A Novel Protection Principle for Ultra-High-Speed Tripping of Lines Terminated on Transformers

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A NOVEL PROTECTION PRINCIPLE FOR ULTRA-HIGH-SPEED TRIPPING OF LINES TERMINATED ON TRANSFORMERS

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Abstract

This paper introduces a novel protection principle for lines connected to the bulk power system at one end (system terminal) and terminated exclusively on power transformers or current-limiting reactors at the other end (transformer terminal). The new protection principle operates as fast as 1 to 2 ms and covers the entire line length without the need for a protection channel. The new principle is based on the current traveling-wave magnitude measured at the system terminal of the line.

1 Introduction

Traveling waves (TWs) are surges of electricity launched by a sudden change in voltage, such as a line fault, that propagate at about 98 percent of the speed of light in free space on overhead lines and at about 45 to 85 percent of the speed of light in free space on cable lines. From the measurement and signal-processing perspectives, a TW is a step change in current or voltage with transition times on the order of a few microseconds. Traditional current transformers (CTs) allow accurate measurement of the current TW magnitude, polarity, and arrival time, and by doing so, they facilitate a TW differential (TW87) scheme [1], available in protective relays since 2017. These relays sample at the rate of 1 Msps (mega-sample per second) and use a direct fiber-optic channel for the TW87 scheme. The TW87 scheme has an excellent track record in the field with trip times as fast as 1 to 3 ms [2].

A power transformer, an autotransformer, and a series reactor have a very high – theoretically infinite – characteristic impedance for TWs. If the protected line does not connect any other lines or shunt capacitor banks, but only a transformer(s), then the line is terminated on a very high characteristic impedance. The line CT at the transformer terminal measures very low current TWs – theoretically zero – because the incident and reflected TWs cancel at the termination with an infinite characteristic impedance. With very low current TWs at the line end that is terminated on a power transformer, the TW87 scheme cannot be applied. Subtransmission lines, however, are often terminated on a power transformer. These lines are not necessarily radial lines because they may feed industrial facilities that comprise large motors and/or cogenerators or they may interconnect unconventional energy sources (wind-powered generators or inverter-based sources).

This paper introduces a TW overcurrent (TW50) protection element that takes advantage of the very high characteristic impedance of a power transformer (TWs do not propagate through a lumped inductance). The paper explains the TW50 element protection principle and illustrates it by using several 1 Msps field records. The paper discusses setting rules and application recommendations for the new TW50 element. This paper is an abbreviated version of [3].

2 Traveling Waves in Lines Terminated on Power Transformers

Consider the system in Fig. 1. A transmission line connects the system terminal (S) with the power transformer terminal (T). The low-voltage side of the transformer typically feeds loads, which may comprise large motors (M) and on-site generation. The load bus (L) can have redundant connections to the system, shown as a dashed line in Fig. 1.

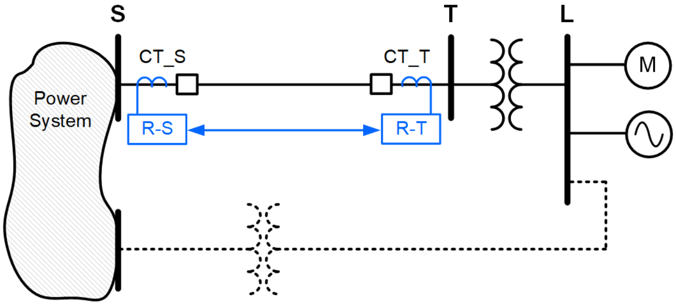

Fig. 1. Line terminated on a power transformer.

These connections can be permanent (the load is operated with multiple sources paralleled) or they may be switched through a bus transfer scheme. In general, the S-T line does not have to be a radial line, and it is protected with two relays installed at each terminal (R-S and R-T). Depending on the power quality requirements for the load site, the protection scheme may be required to trip instantaneously for all line faults, and therefore it may require a pilot scheme or a line current differential scheme. When the line is radial, it may be protected only at Terminal S by using Zone 1 distance elements and time-coordinated distance and directional overcurrent elements.

