Traveling-Wave Overcurrent – A New Way to Protect Lines Terminated on Transformers

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Abstract—**This paper introduces a novel protection principle for lines terminated exclusively on power transformers and current-limiting reactors. The new protection principle operates in as fast as 1 to 2 ms and covers the entire line length without the need for a protection channel. The traveling-wave overcurrent (TW50) element 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 protection principle and illustrates it with several field cases. The paper explains how to program TW differential logic (TW87), available in some protective relays, to perform the TW50 function without a protection channel. The paper provides setting rules and application recommendations for the TW50 element.**

I. INTRODUCTION

Following positive field experience with traveling-wave (TW) fault locators [1] [2], we successfully introduced TW-based protection [3] with field installations starting in early 2017 [4]. To date, the following time-domain line protection elements and schemes have been formulated and successfully deployed in the field [4] [5]:

- TW-based directional element, TW32.
- TW-based differential scheme, TW87.
- Incremental-quantity directional element, TD32.
- Incremental-quantity distance element, TD21.

In a typical application, the TD21 element is configured to trip directly, the TW32 and TD32 elements are used in a permissive overreaching transfer trip (POTT) scheme over a typical protection channel, and the TW87 scheme is used when a direct fiber-optic channel is available. A typical application uses phasor-based protection elements and schemes for dependability in cases where the time-domain protection restrains because of a low TW signal magnitude and other factors [3]. The first microprocessor-based time-domain line protective relay [4] required a standalone backup relay. The successor [5] includes phasor-based protection elements.

Our field experience with time-domain protection is excellent. Line protective relays [4] and [5] have been installed to protect well over a hundred lines, have restrained for thousands of external events, and have operated numerous times for internal faults. They have an excellent security record and a good dependability record. The observed trip times are on the order of 2 to 8 ms for the TD21 element, 1 to 2 ms for the TW87 scheme, and 1 to 2 ms plus the channel time for the POTT scheme.

The time-domain elements and schemes are designed to use today's instrument transformers and control cables, installed based on today's practices. The quality of instrument transformers and cables – in terms of how well they reproduce primary signals – may impact TW-based protection dependability but not security. Current transformers (CTs) and their control cables reproduce TW components in the current signals well. Voltage transformers (VTs) and their control cables introduce significant interfering signals, typically in the form of ringing. Voltage transformers, even capacitively coupled voltage transformers (CCVTs), can reproduce the polarity and timing of the very first TW in the voltage signal, but ringing makes it difficult to identify the subsequent TWs.

Because of the limitations in acquiring voltage TWs, implementations [4] and [5] rely on current TWs (TW32, TW87), the first TW in the voltage (TW32), and the pre-fault voltage (TW32, TW87).

Because the present VTs do not reproduce TWs well, a practical TW-based relay cannot separate the incident and reflected TWs [3] and must operate on the total current TWs. A total current TW is the TW component directly measured from the CT secondary current and is a sum of the incident and reflected current TWs. This limitation of measuring the total current TW only, without the option to separate it into the incident and reflected TWs, creates an obstacle when applying TW-based protection to lines terminated on transformers and current-limiting reactors.

Power transformers (including autotransformers) and series reactors have a very high – ideally infinite – characteristic (surge) impedance. If the protected line does not connect to 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 small current TWs – ideally zero – because the incident and reflected TWs cancel at the termination with an infinite characteristic impedance (a transformer is an open circuit for current TWs). With very low – ideally zero – current TWs at the line end that is terminated on a power transformer, we cannot deploy any current-based TW functionality at that terminal (TW32, TW87, and TW-based fault locating).

Subtransmission lines, however, may be and are often terminated on power transformers. These lines are not necessarily radial lines because they may feed industrial facilities that include large motors and/or cogenerators or they may interconnect unconventional energy sources (wind-powered induction generators or inverter-based sources).

This paper introduces the concept of a TW-based overcurrent element (TW50) and shows how to use it to protect lines terminated on transformers. It also shows how to take advantage of terminations on power transformers to improve application of the TW87 scheme to multiterminal and tapped lines. The paper uses field records to explain, illustrate, and prove the TW50 operating principle. In applications to lines terminated on transformers, the TW50 element allows tripping in 1 to 2 ms without a protection channel.

The paper is organized as follows:

- Section II explains, and illustrates with field records, how current TWs propagate for internal and external faults in lines terminated on power transformers.
- Section III presents the TW50 element logic, including security features to address signals induced by lightning strikes and interfering signals that may be induced in control cables.
- Section IV presents several internal and external fault cases to illustrate the operation and performance of the TW50 element.
- Section V discusses the application of the TW50 element, including the pickup threshold setting calculations, dependability, and the application of the TW87 scheme to lines with transformer-terminated taps.

II. PROPAGATION OF TRAVELING WAVES IN LINES TERMINATED ON 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. 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.

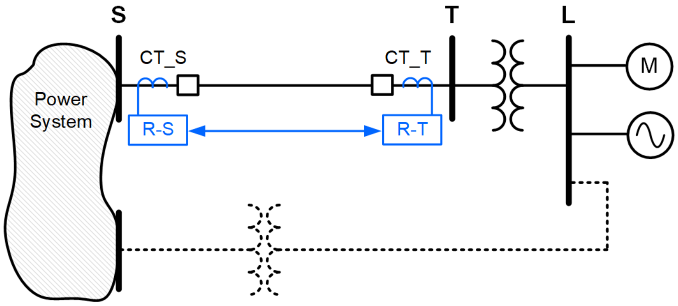

Fig. 1. Line terminated on a power transformer.

A. TW Propagation Under Ideal Conditions

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 open circuits for current TWs.

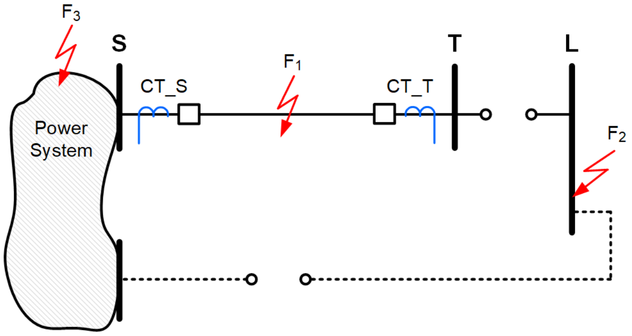

Fig. 2. Equivalent diagram for TW propagation considerations.

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 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 ideally 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 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 to address system faults (reverse faults for the R-T relay) when using the TW50 element to protect the S-T line.

B. TW Equivalent of a Power Transformer

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). The skin effect increases the winding resistance at high frequencies, but the ideally infinite inductance already makes the winding an open circuit, and we can neglect the increased resistance as well. 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.

