# Dependability of Transient-Based Line Protection Elements and Schemes

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# Dependability of Transient-Based Line Protection Elements and Schemes

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*Abstract*—**The paper focuses on the dependability of transient-based line protection. Transient-based protection includes protection elements and schemes that are based on both incremental quantities and traveling waves. The paper starts by sharing results – in terms of operating time, security, and dependability – from transient-based relays deployed in the field. It then gives an analysis of practical factors that may impact dependability and provides evidence-based estimates of how much these factors may impact dependability. Our field experience includes very few zero-crossing faults, which, as this paper explains, are extremely rare. The paper includes an in-depth analysis of the impact of the fault point on wave (fault inception angle) on dependability of TW-based protection, and it dispels a common misunderstanding related to faults at the voltage zero crossing. The paper identifies practical factors that impact dependability, such as current transformer fidelity or transients that appear shortly before the fault that are caused by such events as switching operations and external faults.**

## I. Introduction

Transient-based protection that uses traveling waves (TWs) and incremental quantities [1] is recognized as a practical option for improving line protection in systems with unconventional generation, including inverter-based sources [2] [3]. Fault transients, especially TWs and polarities of incremental voltages and currents, are independent of the source types present in the system. Fully digital relays that are based on transients [4] [5] have been available since the mid-2010s and deployed in the field. The field record of these relays provides hard evidence of the effectiveness of the transient-based line protection principles in traditional systems as well as in systems with unconventional generation.

Because protection security is always paramount, the dependability of these new relays is a result of a balance between the inherent capability of the transient-based protection principles to detect faults (intrinsic dependability) and a defensive design applied for security (intentional reduction in dependability when increasing security).

This paper explains and quantifies dependability limitations for the following transient-based protection elements and schemes [1]: directional (TW32 and TD32), differential (TW87), and distance (TD21). The paper dispels some of the commonly raised dependability-limiting factors, such as the fault point on wave (fault inception angle), while introducing practical dependability considerations, such as ringing signals in the control cables, proximity of the fault relative to discontinuities in the network, surge termination impedances, system short-circuit level, and line length.

The paper summarizes several years of field experience with transient-based line protection and uses field cases to illustrate its points and conclusions.

## II. Transient-Based Line Protection

Transient-based line protective relays [4] and [5] are based on the operating principles that are generally described in [1]. These relays have an excellent track record in the field. This section provides background information on these relays and their field record and is taken directly from [3].

### A. Operating Principles

Transient-based line protection responds to short-lived signal features in the relay input currents and voltages. Fault-generated transients are not powered by the sources present in the system but by the energy stored in the inductance and capacitance of the system components prior to the fault, primarily in transmission lines. To understand this key factor, consider a Thevenin equivalent network during faults. In the Thevenin network, all equivalent sources are removed and their terminals are shorted. The change in voltage at the fault point is the source that drives all the incremental signals in the network. This independence of the fault signal components from physical sources has been valued in protective relaying for decades, long before the days of wind-powered generators and inverter-based sources. It facilitates fast protection that is independent from the load and infeed effects. Transient-based protection is also largely independent of the fault response of the sources – a key feature appreciated today because of the unusual fault response of unconventional sources.

### B. Field Example

Fig. 1 shows the currents and voltages recorded at the terminals of a 40 mi 345 kV 60 Hz transmission line for an internal C-phase-to-ground fault. Transient-based line relays [5] asserted their trip commands in 0.8 ms and the two-cycle $SF_6$ circuit breakers interrupted the fault current in about 23 ms for a total fault clearing time of 24 ms (1.5 cycles). The traveling-wave differential (TW87) scheme operated first (0.8 ms). The permissive overreaching transfer trip (POTT) scheme operated second at about 2 ms into the fault. The POTT scheme works with the traveling-wave (TW32) and incremental-quantity (TD32) directional elements, which asserted in 0.1 ms and 1.5 ms, respectively. This installation uses a direct (point-to-point) fiber protection channel with an end-to-end latency of 0.35 ms.

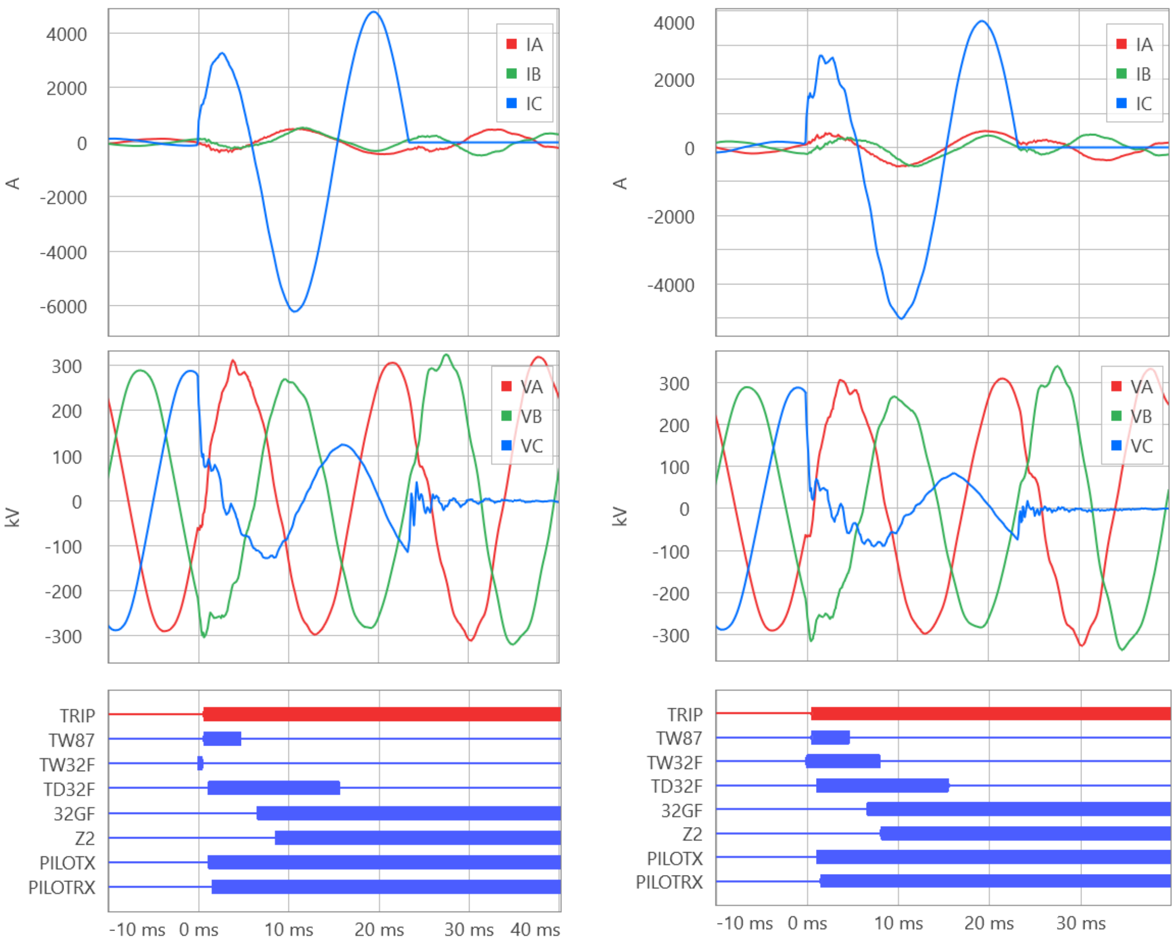


Fig. 1. Current, voltage, and relay bit records at both terminals for an internal CG fault [3].

