Time-Domain Technology – Benefits to Protection, Control, and Monitoring of Power Systems

Ricardo Abboud and David Dolezilek
Schweitzer Engineering Laboratories, Inc.

Revised edition with current title released November 2017

Originally presented at the
International Conference and Exhibition – Relay Protection and Automation for Electric Power Systems, April 2017,
under the title "Case Study of Time-Domain Protection: Field-Proven Benefits to Protection, Control, and Monitoring"

Time-Domain Technology – Benefits to Protection, Control, and Monitoring of Power Systems

Ricardo Abboud and David Dolezilek, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—Power system engineers burdened with the ongoing task of increasing power system reliability are constantly working to improve protective relay safety, speed, security, and dependability. New time-domain line protection operating principles provide ultra-high-speed tripping and allow for traveling-wave fault location (TWFL), which can detect faults and trip lines in just milliseconds. This new fault-detection method provides numerous power system benefits and considerably reduces fault-clearing times.**

I. Introduction

In the never-ending search to improve the behavior and benefits of power system protection, engineers are constantly improving protective relay safety, speed, security, and dependability. Modern relays are largely phasor-based, which means they can experience delays related to the full-cycle observation window that is required for phasor estimation accuracy [1]. Transients that result from faults occurring on overhead transmission lines travel at light-speed and spread across the power line as traveling waves [2]. New time-domain line protection operating principles that use incremental quantities and these traveling waves provide ultra-high-speed tripping, which brings several benefits to the power system and allows for traveling-wave fault location (TWFL). Ultra-high-speed line protection is now a reality—it performs fault detection and line trips in just a few milliseconds. This paper illustrates the benefits of using time-domain principles in a communications-assisted tripping scheme. These principles are based on incremental-quantity (TD32) and traveling-wave (TW32) directional elements working in a permissive overreaching scheme, a traveling-wave differential (TW87) element, and an incremental-quantity distance (TD21) element. All of these elements are ultra-high-speed protection elements and contribute to a considerable reduction in fault-clearing times [3]. Some of the benefits of a fast fault-clearing time include reducing equipment damage, increasing equipment lifespan, improving power quality (related to the reduction of voltage sags), increasing safety (related to the reduction of arc duration), and increasing power system transient stability (related to the reduction in the kinetic energy stored by the rotor during the acceleration period). Traveling-wave-based protection can also be applied to increase the reliability of protection systems when nonconventional power sources are involved.

Single-end impedance-based fault location is widely used in order to provide guidance to maintenance crews so they can find the faulted section on a transmission line as fast as possible. However, this method is affected by several conditions that can cause fault location inaccuracies, such as zero-sequence mutual coupling, zero-sequence modeling errors, system nonhomogeneity, system infeeds, current transformer saturation, and so on [4]. TWFL is not affected by such conditions and can provide extremely precise information regarding the location of the fault in a few milliseconds. Double-end TWFL uses the traveling wave arrival times at the remote and local terminals to estimate the fault location. Single-end TWFL is challenging to implement but not impossible. Using information from only one terminal, it is possible to determine the fault location based on the time differences between the arrival of the first traveling wave and the arrival of the reflections from the fault [5]. TWFL is an accurate and real-time fault location method that can be applied to control the reclosing scheme in hybrid (or nonhomogeneous) transmission lines, as discussed in the following sections. The power system benefits gained from using TWFL methods and the additional benefits of high sampling rates and traveling-wave monitoring are also presented in this paper.

II. Ultra-High-Speed Line Protection

New research on high-performance line protective relays is contributing to the production of relays that are based on incremental-quantity and traveling-wave elements and that are capable of identifying and clearing faults on transmission lines at ultra-high speeds with security. These incremental-quantity and traveling-wave protection operating principles are referred to as time-domain protection principles [6]. New technologies allow the use of hardware with high sampling rates, large data storage, very fast and powerful processing, and extended communications capabilities, making possible a new generation of time-domain-based protection with improved line protection operating times and fault location [1] [2] [3].

As discussed in [2], the transients generated for a fault on a transmission line are used in TWFL methods to produce very precise information about the location of the fault. These traveling waves are generated by any kind of fault except faults that happen at the zero crossing of the voltage wave. Traveling waves propagate with a constant velocity (close to the speed of light) in the direction of both terminals, as shown in Fig. 1. The traveling wave arrival times at the remote (R) and local (S) terminals depend on the fault location, measured as the distance *m* from Terminal S, and they can be used to precisely identify the fault location.