2.1 *Traveling-Wave Considerations*

Fig. 2 shows an equivalent network diagram for TW propagation considerations for the system in Fig. 1. Power system elements that include lumped inductance at their terminals (transformers, motors, generators) are theoretically open circuits for current TWs.

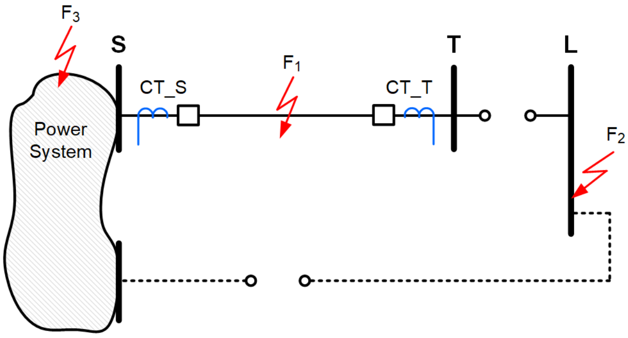

Fig. 2. Equivalent diagram for TW considerations.

Consider the three fault locations in Fig. 2.

An internal fault (F_1) on the S-T line launches TWs that propagate away from the fault in both directions. The TW that arrives at Terminal S reflects off the typically low termination impedance of the system without changing polarity. The Terminal S CT measures a total current TW (the sum of the incident and reflected TWs) that is higher than the incident TW because the reflected TW is of the same polarity as the incident TW. The TW that arrives at Terminal T reflects completely off the theoretically infinite termination impedance and travels back toward the line with the inverted polarity (reflected TW = – incident TW). As a result, the Terminal T CT measures the total current TW that is zero (reflected TW + incident TW = 0). The absence of the total current TW at Terminal T prevents current-only TW-based protection and fault-locating applications at Terminal T.

An external fault in the low-voltage system (F_2) also launches TWs in the overhead lines and cables present in the low-voltage system. However, because the transformer is an open circuit for current TWs, no TWs propagate from the F_2 fault to the S-T line through Terminal T. The parallel connection(s) to the system must have a transformer(s) to match the voltage levels between Buses L and S. Therefore, TWs do not propagate from the F_2 fault to the S-T line through Terminal S either.

An external fault in the high-voltage system (F_3) also launches TWs. These TWs propagate throughout the system and enter the S-T line. Typically, Terminal S has a low termination impedance and only a fraction of the incident TW from the F_3 fault propagates into the S-T line. The worst-case scenario from the protection security perspective is that the entire incident TW enters the protected line from Terminal S for the F_3 system fault. A dependable directional element is required when using the TW50 element to protect the line to address security during system faults (reverse faults for the R-T relay).

2.2 *Power Transformer Equivalent for Traveling Waves*

Consider the transformer winding shown in Fig. 3. The winding has a small capacitance between a pair of adjacent turns and between a turn and the grounded core. A practical winding is assembled in layers, adding a turn-to-turn capacitance between turns located in adjacent layers (not shown in Fig. 3). When considered at very high frequencies (in the range of hundreds of kilohertz to a megahertz), the winding inductance can be assumed infinite (open circuit). We can focus on the capacitance because the impedance of a capacitor decreases while the impedance of an inductor increases when the frequency increases. We can represent the winding by using capacitances between adjacent turns, between layers, and between the ground and the inner-most layer (Layer 1); see Fig. 3.

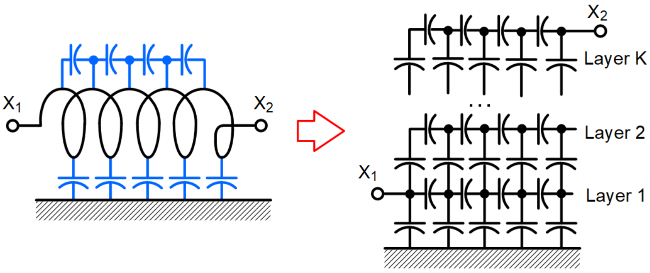

Fig. 3. Winding representation at high frequencies.