The fault in Fig. 1 occurred on a line connected to a relatively strong system dominated by synchronous generators. However, it becomes self-evident that the relays did not trip in response to the fault current supplied by the sources. The TW87 scheme requires remote data to operate. Because the remote data arrived after a 0.35 ms delay and the scheme operated in 0.8 ms, the TW87 scheme acted upon not more than 0.80 ms – 0.35 ms = 0.45 ms of remote data. No source can change its current much in half a millisecond. The TW87 scheme responded to fault-generated transients (traveling waves) that are independent of the sources.

### *C. Field Experience*

The transient-based ultra-high-speed (UHS) line protective relay [4] was released in 2017. A version with embedded backup functions based on fundamental frequency components was released in 2020 [5]. At the time of this writing, the two UHS relay models have accumulated a few thousand relay-years of field experience. The field experience is very positive and can be summarized as follows:

- The transient-based protection elements and schemes are secure. Because the transient-based relays are simpler to use, settings errors are reduced, and as a result, the relays perform better in the field than the previous generation of relays.
- The transient-based protection elements and schemes are highly dependable. The POTT scheme based on the TD32 element is the workhorse of transient-based line protection. The POTT scheme operates for all practical line faults as long as the system is in a steady state before the fault.
- The transient-based protection elements and schemes are very fast and trip on the order of 1 to 5 ms. The relays operate fast regardless of the types of sources in the system.
- Circuit breakers that are rated for two-cycle operation typically clear faults in 1.5 cycles if actuated in 1 to 5 ms. As a result, the total fault clearing time is often between 1.5 and 2 cycles.
- The TW-based fault locator embedded in the relays performs exceptionally well. It is highly dependable and has a field-proven accuracy of about one tower span (300 m or 1,000 ft) regardless of the line length, fault resistance, and system conditions, including source type.
- The TW-based protection elements and schemes are dependable but not 100 percent dependable. The remainder of this paper elaborates on the dependability of these elements and schemes.

Fig. 2 through Fig. 5 show fault records for a few field cases in a 60 Hz system, including different voltage levels, line lengths, fault types and resistance, and source characteristics. The transient-based UHS relays [4] and [5] operated in only a few milliseconds, resulting in a fault clearing time shorter than 2 cycles. The figures illustrate the speed and dependability of the TD32 element. It allows the POTT scheme to operate on the order of 2 to 4 ms when used with a low-latency protection channel: see the PILOTRX signal (trip permission received) in Fig. 1 and the TRIP signal in Fig. 2 through Fig. 5.

Fig. 2 illustrates a case of a fault current supplied by wind-powered generators (Type III). The current does not increase significantly, and it is squelched in about 1 cycle, after which it contains mostly the zero-sequence current coming from the grounded neutral of the interconnecting power transformer.

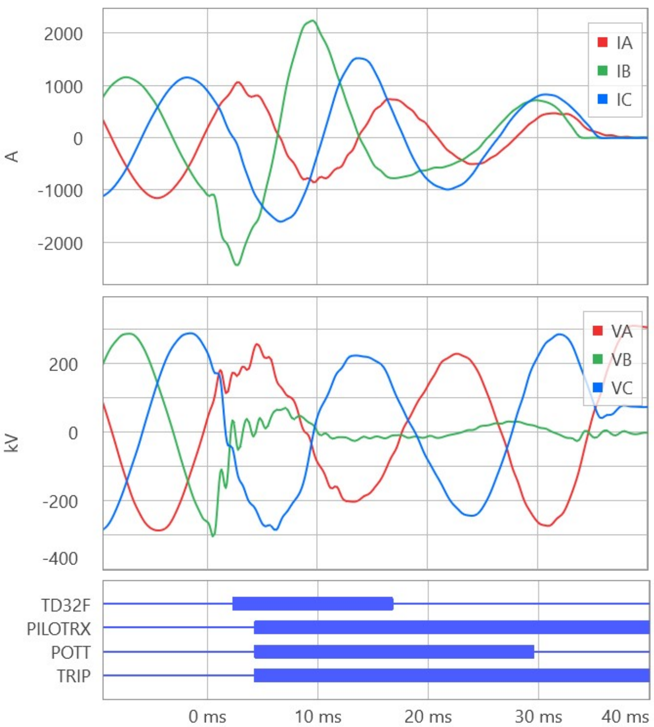


Fig. 2. BG fault cleared in 2 cycles [3].

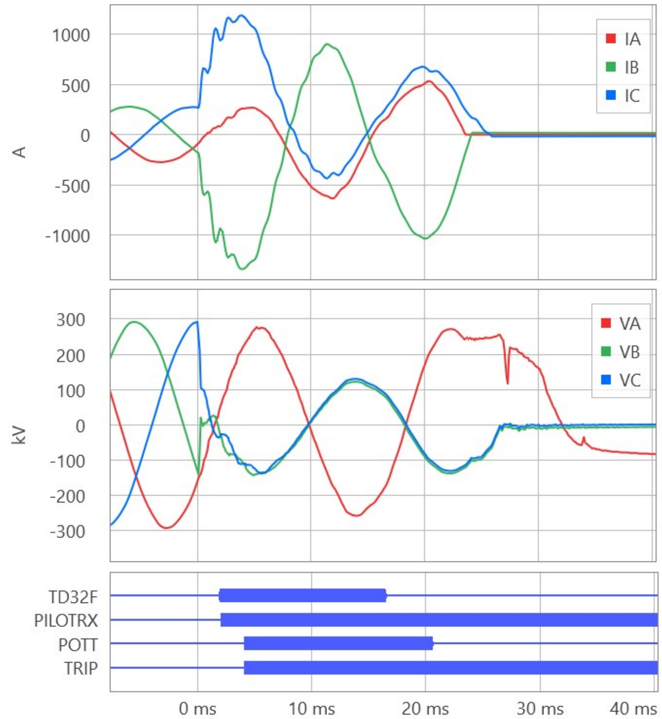


Fig. 3. BC fault cleared in 1.4 cycles [3].

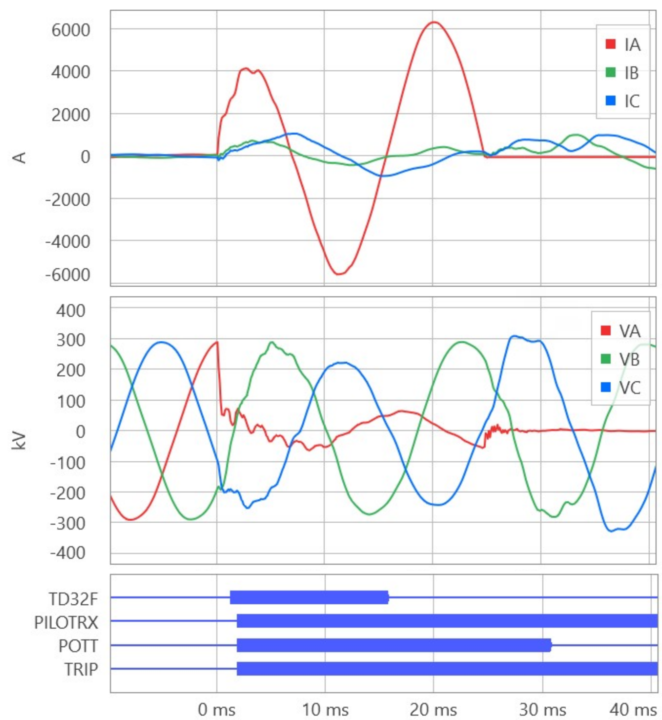


Fig. 4. AG fault cleared in 1.5 cycles [3].