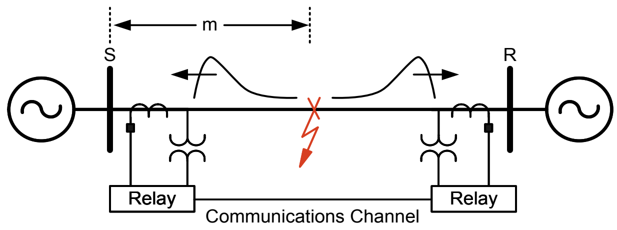

Fig. 1. Traveling waves propagating to Terminals S and R

The use of traveling waves is not limited to locating faults on transmission lines; they can also be used to implement ultra-high-speed line protection with operating times as fast as 1 ms. The propagation time of the traveling waves across a transmission line is the limiting factor [1]. A sampling rate of 1 MHz and specialized filters are applied in the time-domain relay to extract the traveling waves from the raw voltage and current signals in order to provide the operating quantities to the ultra-high-speed line protection elements [6]. The relay has two protection elements (TW32 and TW87) that work based on the traveling waves extracted from the raw signals.

The TW32 element scheme uses phase voltage and current traveling waves to discriminate internal and external faults at each terminal and exchanges this information through a communications channel, as shown in Fig. 1, to implement a permissive overreaching transfer trip (POTT) scheme. The TW32 element determines the fault direction, forward or reverse, by comparing the polarities between the voltage and current traveling waves. In the case of identical polarities, a reverse fault is declared, and in the case of opposite polarities, a forward fault is declared [6].

The TW87 element scheme uses a direct communications channel to compare current traveling waves at both ends of the protected line in order to differentiate between internal and external faults. For an external fault, the arrival times of the first traveling waves measured at both terminals have a time difference that exactly matches the known line propagation time and the waves have opposite polarities. For an internal fault, the first traveling waves at both terminals have the same polarity and have a time difference of less than the traveling-wave line propagation time [6].

III. Benefits of Ultra-High-Speed Line Protection

A. Power Quality Improvement

There are several definitions for power quality. However, from an end user's point of view, bad power quality is associated with any problem manifested in voltage, current, or frequency deviations that can cause failures or misoperations of equipment or processes.

As explained in [7], one of the problems related to poor power quality is voltage sags. A voltage sag is a short-duration decrease (usually between 0.5 and 60 cycles) in voltage magnitude and is usually caused by a short circuit at some point on the power system. A voltage sag is the most important power quality problem affecting many industrial plants, especially those with continuous processes. A voltage sag is not a complete interruption in the supply of power, but the resultant change in voltage can cause the shutdown of the devices deployed in modern industrial plants (e.g., programmable logic controllers, adjustable speed drives, process controllers, and computers). These devices are becoming more sensitive to voltage sags as their complexity increases. Not only are electronic devices affected, but even electromechanical auxiliary relays and contactors applied in motor control centers (MCCs) are sensitive to voltage sags. The motors can stop when these electromechanical devices drop out because of the voltage sag, which can result in the shutdown of an entire process line, causing a production outage that results in severe economic losses [8]. An example of a voltage sag 23 cycles in duration is shown in Fig. 2.

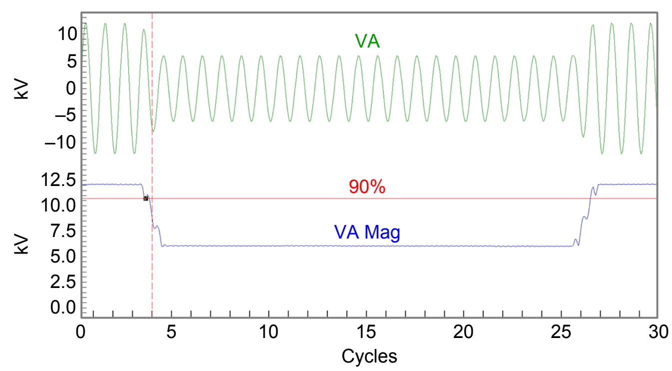

Fig. 2. Example of voltage sag

According to the Electric Power Research Institute (EPRI), voltage sags are the number one cause of power quality problems, representing 92 percent of all distribution and transmission power quality problems in the United States. A voltage sag lasting for a few cycles can result in losses of several million dollars. Potential problems and losses caused by voltage sags include costs to repair damaged equipment, costs of keeping large inventories, bad product quality perceived by manufacturer customers (which affects company reputations), complaints filed by utility customers experiencing losses in business, rework and loss of materials, loss of labor efficiency, extra costs from overtime to recover from plant shutdowns, and costs from penalties due to industrial plant shipping delays [8].