Fig. 3 explains why a small high-frequency current pulse can enter a transformer winding. The high-frequency current pulse enters at one winding terminal (X_1 for example). It partially leaves the winding at the other winding terminal (X_2), and it partially sinks to ground. The winding capacitances are very small and permit only small high-frequency currents to flow into the winding.

Fig. 4 shows a two-winding transformer representation at high frequencies. Each winding has an effective capacitance to ground (see Fig. 3), but also, there is a coupling capacitance between the windings of different voltage levels.

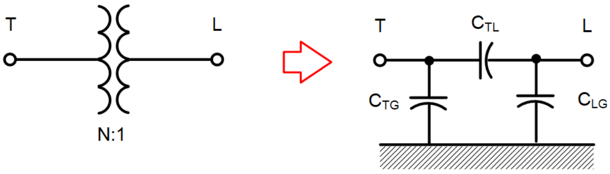

Fig. 4. Transformer representation at high frequencies.

The capacitance between the windings allows a small high-frequency current pulse to “jump” across the transformer. This current is not transformed through the law of induction but is capacitively coupled through the inter-winding capacitance.

Assume an incident TW arrives at Winding L from the low-voltage system. Part of this current impulse sinks to ground through the C_{LG} capacitance. The remainder couples to Winding T through the C_{TL} capacitance. Part of that current sinks to ground through the C_{TG} capacitance, and the remainder enters the high-voltage system (the S-T line in Fig. 1) as an incident TW. Remember that the transformer is, in general, a nearly open circuit and most of the incident TW returns back to the low-voltage system. Fig. 5 illustrates the TW propagation across a power transformer.

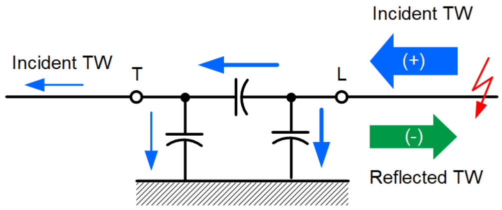

Fig. 5. TW propagation across a power transformer.

It is important to remember that the high-frequency current is not transformed through induction but is capacitively coupled. The transformer ratio does not affect the amount of the current TW that jumps between the two transformer sides. The current TW magnitude is directly proportional to the voltage level and inversely proportional to the line surge impedance. As a result, current TWs launched at the low-voltage side that partially couple to the high-voltage side have a lower magnitude than the current TWs launched at the high-voltage side. This phenomenon gives the TW50 element an inherent setting margin when applied to protect the line that connects the high-voltage transformer winding.

3 TW Overcurrent Protection

We have shown in Section 2 that the current TW magnitude allows differentiating between internal faults on a line terminated with a transformer and faults in the low-voltage system behind the transformer. A directional element is required to differentiate internal faults from external faults in the system (reverse faults from the Terminal T viewpoint). In this section, we discuss the TW50 element logic in detail and explain the TW50 element tripping application.

3.1 TW50 Element Logic

Fig. 6 shows a simplified block diagram of the TW50 element logic. This logic is similar to the TW87 scheme logic [1] available in line protective relay [2], except it is based on local measurements only.

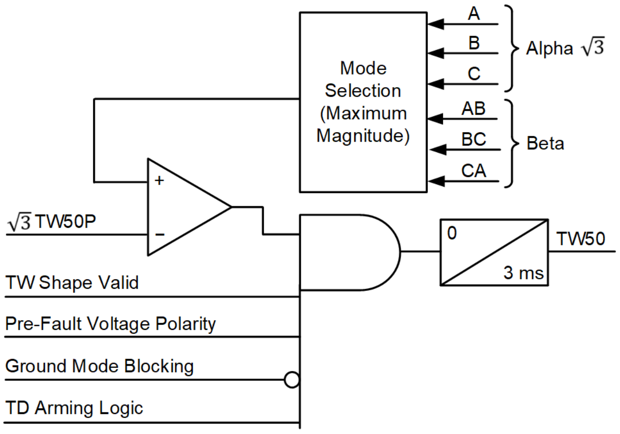

Fig. 6. Simplified TW50 element logic.