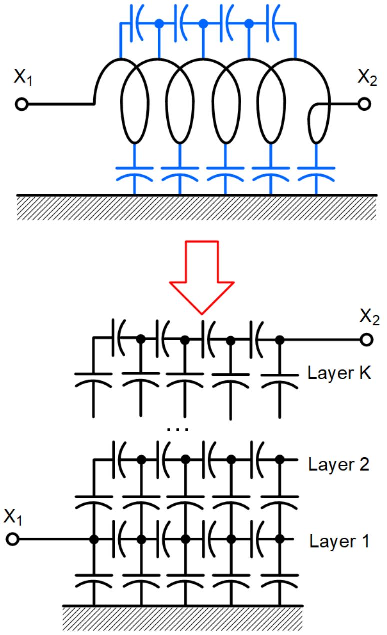

Fig. 3. Transformer winding representation at high frequencies.

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. Of course, the high-frequency current pulse cannot fully transform to the other winding via induction.

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.

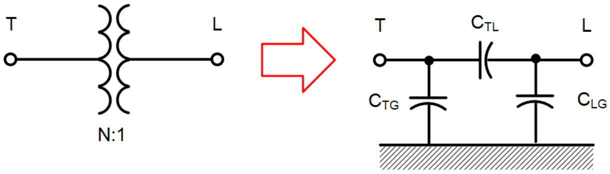

Fig. 4. Transformer representation at high frequencies.

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 reflects back to the low-voltage system. Fig. 5 illustrates the TW propagation across a power transformer.

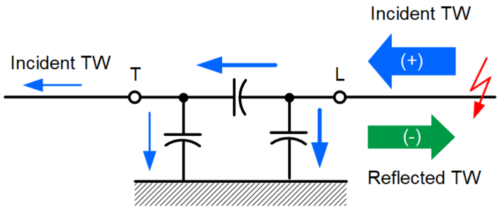

Fig. 5. TW propagation across a power transformer.

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. When estimating the magnitude of the current TW that can jump across the transformer from the low-voltage side to the high-voltage side, we cannot divide the current TW by the transformer ratio. Instead, we must consider the current TW on the low-voltage side. However, 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 – and partially coupling to the high-voltage side – already 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.

C. Termination Effect at the Load and System Buses

Consider a system bus (B) connecting a faulted line and a number (P) of other lines, as in Fig. 6. For simplicity, assume that all lines are similar: all are overhead lines, or all are cable lines, and all lines have approximately the same characteristic impedance (Z_C).

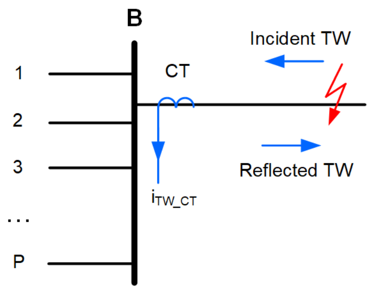

Fig. 6. Bus termination considerations.

When an incident TW arrives from the direction of the faulted line, it encounters a termination impedance equal to one-Pth of the characteristic impedance (for more information, refer to [1]):

$$Z_T = \frac{Z_C}{P} \tag{1}$$

The reflected current TW is:

$$i_{TW\_REFLECTED} = \frac{Z_C - Z_T}{Z_C + Z_T} \cdot i_{TW\_INCIDENT} \tag{2}$$

The CT in the faulted line measures the sum of the incident and reflected TWs in the direction toward the fault:

$$i_{TW\_CT} = -\left(\frac{Z_C - Z_T}{Z_C + Z_T} + 1\right) \cdot i_{TW\_INCIDENT} \tag{3}$$

The minus sign in (3) does not reflect TW propagation direction but the current measurement polarity convention: TWs propagate away from the fault, and the current polarity convention is therefore away from the fault and toward the line ends. Protection CTs, however, measure away from the bus and toward the line, hence the minus sign in (3).

Substituting (1) into (3) and focusing on the current TW magnitude and not polarity, we obtain the following relationship between the incident current TW and the current TW measured by the CT:

$$\left|i_{TW\_CT}\right| = \frac{2 \cdot P}{P + 1} \cdot \left|i_{TW\_INCIDENT}\right| \tag{4}$$

Consider the following three cases:

- If a large number of lines are connected to the same bus as the faulted line (P >> 1), then the measured current TW is twice as large as the incident TW (low-impedance termination):

$$\left|i_{TW\_CT}\right| = 2 \cdot \left|i_{TW\_INCIDENT}\right| \tag{5a}$$

- If no other line is connected to the same bus as the faulted line (P = 0), then the measured current TW is zero (high-impedance termination):

$$\left|i_{TW\_CT}\right| = 0 \tag{5b}$$

- If exactly one other line is connected to the same bus as the faulted line (P = 1), then the measured current TW equals the incident current TW (pass-through between two lines of matching characteristic impedances):

$$\left|i_{TW\_CT}\right| = \left|i_{TW\_INCIDENT}\right| \tag{5c}$$

Now consider a fault in the low-voltage system in Fig. 1 with the goal to estimate the current TW magnitude measured by the R-S relay at Terminal S.

First, we consider TW reflection at Bus L. The worst-case scenario for the magnitude of the current TW that jumps across the transformer is when the faulted line is the only line connected to Bus L. If other lines are connected, they lower the termination impedance at Bus L. By lowering the termination impedance, these additional lines divert the current TW away from the inter-winding capacitance of the transformer and reduce the current TW that can jump across the transformer.

Next, we consider TW reflection at Bus S. The worst-case scenario for the magnitude of the current TW that is measured for faults in the low-voltage system is when many lines are connected to Bus S. The measured current TW is twice the incident current TW that jumped across the transformer. Of course, the incident TW that entered the line at Terminal T attenuates before it arrives at Terminal S. Assuming no attenuation, the worst-case current TW measured at Terminal S ($i_{TW\_CT\_S}$) is:

$$\left|i_{TW\_CT\_S}\right| = 2 \cdot \delta \cdot \left|i_{TW\_INCIDENT(L)}\right| \tag{6}$$

Where parameter δ models the fraction of the current TW that jumps across the transformer and $i_{TW\_INCIDENT(L)}$ is the incident current TW for faults in the low-voltage system.

Knowing the lowest characteristic impedance for the lines in the low-voltage system ($Z_{C\_MIN(L)}$), we can rewrite (6) as (7) by calculating the fault incident current TW as follows:

$$\left|i_{TW\_CT\_S}\right| = 2 \cdot \delta \cdot \sqrt{\frac{2}{3}} \cdot \frac{V_{N(L)}}{Z_{C\_MIN(L)}} \tag{7}$$

Where $V_{N(L)}$ is the phase-to-phase nominal system voltage at Bus L.

We apply (7) in Section V to calculate the TW50 pickup setting at Terminal S for security during faults in the low-voltage system.