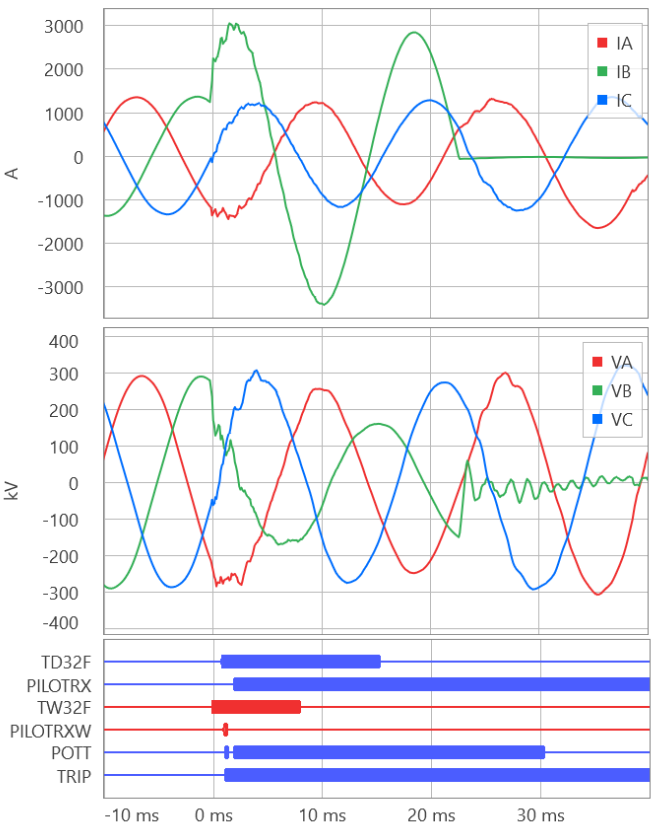

Fig. 5. BG fault cleared in 1.4 cycles [3].

## III. Defensive Design

Protection security is paramount and overrides all other dimensions of relay performance. Relays [4] and [5] follow a defensive design concept because they not only operate very fast but are also based on signals that may be difficult to model and may not be reproduced faithfully by instrument transformers. According to our defensive design philosophy, the relay logic verifies the key assumptions used to develop the protection logic before allowing the logic to trip. This section highlights those defensive design concepts that may impact protection dependability.

### *A. Arming Logic*

Any switching phenomenon causes transients, including operational switching events (breakers or disconnect switches operating under normal conditions), breakers clearing external faults, breakers closing to energize an apparatus, and transformer tap changers regulating voltage, to name the most frequent ones. Allowing a transient-based relay to respond to the transients that are not associated with fault inception may lead to inadvertent operations. Also, if two or more events occur in quick succession, the transients associated with each event and measured by a relay may superimpose. The relay cannot separate the transient components caused by each event, which may lead to security problems.

Relays [4] and [5] respond only to the initial transients by using an arming logic. The arming logic asserts and arms the transient-based elements and schemes after the system has been in a steady state for a few power cycles (e.g., 3 cycles). When the arming logic is asserted, a change in currents will release the transient-based elements and schemes to operate. Subsequently, the arming logic closes the operating window (e.g., in about 1 power cycle), and the relay needs to re-arm before the transient-based protection is allowed to respond to a new transient.

The arming logic arms the transient-based elements and schemes if the following conditions are met for the duration of the arming timer:

- The incremental voltages and currents are small.
- The voltage is near the nominal value.
- No disturbance is detected.
- Currents are balanced.
- A loss-of-potential condition is not present.
- The relay measures and tracks frequency.

The arming logic impacts dependability as follows:

- Any transient that occurs immediately before the internal fault (such as an external fault) can disarm the transient-based elements and schemes.
- The transient-based elements and schemes are disarmed when switching onto a fault.
- A fast power swing may disarm the transient-based elements and schemes.

Sections VI through VIII provide more details.

### *B. Transient Signal Level Validation*

Before using incremental quantities or TWs for protection, relays [4] and [5] verify that these signals are above the noise level and, therefore, can be trusted when deciding to trip. The relays incorporate a high-fidelity data acquisition system (an 18-bit, 1 Msps analog-to-digital converter). Therefore, the associated thresholds for the minimum signal level comparators are relatively low. The minimum signal level validation may impact sensitivity of transient-based protection for faults with very high fault resistance.

### *C. TW Shape Logic*

TWs are sharp changes in voltage or current signals. As such, they have clear polarities (rise or fall) and arrival times (moment of transition). Relays [4] and [5] measure (find and quantify) TWs by using a differentiator-smoother (DS) filter [1]. The DS filter is a least-square estimator that provides the TW magnitude and arrival time. The relay logic compares the ideal expected step in the voltage and current signals, as defined by the magnitude and arrival time from the DS filter, and the actual step measured in the voltage and current signals. The logic allows the use of the TWs for tripping only if the expected and measured TW shapes are similar.

This security condition impacts dependability when the signals show significant distortions, such as those that result from ringing in the secondary current circuits. Section VIII provides more details.

## IV. Fault Point on Wave and Transient-Based Protection

Faults near the voltage zero crossing are generally considered a blind spot for the TW-based line protection. This section rectifies this common misunderstanding.

The fault point on wave is an important parameter in transient relay testing. Faults that occur at the voltage peak and at the voltage zero crossing cause different transients in relay voltages and currents. Protective relays may respond differently (security, dependability, or operating time) depending on if the fault occurs when the pre-fault voltage is large or small, if that voltage is rising or falling, and – during multiphase faults – how large or small the other faulted-phase voltages are. The fault point on wave impacts fault transients and, therefore, transient-based line protection.

Before we analyze the impact of the fault point on wave in more detail, let us specify the fault point-on-wave term by considering the following:

- Fault point on wave refers to the instantaneous value of the pre-fault voltage *at the fault location*, not at the line terminals. Because of the voltage drop across the protected line as a result of the load current, the terminal instantaneous voltages differ from each other and from the voltage at the fault location. It is the voltage at the fault location, not the terminal voltage, that influences the fault transients.
- Fault point on wave refers to the voltage of the *faulted loop,* not any particular phase-to-ground voltage. For example, it refers to the A-phase-to-ground voltage for AG faults and the B-phase-to-C-phase voltage for BC faults. Therefore, the fault point-on-wave voltage fully defines transients for faults that involve only a single loop (single-phase-to-ground faults and phase-to-phase faults). Double-phase-to-ground faults and three-phase faults involve more than one fault voltage, and these multiple voltages are at different points on wave when the fault happens. Similarly, the fault point-on-wave term becomes less crisp during evolving faults. You can use the superposition principle to analyze multiphase faults and evolving faults. When testing relays, it is important to document how the fault point-on-wave test parameter has been applied.
- The fault point-on-wave voltage is often specified by the phase angle (fault inception angle), typically, by using the sine function as the base. In this convention, a fault at the zero crossing is designated by the 0-degree point-on-wave angle and a fault at the positive peak is designated by the 90-degree point-on-wave angle.
- When testing transient-based relays, it is beneficial to vary the point-on-wave angle by using small steps, such as 2 to 5 degrees across the entire spectrum from 0 to 360 degrees. Fault transients are heavily influenced by the fault point-on-wave angle, and the transient fault patterns repeat with a period of 360 degrees when considering TW-based elements and schemes and multiphase faults.