The TW50 element logic responds to all six aerial current TW modes [1], and it selects the highest mode for operation. Beta modes during phase-to-phase faults are higher by $\sqrt{3}$ than alpha modes during phase-to-ground faults. The logic multiplies the alpha modes by $\sqrt{3}$ so it can directly compare the alpha and beta mode magnitudes and apply a common overcurrent pickup threshold (TW50P), irrespective of whether it selects the alpha mode or beta mode for operation.

The TW50 element logic includes a TW validity module [2] to verify that the current TW waveform has a shape that is consistent with a fault on a power line (a step change with the rise time of a few microseconds). If the nature of the transient is inconsistent with a fault, the module does not permit the TW50 element logic to operate.

The TW50 element logic includes a pre-fault voltage polarity module [2] to verify that the current TW polarity is consistent with the polarity of the pre-fault voltage. When a fault occurs on a power line and the pre-fault voltage is positive, then the fault lowers the voltage (change in voltage is negative). The negative change in voltage launches a negative current TW, assuming the current polarity reference is away from the fault. Because the line protection CTs measure the currents by using the polarity convention that is away from the bus and toward the line, the relay measures the current TW for a forward fault as positive. As a result, forward faults that occur when the pre-fault instantaneous voltage is positive result in positive current TWs. Forward faults that occur when the pre-fault instantaneous voltage is negative result in negative current TWs. The pre-fault voltage polarity condition can be understood as a TW directional element polarized with pre-fault voltage. This directional verification brings additional security for reverse faults. When the pre-fault voltage is very low (zero-crossing), the directional condition restrains.

The TW50 element logic includes a ground mode rejection module [2]. The module verifies that the ground mode is relatively low compared with the highest alpha or beta mode. Lightning strikes and switching events may induce small current TWs. However, unlike during line faults, these current TWs typically have a very high ground mode compared with the aerial modes. The ground mode rejection module restrains the TW50 element during lightning strikes and other non-fault events.

The TW50 element logic includes an explicit arming logic supervision [1] [2] to prevent misoperation when energizing the line.

The 3 ms extension timer ensures the downstream relay logic can reliably process the TW50 output, despite the momentary nature of the current TWs.

3.2 TW50 Element Applications

Fig. 7 shows the tripping logic based on incremental-quantity directional (TD32) and overcurrent (TD50) elements [1]. Fig. 8 shows the tripping logic based on the overreaching phase and ground distance elements (Z2). Fig. 9 shows yet another application that leverages the permissive overreaching transfer trip (POTT) pilot logic.

The application logic in Fig. 7 allows the TW50 element logic to open a time window of approximately 0.5 cycle. The logic issues the TRIP signal if, during that time window, the TD32 directional element asserts in a forward direction, the TW32 directional element does not assert in the reverse direction, and the TD50 element detects elevated current. The time window is required to accommodate the difference in the operating times of the TW50 and TW32 elements (0.1 ms), the TD32 element (1 to 3 ms), and the TD50 element (1 to 8 ms). The TW32 element is used in a blocking manner because of the limited dependability of the TW32 element logic (TW32 cannot be guaranteed to assert forward for all internal faults). The TD50 element asserts if the current changes its value in the low-frequency spectrum (power frequency spectrum), and by doing so, it confirms that the event is a fault rather than a lightning strike or an electromagnetic interference in the control cables.

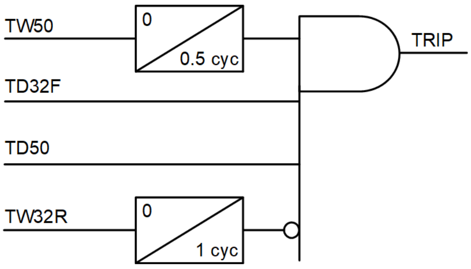

Fig. 7. Tripping logic using incremental-quantity elements.

