Line Distance Protection Near Unconventional Energy Sources

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Abstract

This paper introduces distance elements suitable for protecting lines near wind-turbine generators and inverter-based sources. The paper begins by analyzing issues with distance elements that use memory polarization for directionality and negative-sequence current for faulted-loop selection and reactance comparator polarization. The analysis is based on worst-case assumptions derived from field cases and published findings, it avoids modeling by using proprietary and uncertain information about the sources, and it does not assume that the source fault response complies with any local, international, present, or pending interconnection standards. The paper identifies parts of the distance element logic that do not work well in applications near unconventional sources and replaces the problematic parts with alternatives that perform satisfactorily. The solution is based on an offset distance characteristic to avoid memory polarization. It further uses separate directional elements to directionalize the offset distance elements by taking advantage of the system fault current contribution rather than the source current contribution.

1 Introduction

Laws of physics bind the fault response of a synchronous generator with no or little variability caused by the specifics of the generator design. This predictable short-circuit response has been known from the early days of three-phase power networks and became the foundation for many system protection principles, including line distance protection. The fault characteristics of unconventional energy sources (wind-powered induction generators and inverter-based sources) are not only different than those of synchronous generators but they also may change over time. Unconventional sources have been evolving and will continue to change because of technological improvements, to meet new grid requirements, and because of software upgrades for internal optimization, life extension, or to address quality issues. Unless and until the unconventional source characteristics are standardized, a sound approach to protective relaying near unconventional sources is to not attempt to discover and use characteristics of the unconventional sources, but to devise protection principles that are as independent from the source characteristics as possible.

The paper begins by analyzing issues with distance elements that use memory polarization for directionality and negative-sequence current for faulted-loop selection and reactance comparator polarization. The analysis is not based on modeling by using proprietary and uncertain information about the sources, and it does not assume that the source fault response complies with any local, international, present, or pending interconnection standards. Instead, the analysis is based on worst-case findings derived from field cases.

Based on the worst-case findings, this paper introduces distance elements suitable for protecting lines near unconventional sources. To avoid polarization, the solution is based on apparent impedance with an operating characteristic, offset in the reverse direction for dependability. The paper proves analytically and illustrates with field cases that such apparent-impedance elements are fully dependable for metallic faults, even if the fault current is solely supplied from an unconventional source. The proposed protection logic directionalizes the offset distance characteristic by using separate directional elements in a fashion that is analogous to a weak-infeed pilot logic: instead of relying on the source short-circuit current contribution for forward faults, the weak-infeed directional logic relies on the remote system short-circuit contribution for reverse faults. The term weak-infeed directional logic does not refer to a pilot scheme, but it describes a new type of directional supervision for distance elements. The proposed distance elements include a voltage-based faulted-loop selection logic to avoid the use of the negative-sequence current.

The paper describes the distance element design in detail, justifies its security and dependability, and illustrates it by using field cases. The independence of the proposed distance elements from the details of the construction and control algorithms of unconventional sources makes the elements a dependable and practical solution. These elements can be therefore applied following the traditional engineering process. This paper is an abbreviated version of [3].

2 Distance Element Challenges

The following subsections describe several persistent fault response characteristics of synchronous generators and their use in distance protection. When these characteristics are no longer present, distance elements face challenges.

2.1 *Impact of Source Inertia on Memory Polarization*

Both a synchronous generator and its prime mover (steam, hydro, or gas turbine) have a significant rotating mass. The large rotating mass provides high mechanical inertia for the generated electric power. When a fault occurs in the power network, the rotor of a synchronous generator continues to rotate at an unchanged speed for at least several hundred milliseconds before any appreciable change in speed occurs. This constant speed of rotation allows the concept of memory polarization. Today, memory polarization is widely used in distance elements. Its primary purpose is to make the element reliably directional with a secondary benefit of improving dependability (coverage) of the mho elements for resistive faults through the effect of dynamic expansion of the operating characteristic. Memory polarization of distance elements provides security and dependability for close-in three-phase metallic faults when the fault voltage in all phases is very low or zero and the relay cannot use it to detect the direction of the fault current.