After defining the fault point on wave, we now analyze its impact on the transient-based elements and schemes.

### *A. TW-Based Elements and Schemes*

The TW32 element and TW87 scheme included in relays [4] and [5] require a minimum current TW value before the TW32 element and the TW87 scheme are allowed to operate (see Section III). These relays use analog-to-digital converters with an effective 18-bit resolution and, therefore, can measure even small current TWs. Assume $I_{MIN}$ is the minimum current TW in per unit of the relay nominal secondary current ($I_{NOM}$) that is required by a TW-based protection element or scheme. For example, $I_{MIN}$ can be on the order of 5 percent of the relay nominal current. We calculate the corresponding primary current TW as follows:

$$I_{TW(MIN)} = \sqrt{2} \cdot I_{NOM(SEC)} \cdot CTR \cdot I_{MIN} \tag{1}$$

where CTR is the current transformer (CT) ratio.

A fault that causes a sudden change in voltage ($\Delta V$) launches current TWs consistent with the line characteristic impedance ($Z_C$) as follows:

$$I_{TW(LAUNCHED)} = \frac{\Delta V}{Z_C} \tag{2}$$

The launched current TW (2) is typically amplified by the termination effect, i.e., the current TW measured by using a CT may be as much as 100 percent higher than the current TW that the fault launched. The exact degree of amplification depends on the surge termination impedance. We neglect the amplification to both simplify the analysis and obtain the worst-case scenario. A TW-based element or scheme operates if:

$$I_{TW(LAUNCHED)} > I_{TW(MIN)} \tag{3}$$

We insert (1) and (2) into (3) and solve for $\Delta V$ as follows:

$$\Delta V > \sqrt{2} \cdot I_{NOM(SEC)} \cdot CTR \cdot I_{MIN} \cdot Z_C \tag{4}$$

Equation (4) provides the minimum voltage change at the fault location that results in current TWs that are large enough to be measured by a TW-based relay. Assume $I_{MIN}$ = 0.05 pu (5 percent of the relay nominal secondary current of 5 A), CTR = 200, and $Z_C$ = 350 Ω (typical overhead line), and calculate the minimum voltage of 24.8 kV peak or 17.5 kV rms. The 17.5 kV rms voltage is a small fraction of the nominal voltage for transmission and subtransmission lines.

#### *1) Bolted Faults*

During a bolted (metallic) fault, the voltage change equals the instantaneous pre-fault voltage:

$$|\Delta V| = \sqrt{2} \cdot V_{NOM(PRI)} \cdot \sin(\theta) \tag{5}$$

We insert (5) into (4) and calculate the point-on-wave angle (θ) as follows:

$$\theta > \operatorname{asin}\left( I_{NOM(SEC)} \cdot CTR \cdot I_{MIN} \cdot Z_C \cdot \frac{1}{V_{NOM(PRI)}} \right) \tag{6}$$

Assume a subtransmission line with a nominal voltage of 110 kV. The 17.5 kV rms voltage is 27.6 percent of the phase-to-ground voltage and 15.9 percent of the phase-to-phase voltage. The corresponding point-on-wave voltage angles from (6) are 16 and 9 degrees, respectively. These values show that as long as a phase-to-ground fault happens 16 degrees before or after the voltage zero crossing and a phase-to-phase fault happens 9 degrees before or after the voltage zero crossing, the TW-based elements and schemes have enough current TW signal to work with.

The termination effect (amplification of the current TW launched by the fault when measured at the line terminals) typically relaxes the point-on-wave requirement even further.

For lines with higher nominal voltages, the operating conditions improve in proportion to the voltage level. For example, when the nominal voltage is 500 kV, the 17.5 kV required to launch measurable current TWs is only 6.1 percent of the phase-to-ground voltage and 3.5 percent of the phase-to-phase voltage. These values correspond to the point-on-wave voltage angles (6) of 3.5 and 2 degrees, respectively. A 500 kV line may use CTs of higher ratio leading to the theoretical dead zone of higher than the 3.5 and 2 degrees. In general, however, the theoretical dead zone in terms of the point-on-wave angle for TW-based protection is just a few electrical degrees.

*2) Resistive Faults*

The change in voltage at the fault location during resistive faults is smaller than for bolted faults. As a result, the current TWs are reduced as well. From this perspective, fault resistance and infeed effect impact the TW-based elements and schemes. However, that impact is relatively small. Consider the previous example in which a 17.5 kV rms voltage change is required to launch measurable current TWs. As long as the fault voltage changes by 17.5 kV, the TW-based elements and schemes will operate. Consider a 220 kV line. The 17.5 kV change in fault voltage when the voltage is near peak is only 14 percent of the phase-to-ground voltage.

In general, the TW-based protection elements and schemes (TW32 and TW87) are not limited to bolted faults. We estimate that their sensitivity is similar to that of ground (32G) and negative-sequence (32Q) directional elements, at least for faults that occur when the voltage is near peak.

### B. Incremental-Quantity-Based Elements and Schemes

Relays [4] and [5] derive incremental quantities by subtracting one-cycle-old values from the present instantaneous values. As a result, the incremental-quantity level (peak magnitude in the first cycle following the fault) is independent of the fault point on wave. Of course, the fault point on wave impacts how fast the incremental quantities rise following the fault. As a result, the incremental-quantity-based elements and schemes (TD21, TD32, and POTT) will have a slightly different operating time depending on the fault point on wave. Also, the fault point on wave would have an impact on faults that are close to the dependability limit of a given element. For example, during internal faults close to the reach point of the TD21 element, it may operate or restrain depending on the fault point on wave. Or, for internal faults when the source-to-impedance ratio (SIR) is close to a dependability limit of about 2.5, the TD21 element may operate or restrain depending on the fault point on wave [1].

This section explained that the fault point on wave has a moderate impact on TW-based elements and schemes and a small impact on incremental-quantity-based elements and schemes. The next section justifies that, practically, faults happen when the voltage at the fault location is away from the zero crossing. As a result, we can state that the fault point on wave has very small to no impact on transient-based protection.

## V. Practical Fault Point-on-Wave Considerations

This section considers electrical and mechanical causes for line insulation breakdown and concludes that when the point on wave voltage is small, the probability of a fault is very low. This section also considers faults caused by lightning strikes through a mechanism known as back flashover.

### A. Electrical Insulation Breakdown

When insulator surface contamination, porcelain cracks, and other similar factors cause a breakdown, a certain minimum voltage is required to initiate a flashover and start a fault. Consider that the insulator is exposed to full system voltage (phase-to-ground peak voltage) twice per power system cycle (every 8.3 ms or 10 ms in 60 Hz or 50 Hz systems, respectively). If an insulator has just withstood the full voltage, it is very unlikely that this insulator would fail a quarter of a cycle later when the voltage is very small, i.e., near the voltage zero crossing [3]. Fig. 6 shows a field case of a fault on a 110 kV 50 Hz subtransmission line with two precursors that occurred half a cycle and 0.5 ms before the fault. Note that the precursors and the fault all occurred when the voltage was near its peak. The current TWs associated with the precursors allow calculating the precursor location, and that location aligns exactly with the location of the fault (i.e., the high-current event). Also, the polarities of the current TWs align with the polarities of the faulted-phase voltage at the time of the partial discharge. As a result, we have high confidence that these were truly fault precursors, i.e., events that occurred at exactly the same location as the fault.