D. *Field Example*

In a power system similar to that in Fig. 1, a line protective relay [4] installed at Terminal S triggered a transient record for a fault in the low-voltage system. The protected line is a 161 kV, 72.8 mi overhead subtransmission line terminated on an autotransformer. Fig. 7 shows the relay voltages and currents. Fig. 8 shows the Phase-B alpha mode current TW.

The current TW does not exceed 18 A even though the fault current measured at the relay location is as high as 535 A rms. By comparison, the alpha mode current TW for an internal fault that occurs at the voltage peak, assuming a 350 Ω characteristic impedance of the line, is as high as 375 A. The difference between the external and internal faults is 20-fold (375/18 = 20.9), allowing a high degree of dependability when using the current TW magnitude to detect line faults.

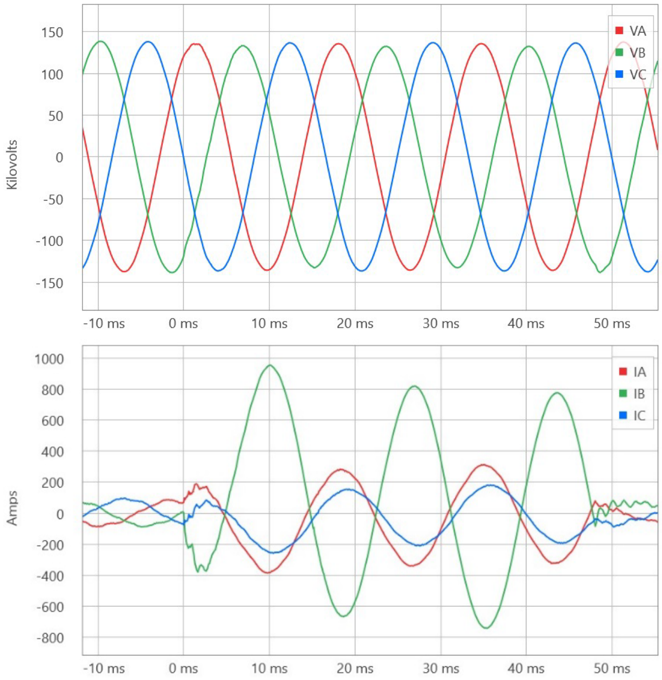

Fig. 7. System relay voltages and currents for a fault in the low-voltage system (field case).

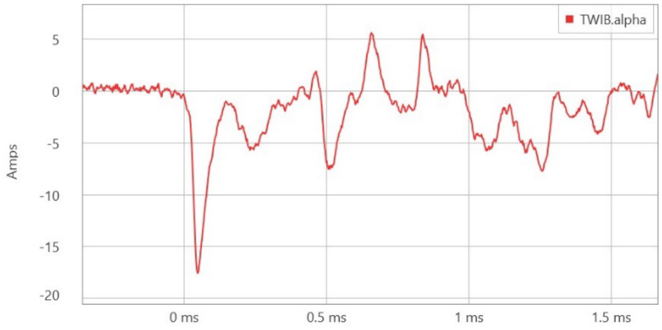

Fig. 8. Current TW for the case in Fig. 7.

E. Line Energization

Closing the circuit breaker at Terminal S in Fig. 1 to energize the line launches TWs that can be as high as those from line faults. To ensure protection security, the TW50 element logic must be blocked during line energization. Line protective relays [4] and [5] include an arming logic. When the breaker opens, the logic disarms all elements and schemes that are based on TWs and incremental quantities, and they remain disarmed for as long as the breaker is open. The arming logic asserts and arms the time-domain protection only after the breaker is closed and the relay voltages and currents have settled on their steady-state values.

F. Transformer Energization

Closing a switching device at Terminal T in Fig. 1 to energize the transformer from the already energized line does not launch significant TWs. Refer to Fig. 4 and observe that closing the switching device only charges the transformer capacitances. The magnetizing inductance does not permit high-frequency currents to flow. The high-frequency current associated with transformer energization is very small and can be disregarded when setting the TW50 element pickup threshold. Of course, the magnetizing inrush current follows the high-frequency current in about 1/6 of a cycle [6], and it is likely to assert the TD32 forward element, the incremental overcurrent elements, the phase overcurrent elements, or even the Zone 2 distance elements. However, a properly set TW50 element remains deasserted when energizing the transformer by closing a switching device at the transformer terminal.

Fig. 9 shows the plot of transformer magnetizing inrush currents and the Phase-CA beta mode current TWs recorded in the field by the line protective relay [4] (the CA beta component is the highest in this case). Fig. 9 shows that the current TW magnitude is limited to about 16 A primary, despite the inrush currents being as high as 800 A primary (peak). Fig. 10 shows the initial dwell time between the moment the breaker closes and the inrush current starts to rise. The dwell time is about 2.8 ms or 1/6 of a cycle as expected; see [6]. Fig. 9 and Fig. 10 illustrate that the magnetizing inrush current does not create any substantial current TWs and that the initial current TWs are due to charging small capacitances associated with the transformer. The pre-inrush current in Fig. 9 and Fig. 10 is the charging current of an energized line.

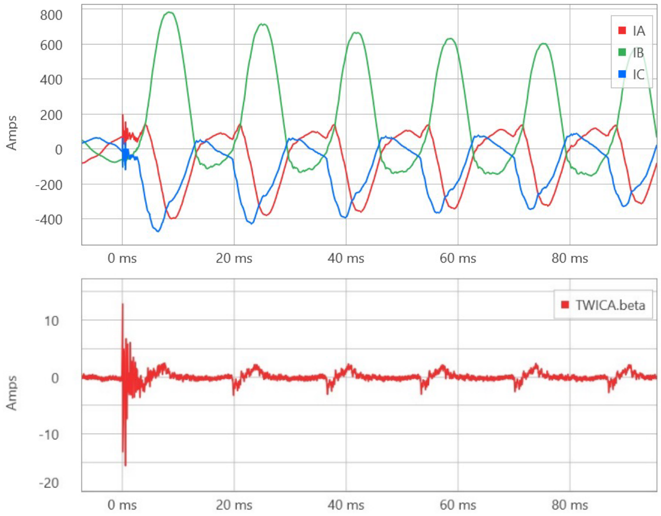

Fig. 9. Transformer inrush currents (field case).

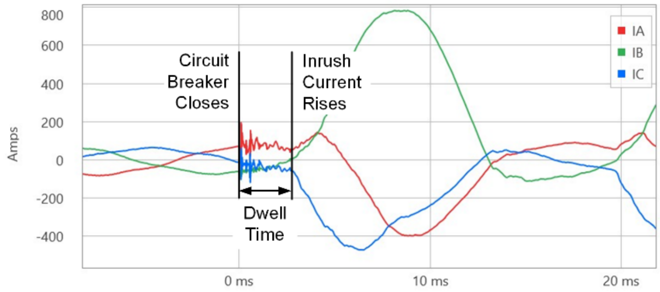

Fig. 10. Initial dwell time of about 2.8 ms.