An unconventional source has a very low inertia (wind-powered induction generators) or no mechanical inertia at all (inverter-based sources). During fault conditions, the source voltage phase angle may change considerably with respect to the pre-fault angle. Also, an inverter-based source may incorrectly measure the system frequency during fault conditions. If so, the source may supply voltages and currents at a frequency that is unintentionally different from the pre-fault frequency. If a distance element uses the pre-fault (memory) voltage angle and extrapolates it based on the pre-fault frequency while the source operates at a different frequency than the pre-fault frequency, then the polarization gradually becomes incorrect with the passing of time. Incorrect memory polarization may result in a loss of security (reverse faults appear forward) or a loss of dependability (forward faults appear reverse). The proposed design avoids using memory polarization in applications near unconventional sources.

2.2 *Impact of Source Inertia on Remote Current Infeed*

The low inertia of an unconventional source brings a new dimension to the infeed and outfeed effects and magnifies the associated challenges for distance protection. Consider faults located close to the remote terminal of the protected line, as in Fig. 1. An underreaching distance zone must restrain for these faults, and an overreaching distance zone must stay dependably asserted for these faults.

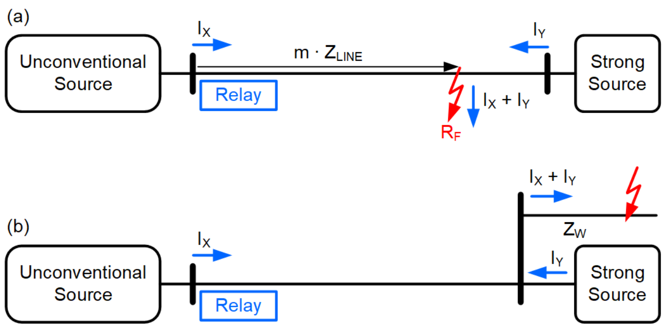

Fig. 1. Resistive fault near the remote terminal (a) and behind the remote terminal (b).

The relay in Fig. 1 measures an apparent impedance as follows.

Internal resistive fault:

$$Z_{APP} = m \cdot Z_{LINE} + R_F \left(1 + \frac{I_Y}{I_X}\right) \tag{1}$$

External metallic fault:

$$Z_{APP} = Z_{LINE} + Z_W \left(1 + \frac{I_Y}{I_X}\right) \tag{2}$$

In both cases, the measured apparent impedance includes an error component (Z_{ERR}) proportional to the product of a certain impedance and an expression that involves the ratio of the remote and local currents. For an internal fault (1), we write:

$$Z_{ERR} = R_F \cdot \left(1 + \frac{I_Y}{I_X}\right) = R_F + R_F \cdot \frac{I_Y}{I_X} \tag{3}$$

and for an external fault (2), we write:

$$Z_{ERR} = Z_W \cdot \frac{I_Y}{I_X} \tag{4}$$

If all generators in the vicinity of the fault have high inertia, the ratio of the two currents in (3) and (4) has a fixed phase angle and the error component creates a persistent underreaching or overreaching effect for the distance elements depending on the relative phase angle between the local and remote currents (Fig. 2). The apparent impedance is static in systems with high inertia and is located at the point marked A in Fig. 2 ($K_{XY} = |I_Y/I_X|$).

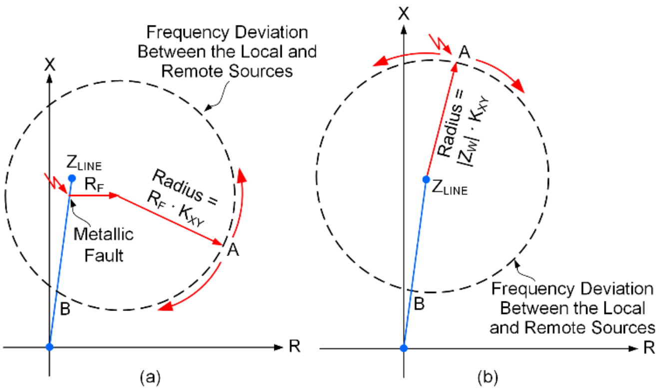

Fig. 2. Apparent impedance for the faults in Fig. 1: internal (a) and external (b).