One way to reduce the effects and related economic losses of voltage sags that originate from short circuits in the power system is to reduce the sag duration; i.e., reduce the time to clear the fault (or short circuit). This can be accomplished with the application of ultra-high-speed line protection.

B. Power System Stability Improvement

A power system consists of generators, transmission lines, transformers, shunt reactors, capacitor banks, and so on. All the generators must operate in synchronism and must maintain that synchronism in all operating conditions to ensure power system continuity [9].

In a lossless system, the active power transfer P depends on the voltage magnitudes V_S and V_R, the series reactance X, and the angle between the voltages (the power angle) δ, as shown in Fig. 3 [10].

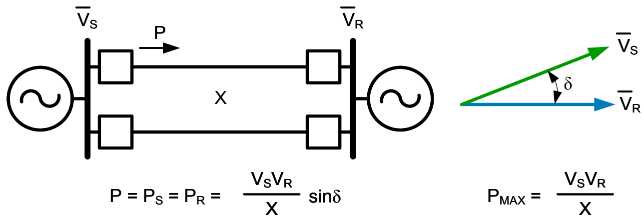

Fig. 3. Active power transfer

The transfer power P is a sine function of the power angle δ. The power system is operated at a given angle δ_0 corresponding to a transfer power P_0, as shown in Fig. 4. The load can be increased in small steps until the tip of the power curve is reached. An increase of the transfer power P follows each increase in the load demand power. Beyond the curve maximum ($\delta > 90°$), a load increase causes a decrease in the transfer power and the system loses synchronism. P_{MAX} represents the steady-state stability limit for an ideal lossless system. This is the maximum power that the power system can transfer in a steady state [10].

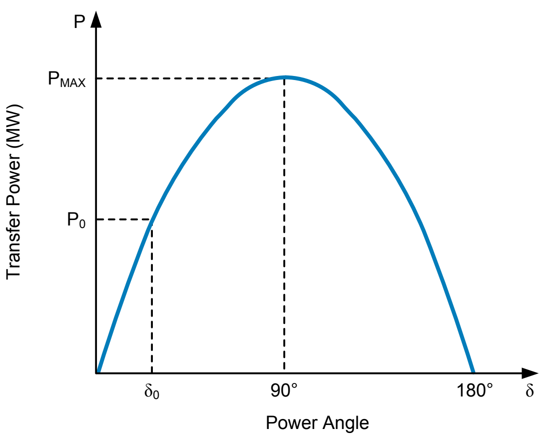

Fig. 4. Power transfer capability

Stability is defined as the power system's ability to resume its normal, stable operating conditions after a disturbance [9]. Short circuits are disturbances that can affect the power system's stability. Upon fault inception, the series reactance X suddenly increases and the power transfer capability curve changes from the prefault curve to the fault curve, as shown in Fig. 5. The fault reduces the system power transfer capability. When a protection scheme operates and takes the faulted line out of service, the post-fault power system transfer capability is greater than the fault transfer capability during the fault, but it is less than the prefault transfer capability.

Fig. 5 depicts the equal-area criteria used to assess transient stability in two-machine power systems. Fig. 5a depicts an unstable system ($A_1 > A_2$). Slow fault clearing causes a large accelerating area A_1, which cannot be compensated for by a corresponding decelerating area A_2 [10].

One way to keep the system stable in the case of Fig. 5a is to reduce the prefault power transfer P_0. However, this approach limits the load that can be connected to the power system, so it cannot be considered a valid solution. Another way is to reduce the reactance shown in Fig. 3, which can be accomplished by constructing new transmission lines (which has a high cost) or by deploying series compensation. A third option is to clear the fault faster in order to reduce the accelerating area A_1. Time-domain relays provide fast fault-clearing time, which reduces the accelerating area A_1 and makes the system stable ($A_1 = A_2$) for the same fault, as shown in Fig. 5b. This option does not limit the load on the power system and has a lower cost than constructing new transmission lines, so this is a good reason to apply fast relays and breakers in power systems.