The logic in Fig. 7 can use the phase (50P), negative-sequence (50Q), or zero-sequence (50G) overcurrent elements instead of or in addition to the TD50 element. The logic may also use additional phasor-based directional supervision: 32P (phase), 32Q (negative-sequence), and 32G (zero-sequence). However, using phasor-based elements may slow down the logic operation to about 1 to 2 cycles, depending on the speed of the applied elements. Such operating times are still very valuable because they are achieved for faults along the entire length of the protected line without a protection channel.

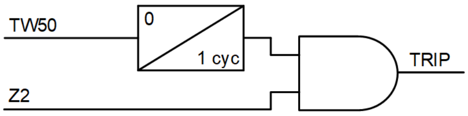

Fig. 8. Tripping logic using overreaching distance elements.

The logic in Fig. 8 is similar to that in Fig. 7, except it relies on the overreaching Zone 2 phase and ground distance elements (Z2) to 1) confirm the fault direction, 2) intentionally limit the reach, and 3) apply the built-in overcurrent supervision with the distance loop current. The TW50 time window is longer in the application in Fig. 8 because the TW50 element must now wait for the Z2 element to pick up and the Z2 element is slower than the TD32 and TD50 elements in Fig. 7. The Z2 element does not have to be set short of the low-voltage bus, and it is allowed to pick up during transformer energization.

The application in Fig. 9 leverages the POTT pilot logic. Using this approach, you can apply the forward (PILOTF) and reverse (PILOTR) protection elements, following your practices and preferences, and use the TW50 element to substitute for the received permissive signal (PILOTRX). The extension timer (DO) is on the order of 0.5 to 2 cycles, depending on the speed of the protection elements used to detect forward faults (PILOTF element(s)). Program the scheme output (POTT) in the trip equation (TR). The logic in Fig. 13 can be used in conjunction with a protection channel. When the channel is available, the TW50 element is not used for tripping. When the channel fails or is taken out of service for maintenance or testing, the TW50 element can be used to substitute for the protection channel.

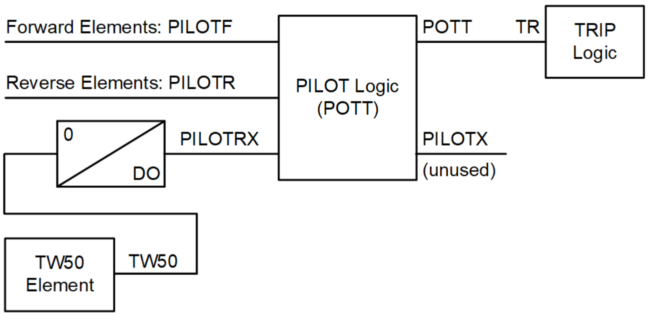

Fig. 9. Tripping logic using the TW50 element to substitute for the POTT protection channel.

The logic in Fig. 7 operates in as fast as 1 to 2 ms and is sensitive to resistive faults. The logic in Fig. 8 operates in approximately 0.75 cycle (depending on the speed of the applied distance elements) and may have a limited resistive coverage. Using a quadrilateral operating characteristic in the Z2 distance element improves the resistive coverage. When applied in relay [2], the logic in Fig. 9 operates as soon as the forward-looking PILOTF protection element(s) asserts, i.e., in 1 to 3 ms when using the TD32 element, in approximately 0.5 cycle when using the 32G and 32Q directional elements, and in 1 cycle or less when using distance elements (Z2).

4 Operation Examples Using Field Cases

In a power system matching the configuration in Fig. 1, a line protective relay installed at Terminal S collected transient records at 1 Msps for faults in the low-voltage system, reverse faults in the bulk power system, and internal line faults. The line is a 161 kV, 72.8 mi overhead line, terminated on an autotransformer. We used line protective relay [2] and programmed the TW87 scheme to accomplish the TW50 functionality [3]. We played back the fault records by using a built-in digital playback function [2]. We used the relay user-programmable logic to implement the TW50 tripping scheme as in Fig. 7. The TW50P threshold was set to 30 A.