If the source behind the distance relay has low inertia and the forward fault is not cleared quickly but prevails for a few hundred milliseconds, the two fault current contribution phasors, I_X and I_Y, may start rotating against each other. This rotation can be understood as a difference in frequencies. For example, the remote current I_Y may have a frequency of 60.00 Hz, while the current I_X from the low-inertia source may have a frequency of 60.25 Hz. A difference of 0.25 Hz creates a change in the relative phase angle of 90 degrees per second (0.25 rotations per second · 360 degrees per rotation). Over a period of 0.5 seconds, for example, the ratio of the two currents in (3) and (4) in our example can rotate by 45 degrees (0.5 seconds · 90 degrees per second). The longer the fault duration and the greater the difference in frequencies, the greater the shift in angle.

It is important to realize that if the local source is unconventional and therefore weak ($|I_X| \ll |I_Y|$), the magnitude of the ratio of the two currents (K_{XY}) may be considerably greater than 1. As a result, the circle that represents the rotating movement of the error impedance in Fig. 2 has a large radius.

Note, however, that the overreaching and underreaching effect takes time to develop. To cause the overreach, the apparent impedance must move from point A in Fig. 2 at the beginning of the fault, to point B later during the fault. The higher the frequency difference, the faster the impedance movement and the sooner the overreach can happen.

If a low-inertia source behind the relay cannot maintain an accurate frequency during faults, the underreaching distance elements in the proposed design can be enabled for only a short period of time following fault detection. If enabled permanently, they may overreach for out-of-zone slowly cleared faults. Similarly, time-delayed overreaching distance elements may face dependability problems as the apparent impedance traverses the impedance plane because of the frequency difference.

2.3 Negative-Sequence Current Response

The negative-sequence current at the terminals of a synchronous generator follows the negative-sequence voltage that the system imposes during faults. A synchronous generator can be represented by a fixed and relatively low negative-sequence impedance. Several system protection principles use this negative-sequence voltage-current relationship of power sources (faulted-loop selection, directional supervision, reactance polarization).

Presently, unconventional sources do not supply a negative-sequence current that follows the negative-sequence voltage through a fixed impedance. The magnitude of the negative-sequence current may be low and it may vary, and its angle may change relatively quickly with respect to the positive-sequence voltage, the negative-sequence voltage, and the zero-sequence current in the grid.

A typical distance element may use the negative-sequence current for directional supervision, faulted-loop selection, and – in the case of the quadrilateral characteristic – to polarize the reactance comparator. As a result of the uncontrolled negative-sequence fault response of an unconventional source, distance protection elements may lose security, dependability, or both. The proposed design avoids using the negative-sequence current in applications near unconventional sources.

2.4 Summary

Unless and until the unconventional source characteristics are standardized, a sound approach to protective relaying near unconventional sources is to not attempt to discover and use characteristics of the unconventional sources but to devise protection principles that are as independent from the source characteristics as possible. Specifically, the design presented in this paper adheres to the following conservative findings:

- The use of memory polarization should be avoided in applications near unconventional sources.
- The use of negative-sequence current in distance element logic should be avoided in applications near unconventional sources unless and until the sources provide a negative-sequence phase angle response, similar to that of a synchronous generator.
- Unless and until unconventional sources maintain an inductive positive-sequence impedance, mho expansion in applications near unconventional sources does not bring the expected benefits, even when the unconventional source perfectly follows the system frequency. Making memory polarization work under frequency excursions does not solve other related problems.
- If a low-inertia source behind the relay cannot maintain the system frequency during faults, the underreaching distance elements can be enabled only for a short period of time. If enabled permanently, they may overreach for out-of-zone slowly cleared faults.
- If a low-inertia source behind the relay cannot maintain the system frequency during faults, the overreaching time-delayed distance elements can face dependability issues unless their operating characteristics are shaped to accommodate large infeed and outfeed effects combined with frequency excursions.

The distance element design proposed in this paper is based on the concepts of apparent impedance and a directional logic that avoids using the source fault contribution during forward faults. We refer to these elements as *weak-infeed distance elements*.