Power system stability is one of the main reasons for pursuing faster transmission line protection. Clearing faults faster than the critical fault-clearing time ensures the stability of power systems and avoids blackouts [10]. Also, as mentioned previously, faster fault clearing increases the amount of power that can be transferred.

Faults are typically cleared in 3 to 4 cycles, considering a typical operating time of 1 to 1.5 cycles (16.67 to 25 ms in a 60 Hz system) for the protective relays and a typical time of 1.5 to 3 cycles (25 to 50 ms in a 60 Hz system) for the breakers to interrupt the current. Applying time-domain relays makes it possible to reduce the fault-clearing time, achieving operating times of 1 to 3 ms. As already mentioned, every millisecond subtracted from the fault-clearing time allows the system to transfer more prefault power. Reference [11] explains that on a line in a particular application, a 1-cycle reduction in fault-clearing time increased the stable power transfer amount by 250 MW, resulting in an additional 15 MW per millisecond.

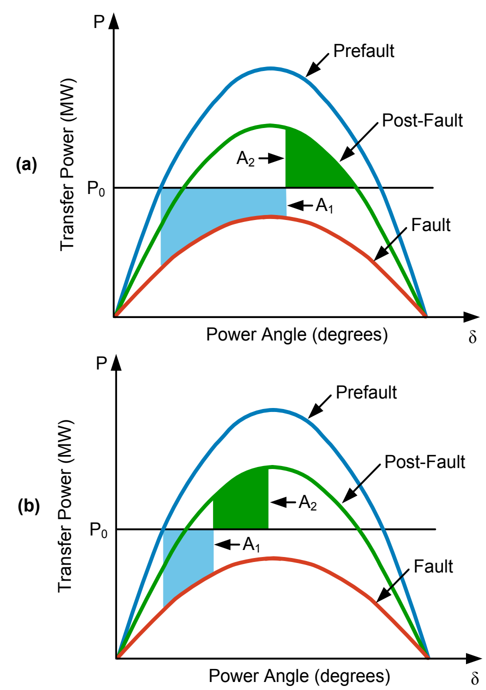

Fig. 5. Power system transfer capability and the equal-area criteria in (a) an unstable system and (b) a stable system

C. *Other Benefits*

The transformer is one of the most critical assets in a transmission substation. Repairing or replacing a transformer is a very expensive, difficult, and time-consuming task, so it is very important to keep the transformer healthy. According to [12], the magnitude and duration of through faults are the dominant causes of accelerated mechanical and thermal wear on transformers. Fig. 6 shows a one-line diagram of a typical through fault event that could occur on a transformer because of an external fault.

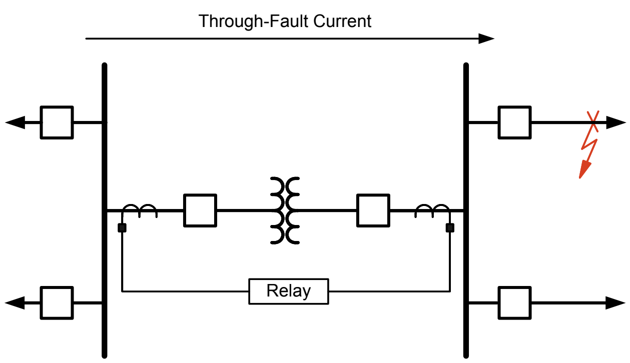

Fig. 6. One-line diagram of a typical through fault event

A transformer is exposed to hundreds of through faults during its operating lifetime, and each through fault has a negative impact on the transformer's life. At a low fault-current magnitude close to the transformer overload level, the thermal stress is more significant than the mechanical stress. At a high fault-current magnitude, the mechanical stress is more significant than the thermal stress and imparts mechanical force on the transformer winding in both the horizontal and vertical directions. A severe through fault can cause a winding to expand horizontally and vertically. When a winding expands horizontally, it can experience mechanical damage and also cause damage to adjacent windings. A vertical force tends to loosen the winding wedges. Therefore, clearing a through fault as fast as possible is key to keeping the transformer healthy, reducing thermal and mechanical wear, and increasing the transformer's life. Faster protection also enhances public and utility personnel safety, limits equipment wear, reduces the probability of internal faults in transformers and generators, increases the total lifespan of equipment, and reduces property damage.