4.1 Forward Fault in the Low-Voltage System (Fig. 10)

The relay detects the presence and direction of the fault by asserting the TD50 and TD32F bits, respectively. Fig. 11 shows the plot of the Phase-B alpha mode current TW. The current TW magnitude is only about 18 A primary because the fault is behind the transformer. The TW50 tripping logic restrains correctly for this external fault.

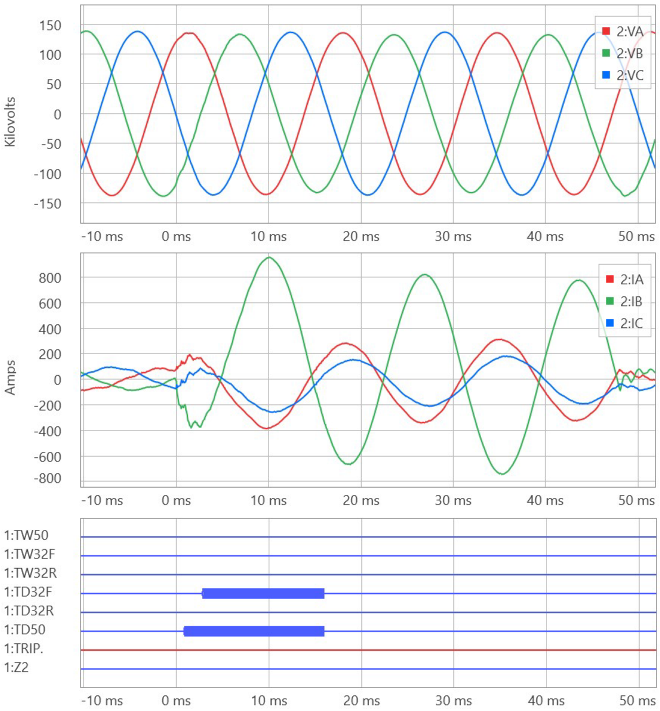

Fig. 10. Relay voltages, currents, and protection bits for a forward fault in the low-voltage system (external fault).

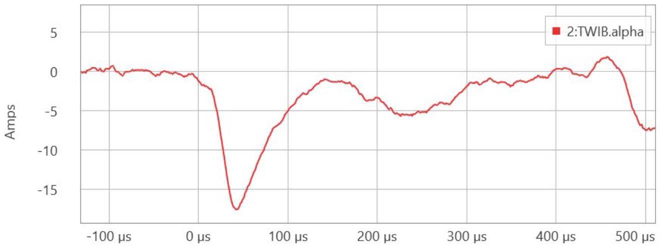

Fig. 11. Current TW for the fault in Fig. 10.

4.2 Reverse Fault in the Bulk Power System (Fig. 12)

The relay detects the presence and direction of the fault by asserting the TD50 and TD32R bits, respectively. Fig. 13 shows the plot of the Phase-C alpha mode current TW. The current TW magnitude is only about 6 A primary. The TW50 tripping logic correctly restrains for this reverse fault not only because the current TW magnitude is low (TW50 deasserted) but primarily because the TD32 element does not assert in the forward direction (in general, the current TW magnitude can be high for a reverse fault and above the TW50P threshold).

4.3 Phase-B-to-Ground Line Fault (Fig. 14)

Fig. 15 shows the plot of the Phase-B alpha mode current TW. The current TW magnitude is about 200 A primary. The TW50 tripping logic in Fig. 7 operates in about 1.5 ms. The Z2 element asserts in about 8 ms, causing the TW50 tripping logic in Fig. 8 to operate in 8 ms for this fault.