3 Apparent Impedance

Consider a three-phase power line with a metallic fault of any type. Assume the source behind the relay injects an arbitrary current with a frequency spectrum at and around the power frequency (consider 0 Hz – 250 Hz, for example); see Fig. 3.

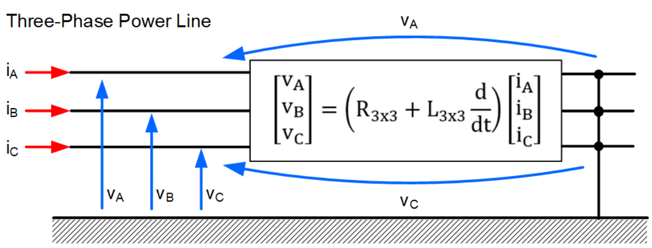

Fig. 3. Arbitrary current injected into a power line causes line voltages consistent with the R-L line parameters.

At relatively low frequencies (less than about 250 Hz), a three-phase power line behaves like a resistive-inductive (R-L) circuit. The phase voltages at the line terminal are linear combinations of phase currents and phase current derivatives. At the power frequency, the voltage phasors are products of current phasors and line impedances (a 3x3 impedance matrix determined by the zero-sequence (Z_0) and positive-sequence (Z_1) line impedances). For simplicity, we can state that the voltage at the terminals of a faulted line is the product of the impedance between the terminal and the fault and the current at the line terminals ($V = Z_{APP} \cdot I$ in the frequency domain and $v = R \cdot i + L \cdot di/dt$ in the time domain). Moreover, and central to our discussion, the voltage-current relationship at the line terminal is independent from the currents. An unconventional source may supply an unusual current pattern with atypical unbalance between the phases and significant off-nominal frequency components. Yet the voltages at the line terminals follow the apparent line impedance ($Z_{APP} = V/I$).

Fig. 4 illustrates this key observation by plotting relay currents and voltages for a forward Phase-B-to-ground (BG) fault on a transmission line where the system behind the relay is an unconventional source (a wind farm). As expected, the currents are heavily distorted and do not show a typical pattern for a BG fault type. Also as expected, the faulted phase voltage (VB) is very low. All relay input signals are heavily distorted.

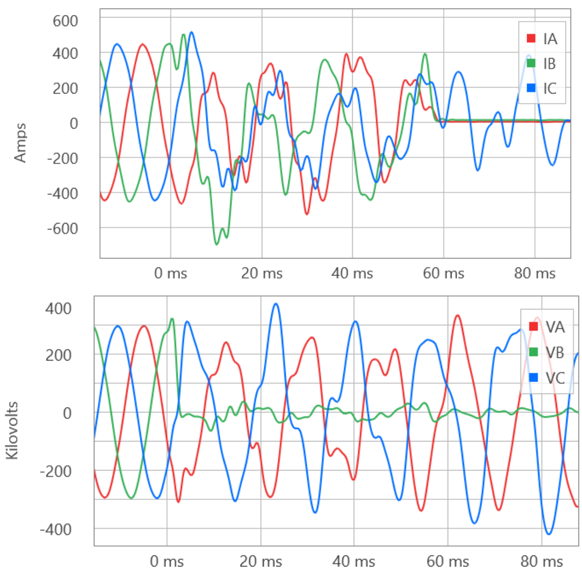

Fig. 4. Line voltages and currents for a BG fault in a system with an unconventional source behind the relay (field record).

Fig. 5 plots the apparent resistance and reactance in the faulted BG loop. The apparent impedance is relatively constant, and it correctly reflects the distance to the fault (the line impedance is about 7.4 Ω secondary and the fault is located at about 30 percent of the line length from the terminal). Phasor measuring errors, considering input signal distortions (Fig. 4) and slight frequency deviation, cause the small variations in the apparent resistance and reactance.

