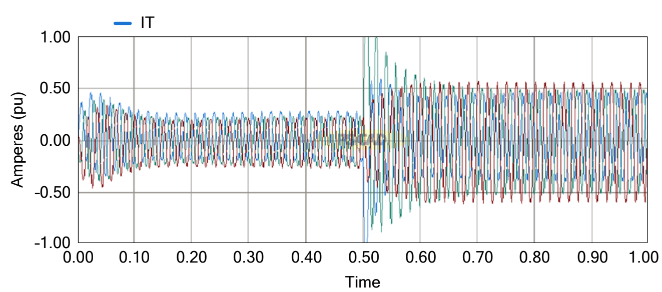

Fig. 13: Simulated 34.5 kV bus phase-to-phase fault

We modified the PSCAD model to determine whether negative-sequence directional supervision could be used to differentiate between legitimate downstream faults and out-of-zone, upstream voltage unbalance. Fig. 14 and Fig. 15 show the difference between downstream and upstream phase-to-phase faults and the resulting directional element decision. In the figures, a value of 1.00 indicates a forward fault and a value of –1.00 indicates a reverse fault. As expected, a fault on the 34.5 kV bus results in a reverse directional decision, whereas a fault on the 4.16 kV bus results in a forward directional decision. In the case of the 34.5 kV bus fault, the negative-sequence impedance transitions between the forward and reverse thresholds because of the post-fault transient response (Fig. 10 through Fig. 13). The negative-sequence directional element parameters are based on recommendations provided in [7]:

- Z2 forward threshold: –0.1 ohms
- Z2 reverse threshold: 0.1 ohms
- I1 restraint factor: 0.1
- Forward current threshold: 0.1 pu
- Reverse current threshold: 0.1 pu
- Line angle: 45 degrees

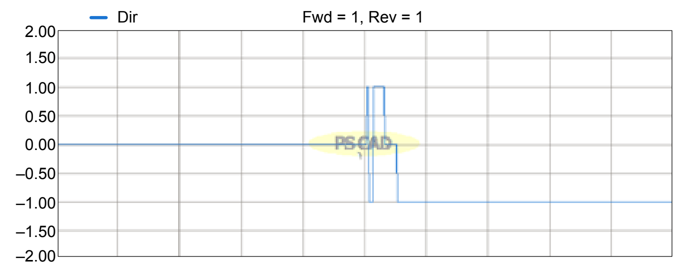

Fig. 14: Directional decision for 34.5 kV bus fault

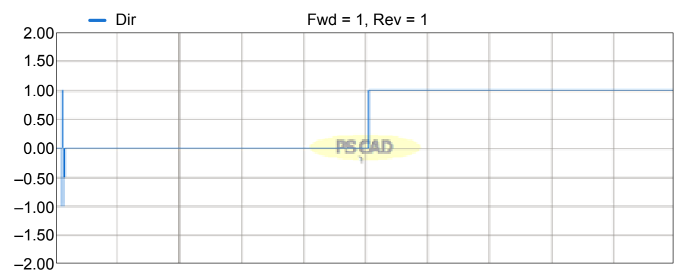

Fig. 15: Directional decision for 4.16 kV bus fault

This conclusion is further solidified using oscillography data from the actual event to compute a simulated negative-sequence impedance directional element decision (Fig. 17). The negative-sequence impedance directional element uses the ratio of negative-sequence voltage and current to obtain a negative-sequence impedance [8]. Z2FTH and Z2RTH are the forward and reverse negative-sequence impedance thresholds, respectively, and Z2 is the measured negative-sequence impedance [8]. Fig. 16 shows the directional element characteristic on the negative-sequence impedance plane. The directional element parameters match those used for the PSCAD simulation. The thresholds have dynamic properties to ensure the element is secure. The measured negative-sequence impedance must be less than Z2FTH to declare a forward fault. The measured negative-sequence impedance must be greater than Z2RTH to declare a reverse fault. A forward fault will appear as a negative value in terms of negative-sequence impedance. Fig. 17 shows that during the event, Z2 is higher than Z2RTH. If a directional 51Q element is set, the relay uses this comparison to declare a reverse fault and block the 51Q element from operating.