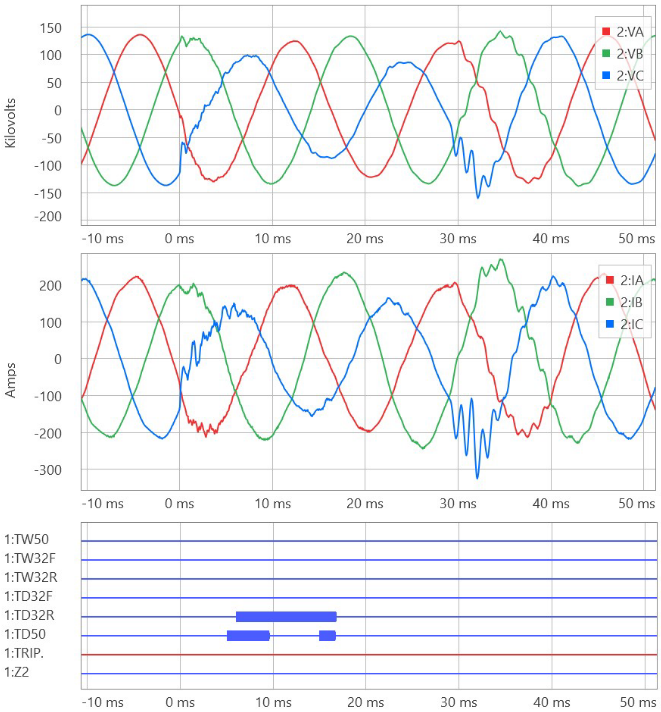

Fig. 12. Relay voltages, currents, and protection bits for a reverse fault in the grid.

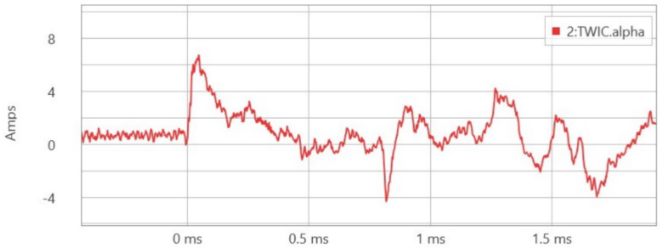

Fig. 13. Current TW for the fault in Fig. 12.

5 Setting the TW50P Threshold

We calculate the TW50P threshold as follows [3]:

$$\mathrm{TW50P} = 2 \cdot \sqrt{\frac{2}{3}} \cdot \delta \cdot \frac{V_{N(L)}}{Z_{C\_MIN(L)}} \cdot k \qquad (1)$$

The factor of 2 in the setting rule (1) recognizes that the current TW measured by the relay is the sum of the incident and reflected TWs and assumes the worst-case scenario of low-impedance termination at the system terminal (Terminal S in Fig. 1) that effectively doubles the magnitude of the measured current TW that jumped across the transformer for faults in the low-voltage system. The factor of $\sqrt{2}/\sqrt{3}$ converts the nominal phase-to-phase rms voltage to the peak phase-to-ground voltage.

The coefficient δ models the fraction of the current TW that couples from the low-voltage to the high-voltage system across the power transformer. Consider using a value for δ between 0.05 and 0.1. The characteristic impedance in (1) is the lowest characteristic impedance among the lines that can be connected to the low-voltage bus (Bus L in Fig. 1) at any time. Assume 350 Ω for overhead lines and 70 Ω for cables.

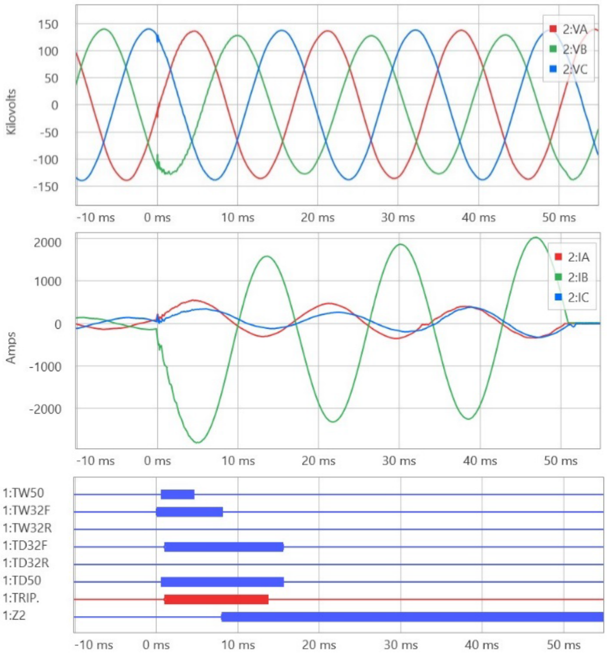

Fig. 14. Relay voltages, currents, and protection bits for a BG line fault.