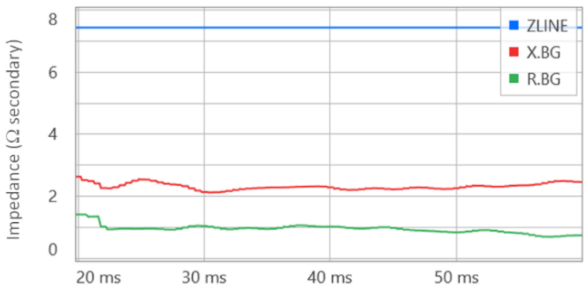

Fig. 5. Well-behaved apparent BG loop resistance and reactance for the heavily distorted waveforms in Fig. 4.

The fundamental finding of this section is that – as intuitively expected – the principle of apparent impedance works in systems with unconventional sources. Using apparent impedance, rather than polarizing with memory voltage or negative-sequence current, makes the distance elements a much more dependable solution for line faults in applications near unconventional sources.

However, during close-in bolted faults, the relay voltage is very low or zero, preventing the apparent impedance distance element from detecting the fault direction. We solve this problem by offsetting the operating characteristic in the reverse direction so that it includes the origin of the apparent impedance plane (see the mho distance operating characteristic in Fig. 6). By doing so, we gain dependability at the expense of making the element nondirectional: the offset apparent-impedance element operates for close-in forward faults and for close-in reverse faults. We will solve this selectivity issue by using a separate directional logic in instantaneous tripping applications and by allowing nondirectional operation in step distance backup protection applications.

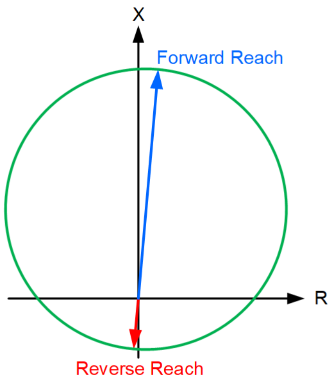

Fig. 6. Offset (nondirectional) apparent-impedance mho operating characteristic.

4 Directional Supervision Suitable for Unconventional Sources

Simple, secure, and dependable distance elements for applications near today's unconventional sources must use directional logic that is independent from the source fault current contribution. To accomplish this objective, we apply the following three directional elements and schemes: forward-looking zero-sequence directional element, weak-infeed directional logic, and incremental-quantity directional element. The term *weak-infeed directional logic* does not refer to a pilot scheme, but it describes a new type of directional supervision for distance elements.

4.1 Zero-Sequence Directional Element

An unconventional source requires a step-up transformer for connecting to a subtransmission and transmission voltage level system. The system-side winding of the step-up transformer is typically connected as a grounded-wye (star). This allows line protective relays to measure reliable zero-sequence current and voltage for line ground faults. Zero-sequence directional (32G) elements face their own challenges, such as mutual coupling or current transformer (CT) saturation during phase-to-phase and three-phase faults, but they are an excellent solution for ground fault direction discrimination near unconventional sources.

4.2 Weak-Infeed Directional Logic

The weak-infeed pilot logic operates by detecting a fault through the reception of a permissive signal from the opposite strong line terminal, confirming it locally with an undervoltage or voltage unbalance condition, and ruling out a reverse fault, as in Fig. 7(a). The core of the weak-infeed principle is to avoid having to detect forward faults, and instead, detect reverse faults to block the scheme.

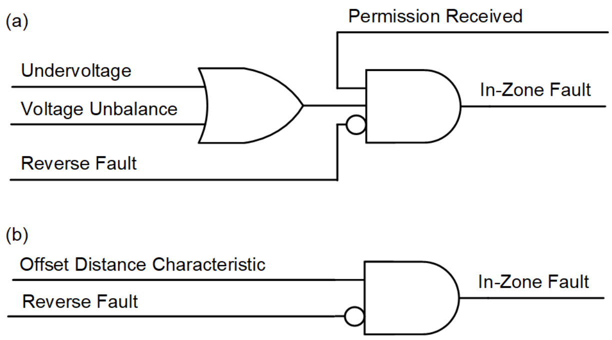

Fig. 7. Weak-infeed pilot logic (a) as an inspiration for the weak-infeed directional distance logic (b).