III. TRAVELING-WAVE OVERCURRENT LOGIC

We have shown in Section II that when protecting lines terminated on transformers, the current TW magnitude allows differentiating between internal faults and faults in the low-voltage system. 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 explain the TW50 element tripping application, discuss the TW50 element logic in detail, and show how to program the TW87 scheme in the line protective relay [5] to effectively provide TW50 element functionality.

A. TW50 Element Tripping Applications

Fig. 11 shows the recommended tripping logic based on incremental-quantity directional (TD32) and overcurrent (TD50) elements. Fig. 12 shows the recommended tripping logic based on the overreaching phase and ground distance elements (Z2). Fig. 13 shows yet another application that leverages the POTT pilot logic.

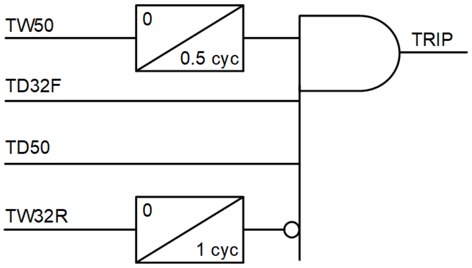

Fig. 11. TW50 element tripping logic based on incremental-quantity elements.

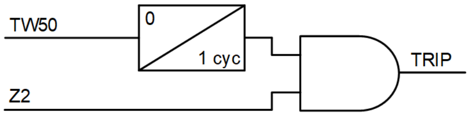

Fig. 12. TW50 element tripping logic based on overreaching distance elements.

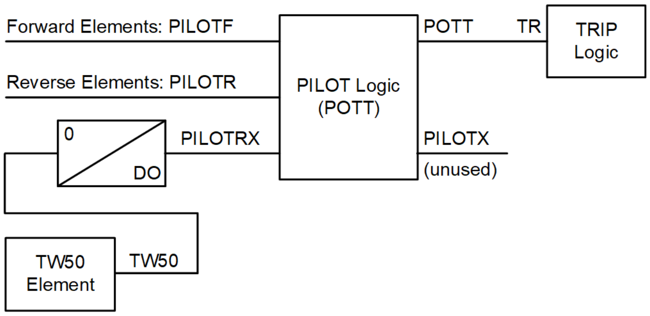

Fig. 13. Using the TW50 element to substitute for the POTT protection channel.

The logic in Fig. 11 can operate in as fast as 1 to 2 ms and is sensitive to resistive faults. The logic in Fig. 12 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 can improve the resistive coverage. The logic in Fig. 13 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 elements, and up to 1 cycle when using distance elements (Z2).

The application logic in Fig. 11 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.

The logic in Fig. 11 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, 32Q, and 32G). 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 without a protection channel for faults along the entire length of the protected line.

The logic in Fig. 12 is similar to that in Fig. 11, 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. 12 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. 11. 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.

For additional security, the logic in Fig. 11 and Fig. 12 can be programmed on a per-phase basis.

The application in Fig. 13 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 cycle 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.

B. TW50 Element Logic

Fig. 14 shows a simplified block diagram of the TW50 element logic. This logic is similar to the TW87 scheme logic [3] [7] available in line protective relays [4] [5], except it is based on local measurements only.

The TW50 element logic responds to all six aerial current TW modes [1] [3], and it selects the highest mode for further processing. 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.

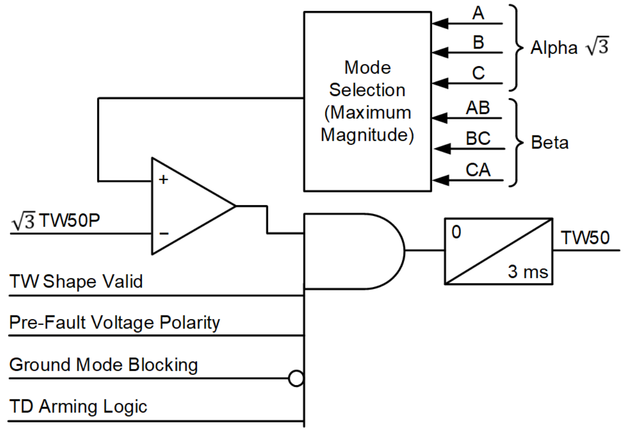

Fig. 14. Simplified TW50 element logic.

The TW50 element logic includes a TW validity module [3] [4] [5] to verify that the current TW waveform has a shape that is consistent with a typical 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 typical fault, the module does not permit the TW50 element logic to operate.

The TW50 element logic includes a pre-fault voltage polarity module [3] [4] [5] 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 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; see (3). 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. References [3] and [7] provide more information.

The TW50 element logic includes a ground mode rejection module [3] [4] [5]. The module verifies that the ground mode is relatively low compared with the highest alpha or beta mode. Lightning strikes and other 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 module restrains the TW50 element during lightning strikes and other non-fault events.

The TW50 element logic includes an explicit arming logic supervision 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.

C. *Using the TW87 Element Logic as the TW50 Element*

The TW87 scheme [3] available in line protective relays [4] [5] follows an operating principle similar to the TW50 principle proposed in Fig. 14, except it uses data from both ends of the line to detect current TWs passing through the protected line. The TW50 element achieves security for external forward faults based on the magnitude of the local current TWs without the need for remote current TWs. We can therefore apply the TW87 element logic in a single-ended fashion, as depicted in Fig. 15.

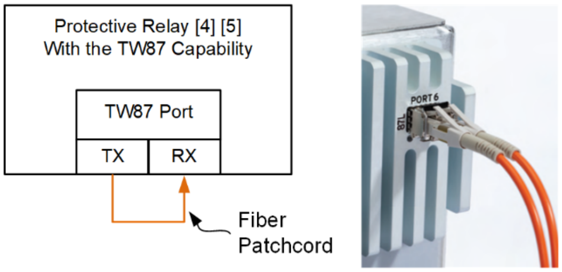

Fig. 15. Using TW87 element logic to implement the TW50 element.

To repurpose the TW87 scheme as a TW50 element, it is necessary to loop back the TW87 communications channel by using a short-range (low power) transceiver and connecting (looping back) the transmit (TX) output to the receive (RX) input of the port. The loopback allows the TW87 element logic to receive its own local current TW. As a result, the TW87 logic calculates an operating signal that is twice the local current TW. The restraining signal always appears lower than the operating signal in the application in Fig. 15. The differential part of the TW87 logic asserts as soon as the differential TW signal is above the factory-selected threshold. A user with calibration access level privileges can change the TW87 differential threshold in devices [4] [5] to effectively set the TW50P threshold. The TW87 logic includes the security modules in Fig. 14 as well as the incremental-quantity overcurrent supervision (TD50) in Fig. 11.