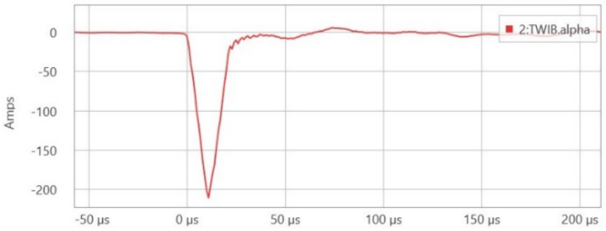

Fig. 15. Current TW for the fault in Fig. 14.

Remember to calculate (1) in primary units or convert the characteristic impedance to secondary ohms before calculating (1) in secondary units. The security multiplier k adds additional margin. Consider using a value for k between 1.5 and 2.

The TW50P threshold (1) applies to the alpha mode current TWs. The threshold must be increased by $\sqrt{3}$ for the beta mode current TWs. The logic in Fig. 6 multiplies the alpha mode current TWs by $\sqrt{3}$, and by doing so, the logic can use one common threshold ($\sqrt{3}\cdot\text{TW50P}$).

The constant δ is the key ingredient in the setting formula (1). We can obtain the value of this constant by using field records. Reference [3] provides more details.

6 Dependability of the TW50 Element

We can calculate the current TW magnitude for internal faults (line faults), as follows [1] [3]:

$$\left|i_{TW\_FAULT}\right| = \sqrt{\frac{2}{3}}\cdot\frac{V_N}{Z_C}\cdot\sin(\Theta) \qquad (2)$$

Equation (2) omits the factor of 2 in order to model the worst-case dependability scenario where the Terminal S termination impedance is not very low and the measured current TW is not amplified by the reflected TW. The angle Θ models the fault point on wave (Θ = 0 degrees: fault at zero crossing, Θ = 90 degrees: fault at peak). Z_C is the characteristic impedance of the protected line. Using (1) and (2), we calculate the minimum point-on-wave angle for which the TW50 element operates:

$$\sqrt{\frac{2}{3}}\cdot\frac{V_N}{Z_C}\cdot\sin(\Theta) > 2\cdot\sqrt{\frac{2}{3}}\cdot\delta\cdot\frac{V_{N(L)}}{Z_{C\_MIN(L)}}\cdot k \qquad (3)$$

Solving for Θ we obtain:

$$\Theta > \operatorname{asin}\left(2\cdot k\cdot\delta\cdot\frac{V_{N(L)}}{V_N}\cdot\frac{Z_C}{Z_{C\_MIN(L)}}\right) \qquad (4)$$

Equation (4) shows that the minimum point-on-wave angle for TW50 operation depends on the transformer ratio as well as the ratio of the line characteristic impedance to the minimum characteristic impedance of any line in the low-voltage system. Using practical values in (4), we conclude that the TW50 element operates dependably for point-on-wave angles above about 20 degrees. Reference [3] provides more details.

7 Conclusions

Current-only TW-based protection and fault locating cannot be applied at line terminals connected to only power transformers or current-limiting reactors. Current TWs measured by relay CTs at those terminals are very low and therefore unreliable. However, external faults beyond these terminals cannot launch current TWs in the protected line. This TW isolation between the low-voltage system and the protected line allows a novel traveling-wave overcurrent protection application at the system line terminal.

This paper presents the TW50 protection principle in detail and illustrates its operation with several field cases. The TW50 protection trips as quickly as 1 to 2 ms for faults along the entire line length without requiring a protection communications channel. The TW50 element dependability is high and justifies enabling the logic. Switch-onto-fault logic, distance Zone 1 elements, and time-coordinated overcurrent elements provide backup protection for the TW50 protection.

8 References

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