We use the inspiration of the weak-infeed pilot logic to devise a method to directionalize the offset distance characteristic. Assertion of the offset impedance signifies a fault within the intended reach. A reverse-looking element detects external (reverse) faults and blocks the offset distance characteristic, as in Fig. 7(b). As a result, the nondirectional distance logic becomes a forward-looking directional distance logic, yet it only uses the fault current supplied from the system during reverse faults.

The weak-infeed directional (32WID) logic can use several operating principles. The 32G element provides robust directional control for ground distance elements, so our focus with respect to the 32WID logic is on phase-to-phase and three-phase faults. Therefore, using the phase-to-phase current as the operating signal is the rational choice for the 32WID logic. To avoid undetermined fault direction for close-in bolted phase-to-phase faults, we avoid self-polarizing and instead use cross-phase polarizing with the healthy voltage or the positive-sequence voltage. To address the case of close-in bolted three-phase faults, we may use memory polarization.

It is central to our discussion to realize that we can rely on memory polarization during reverse faults. During reverse faults, the system, not the unconventional source, maintains the line terminal voltage and drives the fault current. The pre-fault voltage (memory voltage) is therefore an adequate representation of the electromotive force that pushes the current toward the reverse fault.

For dependability, it is critical that the 32WID logic not assert for forward faults when the unconventional source is the dominant source supplying the fault current. During forward faults, the memory polarization can be greatly inaccurate, and the operating current may have an unusual phase angle. We use the overcurrent principle to ensure that the 32WID logic stays deasserted for forward faults in a system configuration in which the unconventional source dominates the fault current. Fig. 8 explains the overcurrent coordination principle (50WID).

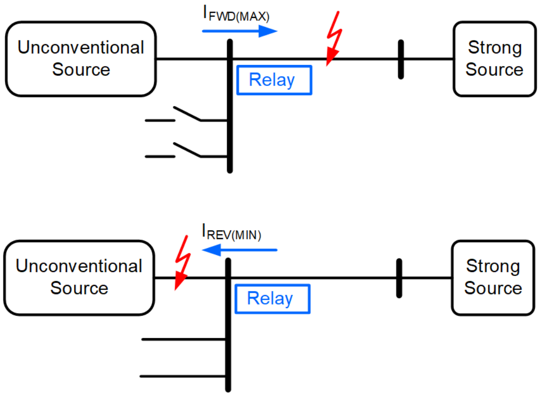

Fig. 8. 50WID overcurrent coordination principle.

Set the overcurrent threshold (50WID) in the 32WID logic below the minimum reverse fault current but above the maximum forward fault current, assuming an unconventional source is supplying the fault current. With reference to Fig. 8, follow this formula when setting the threshold:

$$1.25 \cdot I_{FWD(MAX)} < 50WID < 0.8 \cdot I_{REV(MIN)} \qquad (6)$$

You can use a reverse-looking phase distance element for the 32WID logic, as shown in Fig. 9 with a quadrilateral element. Set the reach of such a reverse-looking element greater than the reverse reach in the offset distance characteristic and set the overcurrent supervision threshold in the reverse-looking phase distance element according to (6).

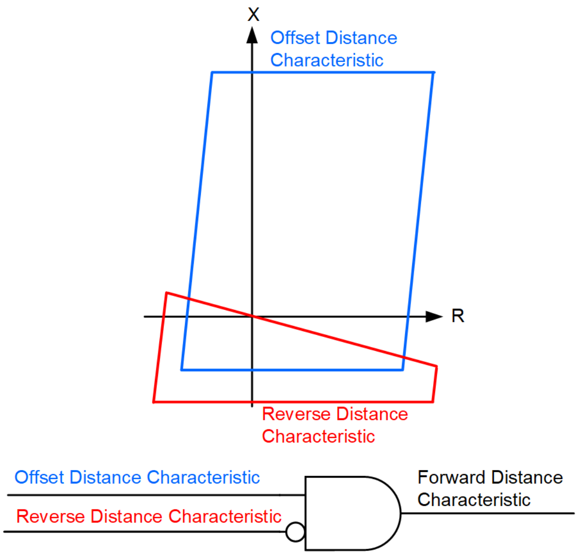

Fig. 9. Using a reverse-looking distance element to directionalize an offset distance characteristic.