This case illustrates that an electrical breakdown requires an adequately large voltage across the insulation to ionize the air portion of the breakdown path. After almost breaking down at the negative voltage peak in Fig. 6, the insulation held until the voltage increased to near the positive peak. At that time, a second precursor occurred, followed by the fault in 0.5 ms.

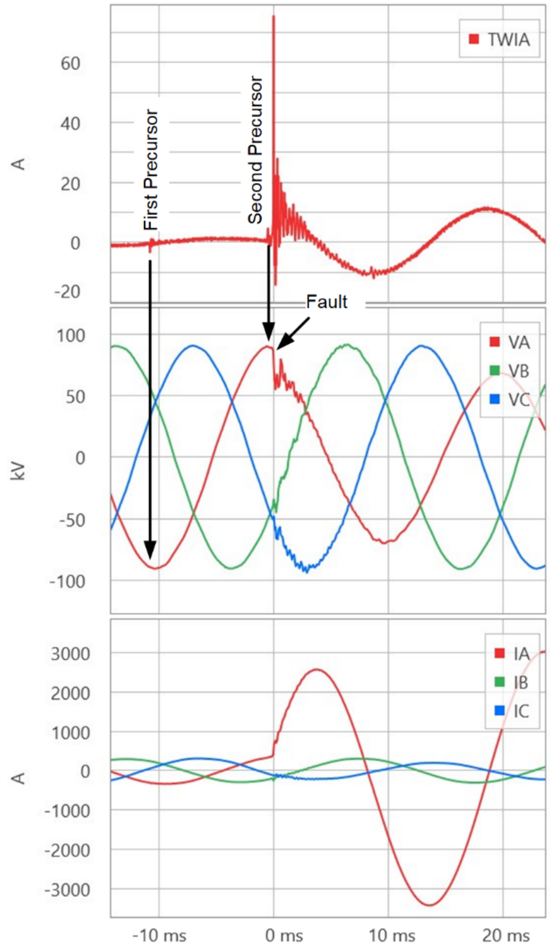


Fig. 6. Faulted-phase current TW, phase voltages, and phase currents for a fault with two precursors.

In general, electrical insulation breakdown happens when the voltage at the fault location is much lower than the voltage peak. But the breakdown voltage is still significant (tens of kilovolts), resulting in launching measurable current TWs. For example, the insulation on a 500 kV line may break down when the voltage is 30 kV peak. This breakdown voltage corresponds to 10 percent of the peak phase-to-ground voltage. Visually, this fault happened close to the voltage zero crossing (a 6-degree point-on-wave angle). Yet, a bolted single-phase-to-ground fault on a 500 kV line at a 6-degree point-on-wave angle launches 30 kV / 350 Ω = 85 A current TWs – a value that is within a measuring range of relays [4] and [5].

Our field experience shows that the lower the system nominal voltage, the higher the fault point-on-wave angle for most faults. For example, most faults on subtransmission lines occur when the voltage is near peak (see Fig. 1 through Fig. 6).

### *B. Mechanical Insulation Breakdown*

When the insulation breaks down because of a mechanical cause, such as a falling tree making contact and causing a high-resistance phase-to-ground fault, the flashover may occur at a lower voltage than the voltage during an electrical breakdown of the insulation. Such a mechanical cause reduces the distance between the parts of a circuit that have different electrical potentials (two conductors or a conductor and ground). Although mechanical faults may occur at relatively low voltage levels, faults near the voltage zero crossing are very unlikely, as explained in this subsection.

Fig. 7 illustrates the mechanical insulation breakdown when the mechanical object that caused the fault moves relatively slowly, such as a tree falling on power conductors. The figure plots the actual distance between the conductors (or a conductor and ground) as a function of time (the blue trace). This distance decreases slowly because of the relatively slow velocity of the mechanical object (the velocity is the slope of the blue line in Fig. 7 and Fig. 8). The figure also plots the flashover distance (red trace) based on the following formula:

$$d_{MIN(t)} = \frac{\left|v_{F(t)}\right|}{E_{MIN}} \tag{7}$$

where $v_{F(t)}$ is the instantaneous voltage in the faulted loop and $E_{MIN}$ is the minimum dielectric strength of air (3 kV/mm).

A flashover happens when the actual distance, which keeps decreasing because of the mechanical cause of the fault, is less than the minimum flashover distance required to withstand the voltage at that time. As we can see in Fig. 7, a slowly moving mechanical object (such as a falling tree, a metallic balloon or a kite, debris lifted by heavy winds, or animals) can cause a fault only when the voltage is near its peak.

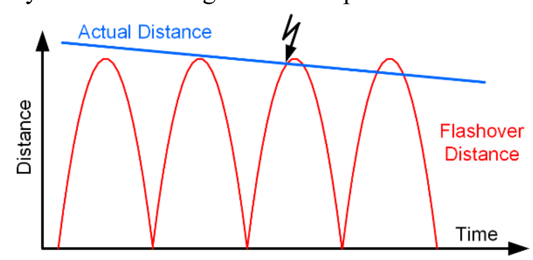


Fig. 7. Actual distance (blue) and flashover distance (red) when a mechanical object causing a fault moves slowly.

Fig. 8 shows the case when the mechanical object moves fast enough to avoid causing a flashover when the voltage is not zero. The line of actual distance is an asymptote to the minimum distance (7) at the time when the minimum distance is zero. We use (7) and write the equation for the minimum velocity of a mechanical object that could cause a fault precisely at the voltage zero crossing:

$$VEL = \frac{d}{dt}\left[\frac{\sqrt{2} \cdot V_{NOM}}{k \cdot E_{MIN}} \cdot \sin(2 \cdot \pi \cdot t \cdot f)\right]_{t=0} \tag{8}$$

where k = 1 for phase-to-phase faults, $k = \sqrt{3}$ for phase-to-ground faults, and f is the system frequency.

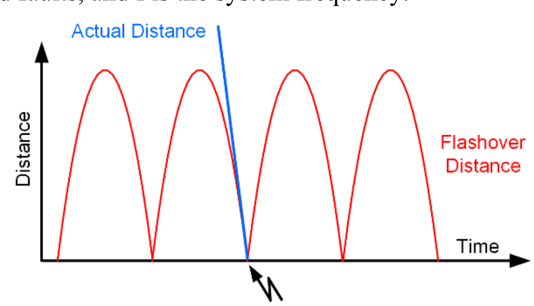


Fig. 8. Actual distance (blue) and flashover distance (red) when a mechanical object causing a fault moves quickly.

We calculate the derivative in (8) for t = 0 and obtain the minimum velocity of a mechanical object that could cause a fault at the voltage zero crossing:

$$\mathrm{VEL} = 2 \cdot \sqrt{2} \cdot \pi \cdot \frac{V_{NOM} \cdot f}{k \cdot E_{MIN}} \quad (9)$$

We verify the units of (9):

$$\frac{V \cdot Hz}{V/m} = \frac{1/s}{1/m} = m/s \quad (10)$$

Fig. 9 shows the minimum velocity in mph for a 60 Hz system and a range of system nominal voltages. Fig. 10 shows the minimum velocity in km/h for a 50 Hz system and a range of system nominal voltages. Both figures assume $E_{MIN}$ = 3 kV/mm.