IV. TWFL Real-World Application

Fast and precise fault location information is critical for the operation and maintenance of electric transmission systems. Knowing the precise fault location reduces the costs of operating and maintaining transmission lines by avoiding long and expensive inspection work on the lines to locate the faulted section. It also allows repairs and transmission line restoration to be carried out quickly, reducing economic losses resulting from the unavailability of the transmission line.

As previously mentioned, single-end impedance-based fault location is a common method used to help maintenance crews find faults on transmission lines, but it is susceptible to inaccuracies [4]. TWFL, on the other hand, does not suffer from these inaccuracies and can therefore provide extremely precise information [2]. Even for series-compensated lines, the fault location is accurate regardless of the level of compensation and the status of the series compensation.

When done correctly, TWFL drastically reduces the cost of identifying the location in need of repair compared with the cost of traditional methods to do the same. Therefore, it is possible for the installation of a TWFL system to be less expensive than the costs it saves during its first use.

The example application discussed in this section has a hybrid or nonhomogeneous transmission line, which is a line that has an overhead section and at least one other section that can be made of either underwater or underground cable. Usually, the autoreclosing element is not enabled for hybrid transmission lines because if the fault is in the underwater or underground cable, then the line cannot be reenergized without repairing the faulted section of the cable. This is a constraint on the operation of such transmission lines. However, if the fault can be located very precisely and in real time, the autoreclosing element can be enabled and dynamically controlled by the fault-location element. For example, if the fault is located in the overhead section, then the autoreclosing element is released, but if the fault is located in the underground or underwater cable, then the autoreclosing element is blocked.

Hybrid transmission lines have added complexity that makes fault location a difficult task. Even the TWFL method is not able to perform properly for this type of line if the intention is to have the fault location in real time. This is because the traveling wave has a different propagation velocity in each segment of the line. The traveling wave propagates much faster in the overhead section compared with the underground or underwater sections. However, modern time-domain relays incorporate an enhanced TWFL element that is able to locate faults on hybrid transmission lines. It is possible to configure the propagation time for up to five different segments, so the TWFL algorithm compensates automatically for the different time propagation in each segment and reports the fault location very precisely and quickly (in a few milliseconds).

An example real-world application of this enhanced TWFL method is shown in Fig. 7. In this application, the hybrid transmission line consists of three different sections: a 45 km overhead section, a 1.5 km underwater section, and a 4.5 km underground section. In the past, it was necessary to install directional relays at each transition point in order to identify the faulted section. This approach has several drawbacks, such as the extra cost to install the directional relays at the transition points (which are usually located in remote places), the extra cost to maintain the directional relays, and the increased systemic failure rate due to the extra devices. On the other hand, the enhanced TWFL method can precisely locate faults on hybrid transmission lines, which makes the task of locating the faults easier, more economical, and more reliable.

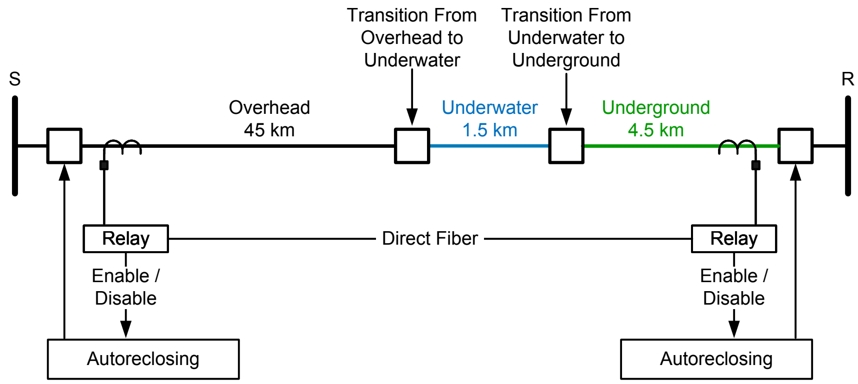

Fig. 7. TWFL in a real-world hybrid transmission line

Locating faults precisely and in real time on hybrid lines enables the power system to cancel reclosing for faults on underground or underwater cable sections of a line while still allowing reclosing on overhead sections of the line. This adaptive autoreclose cancel logic can also be applied to cancel reclosing in other situations, such as for faults located where the transmission line crosses densely populated areas or areas susceptible to fire, or for faults near series capacitors, line taps, major highway crossings, and so on. This is a unique function that allows precise and total control of the autoreclose scheme.