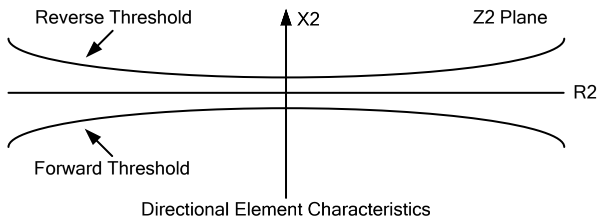

Fig. 16: Directional element characteristic

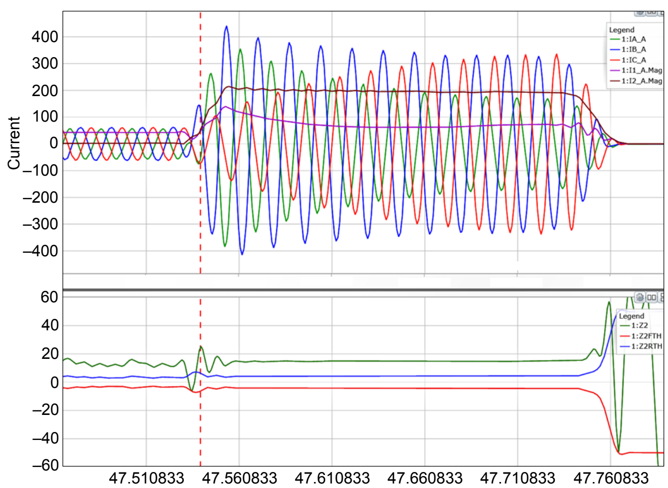

Fig. 17: Simulated directional decision during event

VII. Recommendations for Transformer Protection

The type of load within the zone of protection must be considered while setting 51Q elements. Two approaches can be followed for transformer protection:

1. When current from a CT located at the neutral of the wye-grounded transformer winding is available:
   a. An inverse-time neutral overcurrent should be the first means of providing backup protection for ground faults on the secondary of the transformer that are not cleared by the feeder protection.
   b. A restricted earth fault element could provide sensitive ground fault protection for the wye winding of the transformer.
2. When using 51Q elements:
   a. If nondirectional, the element may detect out-of-zone faults. The pickup must be set above any standing load unbalance observed by the relay. Three-phase motor loads are relatively balanced; therefore, a good level of sensitivity can be obtained. If the transformer carries large single-phase loads, the sensitivity will be compromised. Time delay selection is affected by the need to coordinate with downstream devices and with the maximum clearing time for unbalanced faults on adjacent zones of protection.
   b. If directional, the time delay is selected to coordinate with the downstream devices only. The pickup must be set higher than the maximum load unbalance to be carried by the transformer, regardless of the load characteristic. Sequence components for current are not reliable during inrush conditions; therefore, the negative-sequence directional element may require blocking during transformer energization.

One advantage of 1.a is that it is relatively easy to set because coordination is only performed with the downstream ground relays. Approach 1.b provides sensitive ground fault protection for wye windings and does not need to coordinate with the adjacent zones of protection, resulting in fast operation.

No voltage signals are needed in the relay for 2.a. This approach provides some protection for phase-to-phase faults. However, the element cannot be set very sensitively because of the standing load unbalance. Therefore, high-impedance faults may not be cleared quickly, leading to possible damage to the transformer.

Because 2.b is immune to out-of-zone faults, no additional time delay is necessary to coordinate with these faults. The time delay is selected to coordinate with the downstream devices only. Sensitivity is still dictated by the standing load unbalance.

VIII. Conclusion

Although a feeder or transformer protection zone may be considered radial, faults on adjacent feeders or zones can cause out-of-zone tripping. Careful consideration should be given if the downstream load is comprised mainly of induction motors. In particular, if set sensitively, 51Q elements can be susceptible to such occurrences. Directional supervision can prevent unintended trips without desensitizing the overcurrent elements.

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X. Biographies

Miles Dupuis, P.E. received his BS in Electrical Engineering from the University of Southwestern Louisiana in 1972. Upon graduation he worked as a field engineer for an oil services company doing well logging. He later worked for eight years as a plant engineer for a salt mining company. In 1982,

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