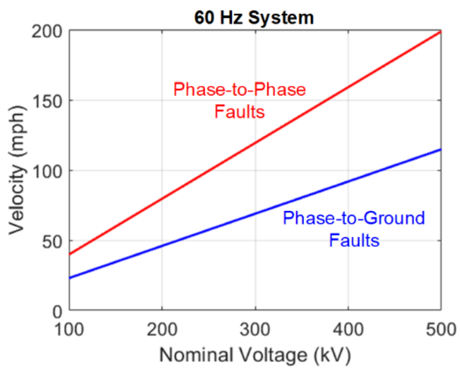


Fig. 9. Minimum velocity of a mechanical object that could potentially cause a voltage zero-crossing fault in a 60 Hz system.

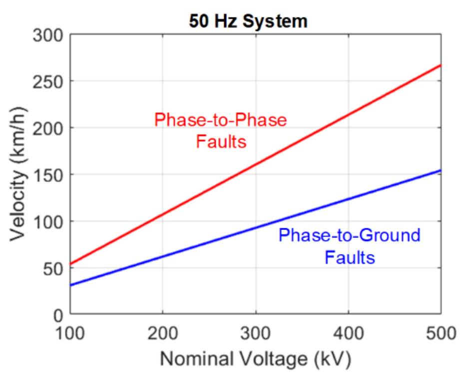


Fig. 10. Minimum velocity of a mechanical object that could potentially cause a voltage zero-crossing fault in a 50 Hz system.

Our calculations show that – at least in theory – a fast object that is timed relative to the voltage zero crossing can cause a fault when the voltage is at zero. However, the minimum velocity required to do so in a 60 Hz system is at the level between about 25 mph for a 110 kV line and a phase-to-ground fault and about 200 mph for a 500 kV line and a phase-to-phase fault.

To further illustrate this discussion, Fig. 11 shows voltage and current waveforms for a fault on a 161 kV line caused by a military aircraft colliding with the line underneath the phase conductors of a long tower span at a river crossing (the conductors were about 75 feet above the ground) [6]. The line included ground wires. However, the fault current shows no zero-sequence component, indicating that the ground wires were not involved in the fault. The fault started as an AB fault, and in 13 ms, it evolved into a symmetrical three-phase fault. The inspection revealed that all three phase conductors were severed.

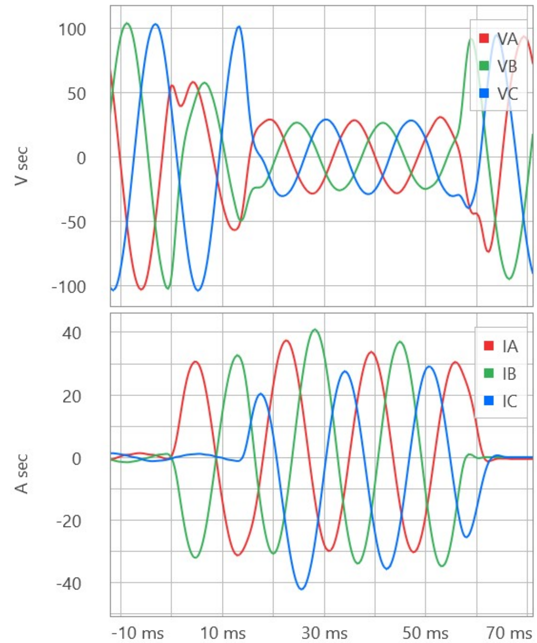


Fig. 11. Relay voltages and currents for a fault caused by an airplane.

Fig. 12 shows a picture of the plane's vertical stabilizer. We can see two damaged areas where two phase conductors likely contacted the stabilizer as the plane flew horizontally underneath the power line. The stabilizer first touched (and pulled with it) the lower conductor (the conductors are located vertically on the tower). Likely, when the stabilizer came closer to the upper conductor, a flashover occurred, causing a phase-to-phase fault (AB fault). Because the fault was metallic (limited arcing) and all three conductors were severed, it is likely that the fault evolved to a three-phase fault because of the further mechanical cause (the plane's body contacted the C-phase conductor).

Fig. 12. Vertical stabilizer showing damaged areas where the stabilizer contacted the power conductors [6] (image used by permission).

The stall speed of the involved aircraft is about 130 knots (150 mph). Therefore, the vertical stabilizer, which acted as a shorting bar, traveled at the velocity of at least three times the minimum velocity required to cause a phase-to-phase fault at the voltage zero crossing on a 161 kV line (64 mph in Fig. 9). Still, the AB fault occurred when the $V_{AB}$ voltage was almost at its peak. The C-phase faulted when the $V_{BC}$ and $V_{CA}$ voltages were also close to their peaks (see Fig. 13). The oscillography record was captured at 20 samples per cycle (s/c). The voltage traces are delayed compared to the actual voltage by about 1 ms (the effect of an antialiasing filter group delay when sampling and storing data at 20 s/c). Therefore, the faults (AB and ABC) happened when the phase-to-phase voltages were at their peaks.

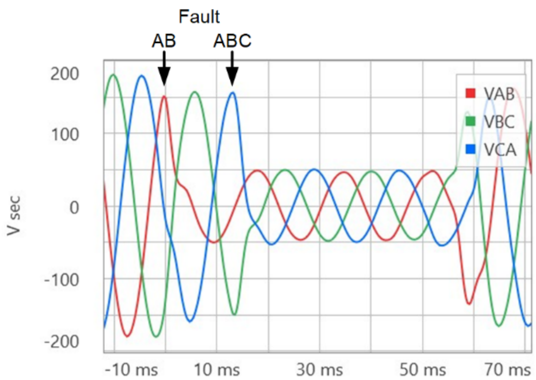


Fig. 13. Phase-to-phase voltages for the fault in Fig. 11.

This case illustrates that even when the mechanical object responsible for a fault travels fast, it is unlikely to cause a fault at the voltage zero crossing. In order to short circuit the conductors when the voltage difference is zero, the object not only needs to travel fast enough to avoid flashing over when the voltage is near its peak but it also needs to bring the two conductors together at a very specific time. Fig. 14 illustrates this requirement by showing the ideal trajectory that would result in a fault at the voltage zero crossing and alternate trajectories that are 1 ms too early and 1 ms too late.

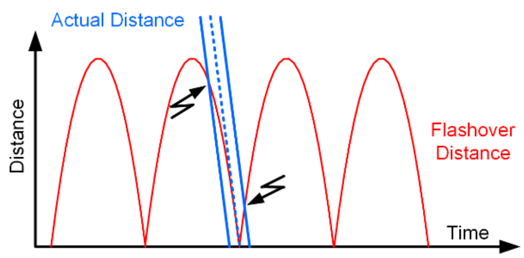


Fig. 14. Actual distance (blue) and flashover distance (red) when a mechanical object causing a fault moves fast but arrives 1 ms too early or 1 ms too late to hit the zero-crossing mark.

Fig. 14 explains why faults are unlikely to occur at the voltage zero crossing even if they are caused by fast-moving metallic objects, such as the vertical stabilizer of a military aircraft.

### C. *Faults Caused by Lightning Strikes*

When a lightning strike causes a fault, the voltage across the insulation at the fault inception time is greatly affected by the lightning strike, and therefore it is not related to the pre-fault voltage across the insulation. As a result, faults caused by lightning strikes can happen at any point on wave.