4.3 Incremental-Quantity Directional Element

The incremental-quantity directional (TD32) element is known to provide high-speed pilot protection [1] [2] including for lines near unconventional sources. The weak-infeed distance element design can use the TD32 element for speed and additional security and dependability. The TD32 element can be used together with the 32G element to directionalize the ground offset distance characteristic, and it can be used together with the 32WID logic to directionalize the phase offset distance characteristic. The 32G supervision is permissive (forward assertion of the 32G element allows operation), while the 32WID supervision is blocking (the 32WID logic inherently looks in the reverse direction and, when it asserts, blocks the distance element operation). We can use the forward assertion of the TD32 element (TD32F bit) to supervise the forward-looking distance elements (permissive logic). Or we can use the reverse assertion of the TD32 element (TD32R bit) to block the forward-looking distance elements (blocking logic). Both versions work well. However, if the remote source is stronger than the local source, then the TD32 element has more favorable operating conditions during reverse faults, and it may be more beneficial to use the blocking logic. If the remote source is weaker than the local source, then the TD32 element has more favorable operating conditions during forward faults, and it may be more beneficial to use the permissive logic. Because the TD32 element only asserts momentarily, and it resets once the incremental signals expire, the directional supervision with the TD32 element must use an extension timer (see Fig. 10).

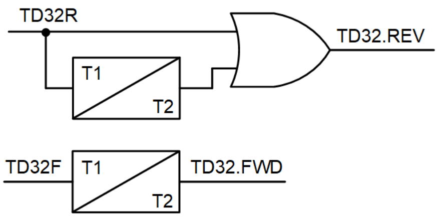

Fig. 10. Blocking (a) and permissive (b) TD32 directional logic for directionalizing overreaching distance protection zones.

Underreaching distance protection applications can use the directional logic in Fig. 10. As explained earlier, it may be necessary to disable the underreaching zone before the frequency deviation of the low-inertia source causes an overreach. The Zone 1 distance element can be temporarily engaged by using a disturbance detection logic or a starting zone or by using the TD32 element for directional supervision and for opening and closing the Zone 1 operating window. Fig. 11 shows a sample logic suitable for underreaching applications.

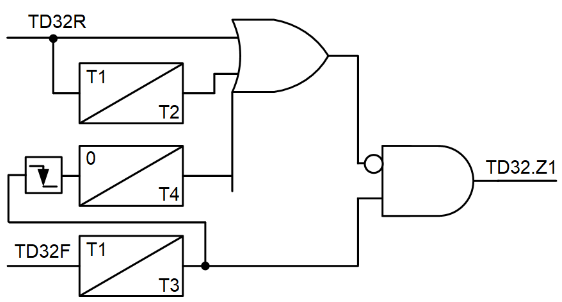

Fig. 11. TD32 directional logic for directionalizing and enabling the underreaching distance protection zone.

5 Conclusions

This paper analyses distance element operation near unconventional sources by making worst-case assumptions regarding the source inertia (very low), source negative-sequence response (the current is low and has an uncontrolled angle respective to the voltage), positive-sequence fault current (low), and the angle between the voltage and current during faults (not inductive and time-varying).

The paper shows that the above worst-case assumptions require a distance element designer to avoid using memory polarization, negative-sequence current polarization for reactance characteristics, negative-sequence-based directional supervision, and negative-sequence-based faulted-loop selection.

The paper describes a weak-infeed distance element logic that avoids the input signal characteristics that may be compromised by an unconventional source. Instead, the weak-infeed logic uses the offset apparent-impedance characteristics for controlling the element reach and a combination of the zero-sequence directional, weak-infeed directional, and optionally, incremental-quantity directional elements for directionalizing the offset distance characteristic. The proposed design uses the undervoltage principle for faulted loop selection.

The paper shows that the principle of apparent impedance works even if an unconventional source supplies an arbitrarily low and distorted fault current. This observation is the foundation for using the offset apparent-impedance characteristic in the weak-infeed distance elements.

Reference [3] provides more information about the new distance element design, it includes supporting evidence for correct operation of incremental-quantity directional elements near unconventional sources, and it includes setting and application considerations for the new weak-infeed distance elements.

6 References

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