V. High-Resolution Oscillography

As previously mentioned, a time-domain relay samples currents and voltages every microsecond (a sampling rate of 1 MHz) in order to extract traveling waves from raw signals and to capture line voltages and currents. It also stores oscillography records according to user-defined triggers.

The time-domain relay time-stamps its high-resolution oscillography records with an accuracy of 100 ns or better in reference to the absolute time if a high-precision IRIG-B time source is connected to it. The oscillography records retrieved from different devices can then be time-aligned and multiple records can be analyzed together. These records can be used to investigate and analyze high-frequency components (such as transient recovery voltage [TRV] and its effects) in voltages and currents throughout the substation or at adjacent substations. TRV can be defined as the voltage appearing across the terminals of the circuit breaker pole after a switching action to interrupt the current [13], as shown in Fig. 8.

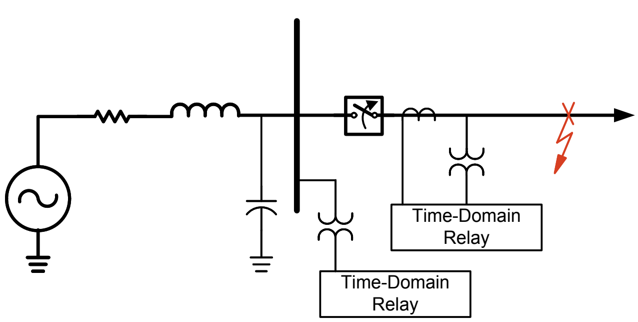

Fig. 8. Circuit breaker switching

TRV has a high amplitude and high frequency, and it can assume very high values within a short period of time, as shown in Fig. 9. This rapid change in voltage can have damaging and undesired effects on the devices in the power system, such as insulation failures and current re ignitions. For instance, TRV can cause stress to the insulation of the circuit breakers, resulting in breakdown and external flashover.

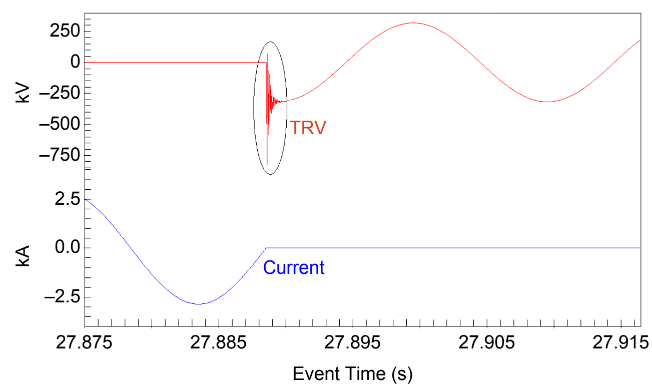

Fig. 9. TRV (50 Hz system)

During the process of interrupting a fault current, an arc is established between the contacts of the circuit breaker. The arc loses conductivity rapidly as the current approaches zero, and in a few microseconds after the current zero crossing, it stops flowing in the circuit and the arc ceases. During this process, the dielectric medium is supposed to regain its insulation property and continue preventing the current flow. The interruption is successful if the interrupting medium can withstand the fast rising of voltage caused by the TRV. However, if the dielectric medium becomes deteriorated because of the TRV, a dielectric breakdown takes place, causing the dielectric medium to become conductive and the current to start flowing again. This phenomenon is called reignition. Fig. 10 shows an example of current reignition where the current flow was reestablished just after the zero crossing. This is a phenomenon that cannot be recorded by protection devices that have traditional sampling rates, so the behavior is considered to be the normal operation of the circuit breaker. Time-domain relays provide waveform captures with high sampling rates, making such phenomena visible.