When lightning strikes the line ground wire or a tower, it may increase the potential of the tower with respect to remote ground for a very brief time (tens of microseconds). The tower potential shifts because of the tower footing resistance, especially at the very high frequencies that are relevant for the short-lived lightning strike. The voltage across the insulation is the difference between the pre-fault line-to-remote-ground system voltage and the tower-to-remote-ground voltage induced by the strike. The voltage across the insulation can be large even if the line-to-remote-ground system voltage is at or near zero. As a result, a flashover can occur at any fault point on wave, including the zero crossing. This phenomenon is referred to as a back flashover because, in a way, it is the high tower potential flashing over to the "low" conductor potential.

The lightning strike lasts for just a few tens of microseconds, and the tower potential returns to zero shortly after the flashover. Once the arc is initiated, however, the fault continues. If the strike occurred at the voltage zero crossing, it may appear as if the fault occurred when the voltage across the insulation was zero. This is not so, however. The voltage across the insulation was momentarily large because of the shift in the potential of the tower respective to remote ground.

Because of the sharp and significant changes across the insulation, the fault launches TWs even if it happens at the voltage zero crossing. Consider the fault case in Fig. 15.

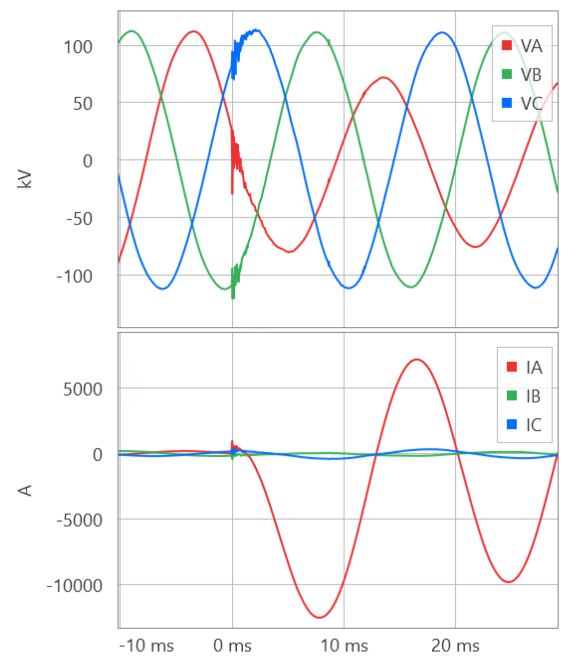


Fig. 15. Voltages and currents for a fault confirmed to be caused by a lightning strike.

By using a lightning strike detection and geolocation database, the utility confirmed that a lightning strike occurred at the time and location of the fault, as recorded by protective relay [5]. The fault type is AG and the pre-fault $V_A$ voltage at the terminal was only about 24 kV. The line is lightly loaded and the voltage at the fault location was also close to 24 kV. The highest current TW that can be launched by a fault when the voltage changes by 24 kV is 24 kV / 350 Ω = 68.6 A. The termination effect can double that value, and the relay will measure a current TW not higher than 137 A. Fig. 16, however, shows the A-phase current TW of about 582 A.

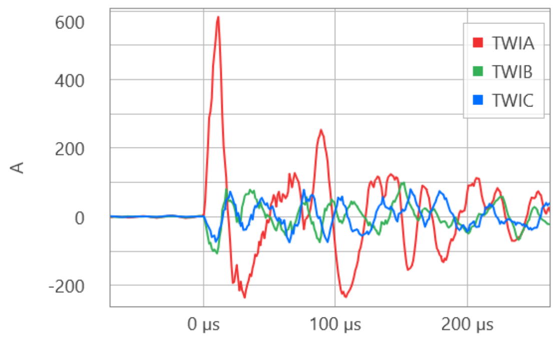


Fig. 16. Current TWs for the fault in Fig. 15.

If we continue to assume the termination effect doubled the measured current TW, we conclude that the fault launched a current TW of about 582 / 2 = 291 A. This current TW level corresponds in turn to the change in voltage of about 291 A · 350 Ω = 102 kV. If the termination effect increased the measured current TWs by less than 100 percent, then the voltage change would have to be larger than 102 kV. Note that the peak pre-fault voltage is only about 112 kV.

This simple calculation:

- Proves that the change in voltage that launched current TWs was much higher than the pre-fault voltage.
- Shows that the current TWs are much higher than if they were launched by the change in voltage corresponding to the small point-on-wave angle.

We conclude that back flashovers can cause faults at the voltage zero crossing, but those faults still launch considerable current TWs because the fault is effectively caused by an external voltage source that is much higher than the low pre-fault voltage across the insulation.

## VI. Faults During Power Swings

A power swing that progresses when a fault occurs has limited impact on TWs and incremental quantities. Of course, the voltage at the fault location changes as the swing progresses. Therefore, the swing has an impact on the level of TWs and incremental quantities that the fault generates. Overall, however, transient-based line protection is a good solution to cover faults that occur during power swings.

Relays [4] and [5] derive the incremental quantities by subtracting one-cycle-old values. This method improves dependability compared to obtaining incremental quantities through high-pass filtering, but it also allows a fast power swing to create standing incremental quantities. During a fast power swing, the one-cycle-old values differ from the present values because the voltage and current signals oscillate in magnitude and phase/frequency. When the two (present and one-cycle-old) values are subtracted, a small incremental signal appears.

Additionally, to select the one-cycle-old values, the relay measures frequency. The measured frequency lags the real frequency slightly during fast power swings. As a result, the relay subtracts values that are shifted by close to one cycle instead of values that are shifted by exactly one cycle. This slight error increases the level of the standing incremental signals during a fast power swing.

When a fault occurs under these circumstances, the standing incremental-signal component superimposes on the fault-generated incremental-signal component. This may cause security and dependability issues if the standing component is as large or larger than the fault-induced component.

Relays [4] and [5] use an arming logic to supervise the transient-based protection elements and schemes (see Subsection III.A). The arming logic monitors the level of the standing incremental quantities and disarms the transient-based protection if the standing incremental quantities become too large. The faster the power swing progresses, the higher the level of the standing incremental quantities and the sooner the arming logic disarms the transient-based protection. The arming logic stays armed during stable swings and during relatively slow unstable swings. As a result, relays [4] and [5] provide transient-based protection during power swings until the swing becomes unstable and slips several poles. Out of precaution, when the swing becomes unstable and the system starts slipping poles relatively quickly, not only are the incremental-quantity-based protection elements and schemes disarmed but also the TW-based protection elements and schemes.

## VII. Dependability of Incremental-Quantity-Based Protection Elements

The incremental-quantity-based protection elements (TD32 and TD21) in the transient-based relays [4] and [5] are dependable. The fault point on wave, line length, termination effects, and so on have either no impact or very little impact on their operation.

### *A. TD32 Directional Element*

The TD32 element is very dependable and sensitive, making the TD32-based POTT scheme the workhorse of transient-based line protection. The element can only miss faults if they occur between a quarter and two cycles after an unrelated transient or if the system was not in a balanced steady state prior to the fault, such as during fast unstable power swings. Otherwise, the element responds to faults regardless of the following factors:

- Line length, including extremely short lines and long series-compensated lines.
- Fault resistance, including ground faults with high resistance.
- Fault point on wave.
- Surge termination impedances and system strength (SIR).

Relays [4] and [5] provide a pickup threshold to supervise the operation of the POTT scheme when initiated by the TD32 element. You can use this setting to intentionally limit the sensitivity of the TD32-based POTT scheme.