The application in Fig. 15 allows ultra-high-speed protection based on current TWs, without a protection channel, because of the guarantee that current TWs will not appear at Terminal S in Fig. 1 for faults behind the transformer. User-programmable logic in a line protective relay [5] can be used to implement the TW50 applications in Fig. 11, Fig. 12, and Fig. 13.

IV. OPERATION EXAMPLES USING FIELD CASES

In a power system matching the configuration in Fig. 1, a line protective relay [4] installed at Terminal S collected transient records for faults in the low-voltage system, reverse faults in the bulk power system, and internal line faults. The protected line is a 161 kV, 72.8 mi overhead line, terminated on an autotransformer. We used line protective relay [5] and programmed the TW87 scheme (Fig. 15) to accomplish the TW50 functionality according to Fig. 14. We played back the fault records by using a built-in digital playback function [4] [5]. We used the relay user-programmable logic to implement the TW50 tripping scheme as in Fig. 11. The TW50P pickup threshold was set to 30 A. The TW87 element logic applied the threshold to the beta mode current TWs and the alpha mode current TWs (without the √3 multiplier).

A. *Forward Fault in the Low-Voltage System*

Fig. 16 shows the plots of relay voltages, currents, and protection bits (this is the same case shown in Fig. 7). The relay detects the presence and direction of the fault by asserting the TD50 and TD32F bits, respectively. Fig. 17 shows the plot of the Phase-B alpha mode current TW. The current TW magnitude is only about 18 A primary. The TW50 tripping logic restrains correctly for this external fault.

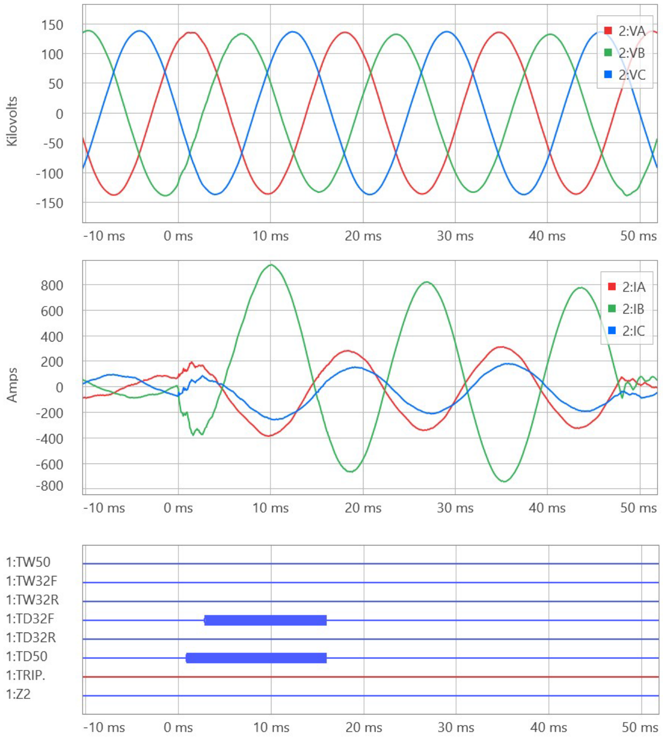

Fig. 16. Relay voltages, currents, and protection bits for a forward fault in the low-voltage system (external fault).

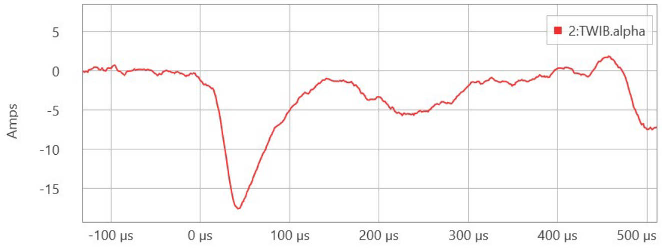

Fig. 17. Current TW for the fault quantities in Fig. 16.

B. *Reverse Fault in the Bulk Power System*

Fig. 18 shows the plots of relay voltages, currents, and protection bits. The relay detects the presence and direction of the fault by asserting the TD50 and TD32R bits, respectively. Fig. 19 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).

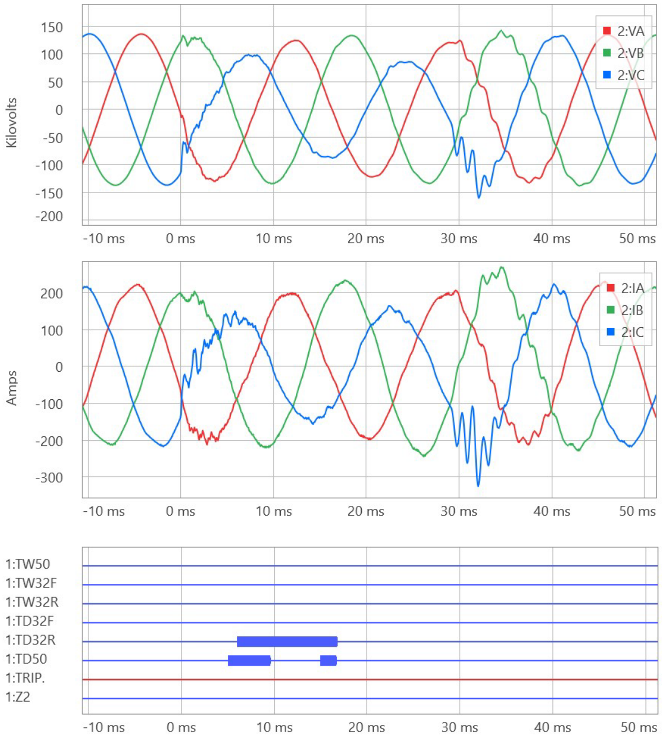

Fig. 18. Relay voltages, currents, and protection bits for a reverse fault in the grid.

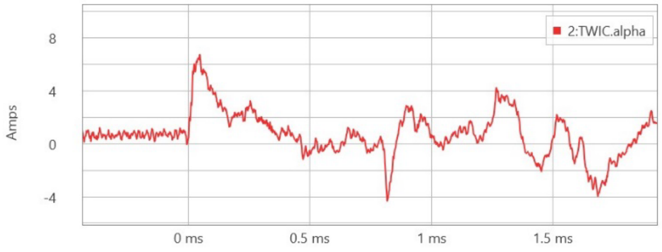

Fig. 19. Current TW for the fault quantities in Fig. 18.

C. *Phase-B-to-Ground Line Fault*

Fig. 20 shows the plots of relay voltages, currents, and protection bits. Fig. 21 shows the plot of the Phase-B alpha mode current TW. The current TW magnitude is about 200 A primary. The TW50 tripping logic operates in about 1.5 ms. The Z2 element asserts in about 8 ms, causing the TW50 tripping logic in Fig. 12 to operate in 8 ms for this fault.