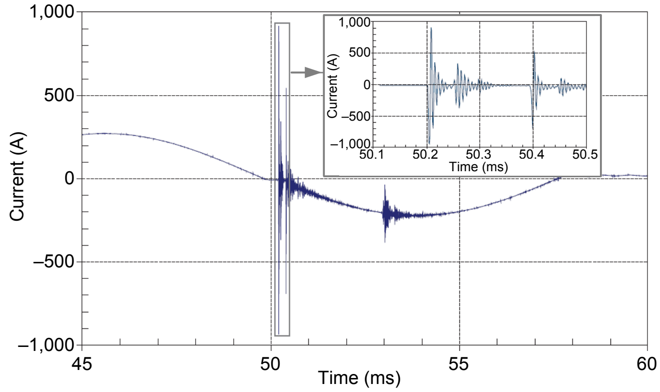

Fig. 10. Current reignition (60 Hz system)

Current reignition due to the breakdown of the dielectric medium in the circuit breaker has harmful effects on the power system (the opposite of the benefits explained in Section III) because of the longer time to clear the fault. In addition, circuit breakers can fail to interrupt the current and explode, causing extensive material damage and compromising power system reliability.

The TRV withstand capability is a specification item for the circuit breakers, and it is provided on their data sheets. It is specified in terms of peak value and the time in microseconds it takes to reach the peak. Applying time-domain relays as depicted in Fig. 8 makes it possible to capture voltages and currents for the circuit breaker operations with a 1 MHz sampling rate to verify that the actual TRV is within the circuit breaker withstand capability or to detect potential problems with the circuit breaker during the interruption process.

High-resolution oscillography records reveal unwanted events in the power system that cannot be seen via other methods. Without this visibility, the events are not recognized as unintended behavior of the primary equipment, no maintenance or repair is scheduled, and the power system continues to operate in a compromised state. With this visibility, the need for performance-based maintenance is identified and can be scheduled to maximize the health and performance of the electric power system.

VI. Nonconventional Power Sources

Nonconventional power sources, such as wind and solar power plants, pose several challenges to protection engineers [14]. One of these challenges is that certain types of controls associated with these sources have complex characteristics that are difficult to accurately represent in the models used to calculate the short-circuit current that these power sources contribute to faults. Also, the magnitude of this current contribution can be very limited because of the type of conversion that is necessary to connect such sources to the power grid. This limited magnitude can cause problems with properly setting the protective relays at the point of interconnection (POI) and the collector feeders [15].

Reference [15] states that the ability to predict and model the sources of fault current is fundamental to properly setting protective relays, but this is very difficult to do for nonconventional power sources such as renewable power plants. However, the traveling waves that are launched from a fault are not dependent on the power sources, so traveling-wave-based protection can be applied and set to work properly even when the power source model is not completely known.

Typically, it is recommended to treat nonconventional power sources as weak and to apply existing protection principles. Figure 3-26 from [15] shows an example of the current contribution from a Type IV wind turbine generator (WTG) for a three-phase fault in the power system. The duration of this type of fault current surge can be in the order of one half cycle (8 ms) and is dictated by the controls associated with the nonconventional resources. Time-domain principles based on incremental quantities and traveling waves offer protection operating times on the order of 2–6 ms, thereby having an actuation time within the current surge window and providing a promising option for line protection on lines interfacing with nonconventional power sources.

VII. Conclusion

Time-domain technology is an emerging area in the protection, monitoring, and control of power systems. This technology provides several benefits, including (but not limited to) the following:

- Improves power system stability and safety.
- Improves power quality.
- Reduces wear and improves lifespan of power system assets.
- Reduces the probability of internal faults on transformers and generators.
- Enhances public and utility personnel safety.
- Reduces property damage.
- Provides the most accurate fault location in real time and is immune to problems that affect impedance-based fault location methods.
- Allows adaptive autoreclosing cancel logic in real time based on the fault location.
- Provides 1 MHz sampling rates, allowing the investigation and analysis of high-frequency phenomena in the power system.
- Improves protection system performance at the POI for nonconventional power sources.

Time-domain technology introduces a totally new era for power system protection. Previous efforts, such as phasor-based digital relays, brought several benefits to the power system, but there was room for improvement. This new time-domain technology provides some of the necessary improvements and increases power system reliability, as discussed in this paper. With the high-resolution oscillography records made possible by time-domain relays, engineers have an unprecedented tool to analyze the phenomena in the power system. It is possible to more closely examine the voltages and currents and see details that have never been seen before. This new power system visibility provides explanations for known problems and makes it possible to identify and explain previously unknown problems.