### B. TD21 Distance Element

The TD21 element is dependable with the following limitations:

- It operates only in relatively strong systems (the SIR is below about 2.5). The element is secure under all scenarios, and it does not need to be disabled when the system becomes weak under certain contingencies.
- It may lose some dependability for faults close to the reach point depending on the fault point on wave.
- It operates dependably for metallic faults. As is the case for any distance element, it does not operate for resistive faults when the infeed effect is significant.
- It is less dependable on series-compensated lines than on noncompensated lines because it uses a more conservative restraining logic.

Overall, you can count on the TD21 element for close-in metallic faults in relatively strong systems. The TD21 element is not a solution for line protection near weak sources, such as wind and solar farms.

## VIII. Dependability of Traveling-Wave Protection Elements and Schemes

The TW-based protection elements and schemes (the TW32 element and the TW87 scheme) in the transient-based relays [4] and [5] are dependable but not perfectly dependable. The following factors may impact their operation (listed in order of importance).

### A. Termination Impedance

Voltage transformers (VTs) are very poor sensors for measuring voltage TWs. Therefore, relays [4] and [5] use mostly current TWs. A CT measures the total current TWs, i.e., the incident TW arriving from the fault superimposed on the TW reflected from the terminal. Compared to the incident TW, a TW that reflects from a high termination impedance is opposite in polarity and of equal magnitude, resulting in a total current TW of zero. Therefore, relays cannot measure current TWs if the line is terminated on a high surge impedance. The term surge impedance refers to the impedance at very high frequencies, not the impedance at the power frequency. A high surge impedance occurs when the line is terminated exclusively on a power transformer, autotransformer, or a current-limiting reactor. A similar concern (inability to measure current TWs) occurs in applications when an inductive load – such as an interposing transformer or an electromechanical relay – is connected in series with the current inputs of a TW-based relay.

Reference [7] explains how to use a TW-based overcurrent element (TW50) to protect lines terminated on transformers.

Typically, the bus capacitance, other lines connected to the same bus as the protected line, and capacitor banks provide a low surge impedance, allowing the application of TW-based elements and schemes. A low surge impedance has an additional benefit of amplifying the measured current TWs compared to the incident current TW and increasing the current TW signal level by as much as 100 percent.

### B. Ringing in Secondary Circuits

VTs do not reproduce voltage TWs faithfully. Practically, we can only count on measuring the polarity of the first voltage TW. We cannot count on measuring the arrival time or magnitude, and we cannot count on identifying any subsequent voltage TWs. As a result, the TW32 element is the only element in relays [4] and [5] that uses voltage TWs. It uses only the initial voltage TW polarity.

Some VTs may have a very poor frequency response, and the TW32 element may fail to assert. Because a VT cannot invert the first voltage TW polarity, the TW32 element is secure, but it may lose dependability. The reduced dependability of the TW32 element is a secondary factor, however. The TW32 element accelerates the directional decision by only 1 to 1.5 ms compared to the very dependable TD32 element.

In general, CTs have sufficient fidelity to allow using currents for TW-based protection. However, in a small percentage of applications, we see heavy ringing in the secondary current circuits. When this ringing reaches a level that jeopardizes proper measurement of the current TWs, relays [4] and [5] block the TW-based protection. These relays incorporate an electromagnetic interference (EMI) logic that monitors the installation for standing EMI noise.

You can expect excessive ringing in the current signals when using CTs with unshielded secondary windings and long unshielded control cables that run parallel to the substation buses. Typically, the factors that cause ringing do not change over time. Therefore, either a given application will be well suited for TW-based protection or – in a small percentage of applications – you will realize there is a dependability problem after the first fault you analyze.

### C. Fault Resistance

Metallic faults cause the highest possible change in voltage at the fault location and launch the highest possible current TWs. Fault resistance decreases the voltage change and the current TW level, especially when combined with the remote infeed effect, which supports the voltage at the fault location and limits the voltage change at the fault location. As a result, the TW32 element and the TW87 scheme have a limit in terms of the fault resistance they can cover. However, because relays [4] and [5] include a high-accuracy data acquisition system, that limit is not very stringent, and the TW-based protection works for resistive faults unless the fault resistance becomes very high.

### D. Line Length and Proximity Effects

TWs propagate in overhead lines at nearly the speed of light. When they travel and reflect at discontinuities that are located just a few miles away, these TWs arrive in quick succession. Any TW-based relay has a finite temporal resolution in terms of identifying one TW from a successive TW. Two or more TWs that arrive in quick succession may blend and defeat the "TW-finding" logic in a relay. As a result, the TW-based protection may lose dependability when the line fault is located very close to a line terminal or a line tap (if present).

Reference [8] provides an in-depth analysis of issues related to terminations, line length, and other similar factors.

Relays [4] and [5] do not allow TW32 applications on lines that are shorter than 10 miles. The TW87 scheme can be applied to lines of any length except it may be less dependable for faults very close (0.5 to 1 mi) to either line terminal. When the line is long, the decreased dependability for the 1 to 2 mi section closest to the line terminals is negligible. When the line is very short, the 1 to 2 mi section is a larger fraction of the total line length.

Overall, TW-based line protection is dependable, but it requires backup in the form of distance elements, a directional comparison scheme, or a line current differential scheme.

In applications near unconventional sources, transient-based protection elements and schemes can have higher dependability than some traditional protection elements and schemes [2] [3]. Transient-based relays still require backup by using line current differential relays, such as [9], and distance elements suitable for applications near unconventional sources [10].

## IX. Conclusions

The transient-based line protection elements and schemes incorporated in relays [4] and [5] have demonstrated excellent speed and security over five years of deployment in the field. Today, these relays are wired to trip and routinely operate in just a few milliseconds, resulting in fault clearing times of 1.5 to 2 power cycles when two-cycle circuit breakers are installed.

The field experience allows us to quantify dependability of the transient-based line protection elements and schemes, considering practical factors such as the fault point on wave, termination impedances, SIR, fault resistance, and the fidelity of the voltage and current transformers.

Incremental-quantity-based protection (the TD32 element in a POTT scheme and the TD21 element) is very dependable. The TD32-based POTT scheme is the workhorse of transient-based line protection. The TD21 element is fast and secure. It is dependable for metallic faults in applications in strong systems.

TW-based protection (the TW32 element and the TW87 scheme) is relatively dependable and is impacted mostly by the poor quality of the current measurement chain (CTs with unshielded secondary windings and unshielded control cables that run parallel to high voltage conductors) and by very high fault resistance.

We have analyzed the impact of the fault point on wave and concluded that it is not a limiting factor for dependability of transient-based line protection, including TW-based elements and schemes. Our findings in this respect can be used for more realistic testing of transient-based protection elements and schemes in relation to the fault inception angle.

Transient-based line protection elements and schemes can be more dependable than other forms of protection in systems with unconventional sources and during power swings. When backed up by line current differential relays, transient-based relays are an excellent choice for line protection, considering the increasing penetration of unconventional sources with low fault currents and low inertia.

## X. Acknowledgments

The author acknowledges Russell Patterson, Gary Kobet, Joshua Hughes, and Eric Rosenberger for providing the field examples in Section V.

## XI. References


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## XII. Biographies

**Bogdan Kasztenny** has over 30 years of experience in power system protection and control. In his decade-long academic career (1989–1999), Dr. Kasztenny taught power system and digital signal processing courses at several universities and conducted applied research for several relay manufacturers. 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, an IET 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 60 U.S. patents, and is an associate editor of the *IEEE Transactions on Power Delivery*.


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