D. *Phase-C-to-Phase-A-to-Ground Line Fault*

Fig. 22 shows the plots of relay voltages, currents, and protection bits. Fig. 23 shows the plot of the Phase-C-to-Phase-A beta mode current TW. The current TW magnitude is about 230 A primary. The TW50 tripping logic operates in about 1 ms. The TW50 application that uses the Z2 element operates in about 9 ms.

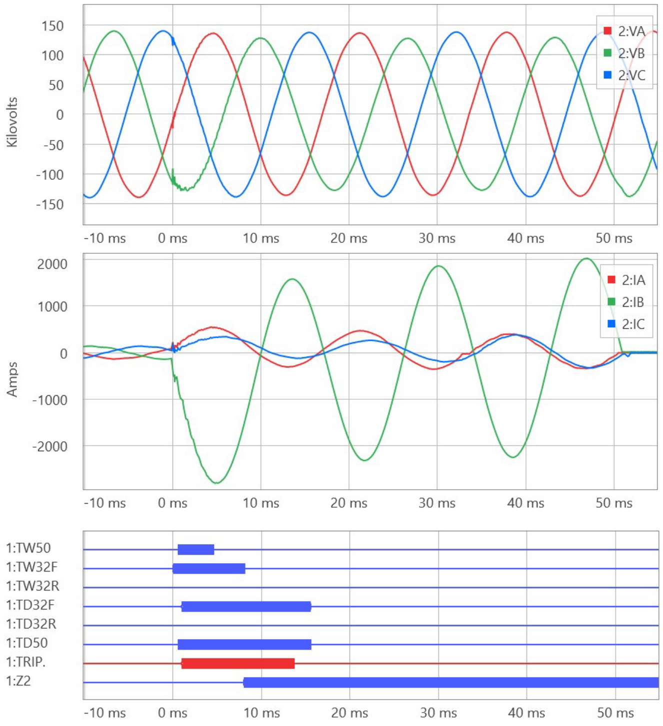

Fig. 20. Relay voltages, currents, and protection bits for a BG line fault.

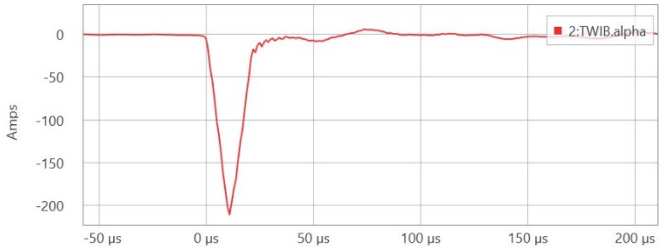

Fig. 21. Current TW for the fault quantities in Fig. 20.

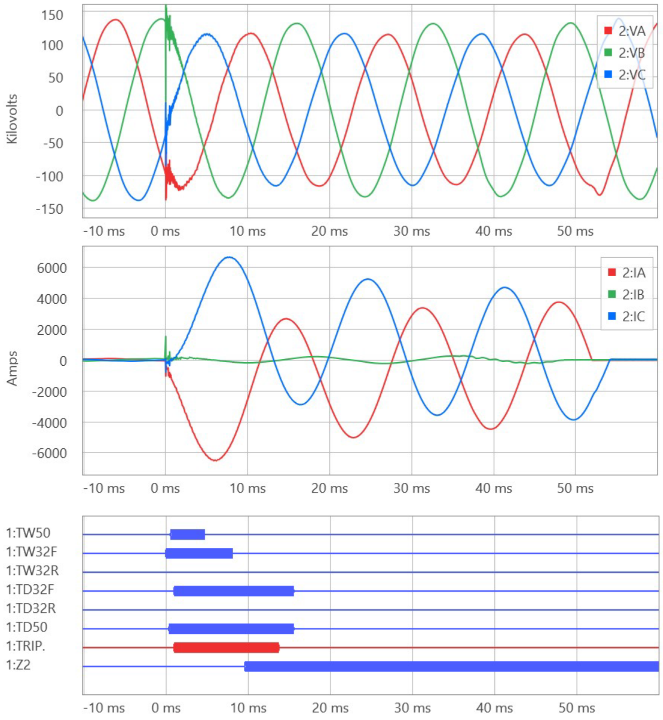

Fig. 22. Relay voltages, currents, and protection bits for a CA line fault.

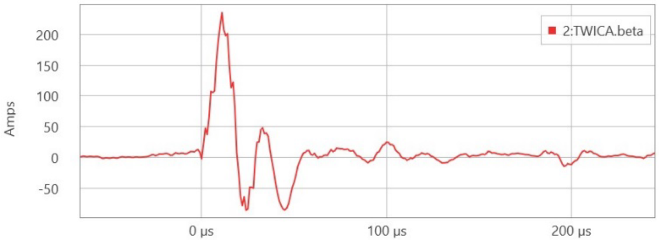

Fig. 23. Current TW for the fault quantities in Fig. 22.

V. APPLICATION CONSIDERATIONS

A. *TW50 Pickup Threshold*

1) *Setting the TW50 Pickup Threshold for Security*

We use (7) and calculate the TW50P pickup threshold as follows:

$$\mathrm{TW50P} = 2 \cdot \sqrt{\frac{2}{3}} \cdot \delta \cdot \frac{V_{N(L)}}{Z_{C\_MIN(L)}} \cdot k \tag{8}$$

The setting rule (8) can be better understood with the following description. The factor of 2 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 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 (8) is the lowest characteristic impedance among the lines that can be connected to the low-voltage bus (Bus L in Fig. 1). Assume 350 Ω for overhead lines and 70 Ω for cables. Remember to perform calculations (8) in primary units or convert the characteristic impedance to secondary ohms before calculating (8) in secondary units. The security multiplier k adds additional margin. Consider using a value for k between 1.5 and 2.

The TW50P pickup threshold (8) 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. 14 multiplies the alpha mode current TWs by $\sqrt{3}$, and by doing so, the logic is able to use one common threshold ($\sqrt{3} \cdot \mathrm{TW50P}$).

The constant δ is the key ingredient in the setting formula (8). We can obtain the value of this constant by using field records, as follows:

STEP 1. Obtain the fault records from the Terminal S relay (megahertz sampling) and from the faulted line relay (1–2 kHz sampling is sufficient) for a fault in the low-voltage system.

STEP 2. Use the Terminal S relay record to obtain the magnitude of the highest current TW mode for the fault, I_{TW_MAX}.

Step 3. Use the faulted line relay record to obtain the instantaneous pre-fault voltage in peak volts for the mode from Step 2, V_{PRE}.