VIII. References

[1] E. O. Schweitzer, III, B. Kasztenny, A. Guzmán, V. Skendzic, and M. V. Mynam, "Speed of Line Protection – Can We Break Free of Phasor Limitations?," proceedings of the 68th Annual Conference for Protective Relay Engineers, College Station, TX, March 2015.

[2] E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "Locating Faults by the Traveling Waves They Launch," proceedings of the 67th Annual Conference for Protective Relay Engineers, College Station, TX, March 2014.

[3] E. O. Schweitzer, III, B. Kasztenny, and M. V. Mynam, "Performance of Time-Domain Line Protection Elements on Real-World Faults," proceedings of the 69th Annual Conference for Protective Relay Engineers, College Station, TX, April 2016.

[4] K. Zimmerman and D. Costello, "Impedance-Based Fault Location Experience," proceedings of the 58th Annual Conference for Protective Relay Engineers, College Station, TX, April 2005.

[5] E. O. Schweitzer, III, A. Guzmán, M. Mynam, V. Skendzic, and B. Kasztenny, "Accurate Single-End Fault Location and Line-Length Estimation Using Traveling Waves," proceedings of the 13th International Conference on Developments in Power System Protection, Edinburgh, United Kingdom, March 2016.

[6] B. Kasztenny, A. Guzmán, N. Fischer, M. V. Mynam, and D. Taylor, "Practical Setting Considerations for Protective Relays That Use Incremental Quantities and Traveling Waves," proceedings of the 43rd Annual Western Protective Relay Conference, Spokane, WA, October 2016.

[7] Pacific Gas and Electric Company, "Short Duration Voltage Sags Can Cause Disruptions," June 2000. Available: http://www.pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/powerquality/voltagesags.pdf.

[8] V. P. Mali, R. L. Chakrasali, and K. S. Aprameya, "A Technical Investigation of Voltage Sag," American Journal of Engineering Research (AJER), Vol. 4, Issue 10, October 2015, pp. 60–68.

[9] Circuit Globe, "Power System Stability," Available: http://circuitglobe.com/power-system-stability.html.

[10] P. Kundur, Power System Stability and Control. McGraw-Hill, Inc., New York, NY, 1994.

[11] R. B. Eastvedt, "The Need for Ultra-Fast Fault Clearing," proceedings of the 3rd Annual Western Protective Relay Conference, Spokane, WA, October 1976.

[12] IEEE Standard C57.109-1993, IEEE Guide for Liquid-Immersed Transformers Through-Fault-Current Duration.

[13] IEEE Standard C37.011-2011, IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers.

[14] B. Chen, A. Shrestha, F. A. Ituzaro, and N. Fischer, "Addressing Protection Challenges Associated With Type 3 and Type 4 Wind Turbine Generators," proceedings of the 68th Annual Conference for Protective Relay Engineers, College Station, TX, March 2015.

[15] IEEE PES Joint Working Group, "Fault Current Contributions From Wind Plants." Available: http://www.pes-psrc.org/Reports/Fault%20Current%20Contributions%20from%20Wind%20Plants.pdf.

IX. Biographies

Ricardo Abboud received his B.S.E.E. degree in electrical engineering from Universidade Federal de Uberlândia, Brazil, in 1992. In 1993, he joined CPFL Energia as a protection engineer. In 2000, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a field application engineer in Brazil, assisting customers in substation protection and automation. In 2005, he became the field engineering manager, and in 2014, he became the engineering services manager. In 2016, he transferred to Pullman, Washington, and is currently an international technical manager. He is a certified instructor at SEL University and has authored and coauthored several technical papers.

David Dolezilek received his B.S.E.E. from Montana State University and is the international technical director at Schweitzer Engineering Laboratories, Inc. He has experience in electric power protection, integration, automation, communication, control, SCADA, and EMS. He has authored numerous technical papers and continues to research innovative technology affecting the industry. David is a patented inventor and participates in numerous working groups and technical committees. He is a member of the IEEE, the IEEE Reliability Society, CIGRE working groups, and two International Electrotechnical Commission (IEC) technical committees tasked with the global standardization and security of communications networks and systems in substations.

20170712 • TP6795-01