Step 4. Calculate the launched current TW magnitude as follows:

$$I_{TW\_LAUNCHED} = \frac{V_{PRE}}{Z_C} \tag{9}$$

Step 5. Calculate the coefficient δ as follows:

$$\delta = \frac{I_{TW\_MAX}}{I_{TW\_LAUNCHED}} \tag{10}$$

It is better to perform the above procedure in primary amperes and volts to avoid correcting for different CT ratios of the Terminal S relay and the faulted line relay and converting the characteristic impedance into secondary ohms.

Example 1

Consider a system in Fig. 1 with a 161 kV/69 kV transformer and the low-voltage system connecting one overhead line. Assume 5 percent coupling between the low- and high-voltage transformer windings ($\delta = 0.05$) and an additional security margin of 50 percent ($k = 1.5$). The TW50P setting in primary amperes is:

$$TW50P = 2 \cdot \sqrt{\frac{2}{3}} \cdot 0.05 \cdot \frac{69{,}000\ V}{350\ \Omega} \cdot 1.5 = 24\ A \tag{11}$$

2) Dependability of the TW50 Element

We can use (7) to calculate the current TW magnitude for line (internal) faults, as follows:

$$\left|i_{TW\_FAULT}\right| = \sqrt{\frac{2}{3}} \cdot \frac{V_N}{Z_C} \cdot \sin(\Theta) \tag{12}$$

Equation (12) can be better understood with the following description. The equation omits the factor of 2 in order to model the worst-case dependability scenario where the Terminal S termination impedance is not small and the measured current TW is not amplified by the reflected TW. The angle Θ models the fault point on wave ($\Theta = 0$ degrees: fault at zero crossing, $\Theta = 90$ degrees: fault at peak). Z_C is the characteristic impedance of the protected line.

Example 2

Continue from Example 1 and calculate the minimum point on wave angle for which the TW50 element operates. The incident current TW for an internal fault is:

$$\sqrt{\frac{2}{3}} \cdot \frac{161{,}000\ V}{350\ \Omega} \cdot \sin(\Theta) = 375\ A \cdot \sin(\Theta) \tag{13a}$$

Assuming the 24 A pickup setting from Example 1, the lowest point-on-wave angle for which the TW50 element with the 24 A setting operates is:

$$\Theta = \operatorname{asin}\left(\frac{24\ A}{375\ A}\right) = 3.7\ \text{degrees} \tag{13b}$$

The instantaneous phase-to-ground voltage in a 161 kV system when the point-on-wave angle is 3.7 degrees is only 8.5 kV. It is very unlikely that a short circuit will occur at the time when the voltage is that low. Even if we assume a uniform distribution of the point-on-wave angle for line faults, the 3.7-degree blind spot around the voltage zero-crossing is only $2 \cdot 3.7 / 180 = 4$ percent of all possible points on wave (meaning the TW50 element is dependable for 96 percent of point-on-wave values).

When Terminal S has a very low termination impedance, the current (12) doubles and the TW50 element yields even better results.

Resistive faults launch lower current TWs. However, as long as the resistive fault in our example changes the voltage at the fault location by more than 8.5 kV, the TW50 element logic will operate.

We can generalize Example 2 and calculate the minimum point-on-wave angle for which the TW50 element operates:

$$\sqrt{\frac{2}{3}} \cdot \frac{V_N}{Z_C} \cdot \sin(\Theta) > 2 \cdot \sqrt{\frac{2}{3}} \cdot \delta \cdot \frac{V_{N(L)}}{Z_{C\_MIN(L)}} \cdot k \tag{14}$$

Solving for Θ we obtain:

$$\Theta > \operatorname{asin}\left(2 \cdot k \cdot \delta \cdot \frac{V_{N(L)}}{V_N} \cdot \frac{Z_C}{Z_{C\_MIN(L)}}\right) \tag{15}$$

Equation (15) 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.

Let us use (15) to estimate the absolute worst case for which the TW50 element is dependable. Considering various combinations of cables and overhead lines, the ratio of the characteristic impedances can be about 350/70, 350/350, 70/70, or 70/350. The worst-case scenario is 350/70 (the protected line is an overhead line, and the low-voltage system includes cables). Power transformers step down voltage by at least a factor of 2. Assuming $k = 1.5$ and $\delta = 0.05$, we obtain:

$$\Theta > \operatorname{asin}\left(2 \cdot 1.5 \cdot 0.05 \cdot \frac{1}{2} \cdot \frac{350}{70}\right) = 22\ \text{degrees} \tag{16}$$

At a point-on-wave angle of 22 degrees, the instantaneous voltage is 37 percent of the nominal voltage.

Equation (16) tells us that under the worst-case conditions, the TW50 element will operate if the fault changes the voltage at the fault location by more than 37 percent of the nominal voltage. For metallic faults, the element will operate for faults with a point-on-wave angle higher than 22 degrees.

B. Overcurrent Supervision Settings

The role of overcurrent supervision (TD50 in Fig. 11, built-in overcurrent supervision in the Z2 elements in Fig. 12, or the 50P elements if used in addition to or instead of the TD50 elements) is to ensure the TW50 element operates for a fault and not for high-frequency signals related to lightning strikes or for interfering signals induced in the control cables.

Set the overcurrent supervisory elements to assert for line-end faults; assume the fault resistance you desire to cover, with margin. The overcurrent supervisory elements are permitted to assert for transformer inrush currents and faults in the low-voltage system.

C. *Zone 2 Reach Settings*

Set the overreaching supervisory phase and ground distance elements (Z2) to assert for line-end faults, with margin. Consider using quadrilateral operating characteristics for better fault resistance coverage. The Z2 elements are permitted to assert for transformer inrush currents and faults in the low-voltage system.

D. *Application to Hybrid Lines*

The TW50 protection can be applied when the protected line in Fig. 1 is a hybrid line and consists of both overhead and cable sections. Current TWs transmit and reflect at the joints between the overhead and cable sections. In general, the current TW increases when a TW leaves the overhead section and enters the cable section and it decreases when the TW leaves the cable section and enters the overhead section [8].

When a current TW leaves a line section that has a Z_{C1} characteristic impedance and enters a section that has a Z_{C2} characteristic impedance, the transmitted current TW is as follows [8]:

$$i_{\text{TW\_TRANSMITTED}} = \frac{2 \cdot Z_{C1}}{Z_{C1} + Z_{C2}} \cdot i_{\text{TW\_INCIDENT}} \qquad (17)$$

When the TW travels from an overhead section (350 Ω) to a cable section (70 Ω), then 2 · 350 / (350 + 70) = 167 percent of the incident current TW continues on the cable section. When the TW travels from a cable section (70 Ω) to an overhead section (350 Ω), then 2 · 70 / (350 + 70) = 33 percent of the incident current TW continues on the overhead section.

When the protected line in Fig. 1 consists only of two sections, an overhead section connecting Terminal T and a cable section connecting Terminal S, then apply an additional 70 percent margin to the TW50P setting. The 70 percent margin is the worst-case scenario. If the line has more than two sections, the current TW at Terminal S is reduced and no additional margin is needed.

Alternatively, you can examine each transition starting at Terminal T and progressing toward Terminal S in Fig. 1. Apply the 0.33 multiplier (cable-to-overhead transition) or the 1.67 multiplier (overhead-to-cable transition) accordingly and arrive at a more accurate estimate of the current TW magnitude. The TW50P setting reduction compared with (8) is possible because as a current TW propagates through a hybrid line, its magnitude decreases because multiple TWs are reflected from the transition points and travel away from Terminal S. Reference [8] provides guidelines for TW analysis in hybrid lines.

E. *Application to Tapped Lines and Multiterminal Lines*

Consider the tapped line in Fig. 24. Because the low-voltage sides of all taps are separated through power transformers, downstream faults cannot launch large TWs in the line. Therefore, the TW50 tripping logic, as in Fig. 11, Fig. 12, and Fig. 13, can be used for selective ultra-high-speed tripping without a protection channel. Circuit breakers at the line taps can be tripped based on an undervoltage condition or through a direct transfer trip logic. If the line includes sectionalizers (downstream disconnect switches), the TW50 protection must be inhibited during sectionalizing because connecting line sections launches TWs.

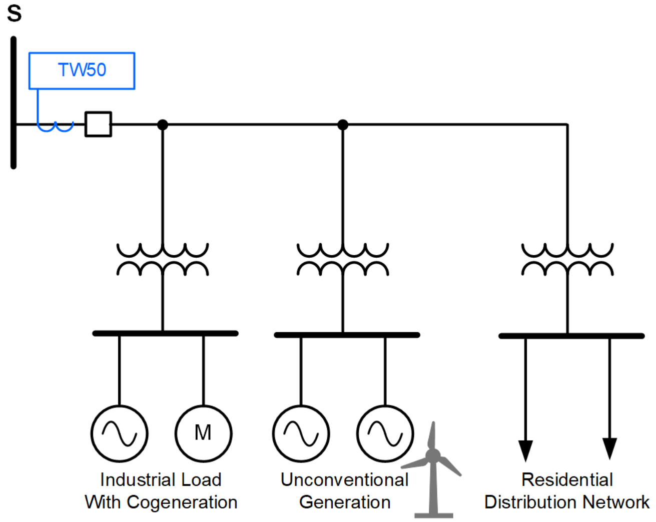

Fig. 24. Using TW50 element logic to protect tapped lines when all taps are connected through power transformers.

Fig. 25 shows an example of a multiterminal line with several taps. In this case, TWs can enter and leave the protected line during external faults, and the TW87 scheme must be applied instead of the simple TW50 tripping logic. The TW87 scheme [3] [4] [5] incorporates location-dependent blocking regions for selectivity during faults on sections that can launch TWs (Tap T2 in Fig. 25). There is no need to use blocking regions for all taps that are connected through power transformers (Taps T1, T3, and T4 in Fig. 25). References [3] and [7] provide more information on the TW87 operating principle and applications.

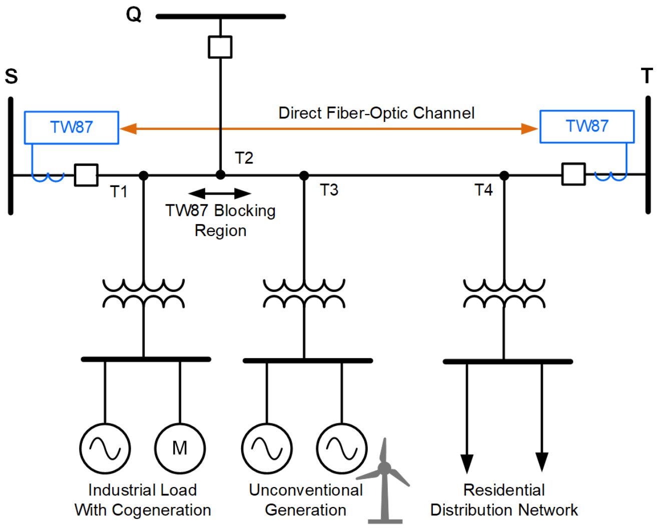

Fig. 25. Using the TW87 scheme to protect multiterminal tapped lines when taps are connected via power transformers.

VI. CONCLUSIONS

TW-based protection (TW87, TW32) 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 – ideally zero – 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 (TW50) 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 paper introduces the TW50 setting rules and estimates the expected TW50 dependability for line faults.

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 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 element logic.

VII. REFERENCES

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VIII. BIOGRAPHIES

Bogdan Kasztenny has over 30 years of experience in power system protection and control. In his decade-long academic career (1989–99), Dr. Kasztenny taught power system and digital signal processing courses at several universities and conducted applied research for several companies. In 1999, Bogdan left academia for relay manufacturers where he has since designed, applied, and supported protection, control, and fault-locating products with their global installations numbering in the thousands. Bogdan is an IEEE Fellow, a Senior Fulbright Fellow, a Distinguished CIGRE Member, and a registered professional engineer in the province of Ontario. Bogdan has served as a Canadian representative of the CIGRE Study Committee B5 (2013–2020) and on the Western Protective Relay Conference Program Committee (2011–2020). In 2019, Bogdan received the IEEE Canada P. D. Ziogas Electric Power Award. Bogdan earned both the Ph.D. (1992) and D.Sc. (Dr. habil., 2019) degrees, has authored over 220 technical papers, holds over 55 U.S. patents, and is an associate editor of the *IEEE Transactions on Power Delivery*.

Mangapathirao (Venkat) Mynam received his MSEE from the University of Idaho in 2003 and his BE in electrical and electronics engineering from Andhra University College of Engineering, India, in 2000. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2003 as an associate protection engineer in the engineering services division. He is presently working as an engineering director in SEL research and development. He was selected to participate in the U. S. National Academy of Engineering (NAE) 15th Annual U. S. Frontiers of Engineering Symposium. He is a senior member of IEEE and holds patents in the areas of power system protection, control, and fault location.

Stephen Marx received his BSEE from the University of Utah in 1988. He joined Bonneville Power Administration (BPA) in 1988. He is presently the District Engineer in Idaho Falls, Idaho, for BPA. He has over 30 years of experience in power system protection and metering. He has been a lecturer at the Hands-On Relay School in Pullman, Washington, since 2007. He is a registered professional engineer in the state of Oregon. He is a member of IEEE and has authored and coauthored several technical papers.

Ralph Barone has over 30 years of experience in power system protection and control. Ralph received his BASc degree in electrical engineering from the University of British Columbia in 1988. He worked for BC Hydro from 1988 to 2019 in HVDC, Telecom, and Protection and Control. Ralph is a registered Professional Engineer in the province of British Columbia.

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