Experience in application of Traveling Wave Fault Detection

Leandro de Marchi Pintos – GE Grid Solutions, Brazil
Carlos Pimentel – GE Grid Solutions, Brazil
Gilmar Krefta – K Consulting, Brazil

1 Introduction

The need to detect and locate faults in transmission lines quickly and accurately has grown significantly in power systems globally, especially in recent decades. Changes in the market model have caused transmission companies to change the way they manage and operate their assets since they are paid not by the transmitted power but by the availability of the line they operate [1]. Thus, protection and fault location systems based on new techniques that are faster and more accurate than the traditional ones, essentially based on phasors, have attracted the interest of several utilities to overcome accuracy limitations of traditional phasor-based approaches. Furthermore, the increasingly significant penetration of renewable generation in the system, whose responses to transients are different from conventional generation systems, have demanded protection systems with faster actuation times than conventional protection relays in order to prevent systemic collapses in large scale [2].

In this context, the use of traveling waves in fault detection both for fault location and protection functions has been studied for application in power transmission systems on a larger scale [3]. The use of fault location systems based on traveling waves, instead of phasors, has been studied for decades, and the first publications date from the 1930s [4]. Since then, several articles and theses have been published, where different types of traveling wave fault locators were classified according to their method of application, and protection systems using this technique were presented.

With the evolution of equipment for protection and control, mainly in the 80s, the first equipment that used the concepts of traveling waves for selectivity and protection began to appear on the market in static relays where the actuation times became less than 5 ms, reaching 2 ms, something by that time impossible using conventional techniques. Furthermore, in the same decade the first traveling wave fault locators appeared, where accuracies in fault locations of hundreds of meters were achieved without significant influence of the length of the transmission lines or electrical parameters, such as reactive compensation [3].

From this study could be seen that is even more remarkable the interest of power system engineers in the application of systems that guarantee more accurate fault location, compared to conventional techniques [1], as well as in protection systems with faster operating times than conventional systems, normally aiming to minimize transient stability problems in the protected electrical system [5].

2 Traveling Wave in Power Systems

The traveling wave phenomena (*TW – Traveling Waves*) on power transmission lines arise from a number of causes, of which the most common are faults, switching operations and lightnings, and the propagation speed of current and voltage waves in overhead power lines is in general close to the speed of light [6]. These traveling waves are typically composed of a wavefront usually with a short rising time and a long falling time [1].

The use of traveling wave detection techniques, mainly for fault location, has been cited in the literature since 1931 [4] and became popular in the following decade after Bewley proposed a graphic method to determine the reflection time instants of the traveling waves, known as Bewley-Lattice diagram [7]. That method allowed a relatively simple analysis of the traveling wave behavior in time and space mainly for fault location where the time is represented vertically and distance horizontally. Figure 1 shows a typical Bewley diagram for a transmission line with the reflections and refractions caused by the traveling waves when a fault is present on a power system.

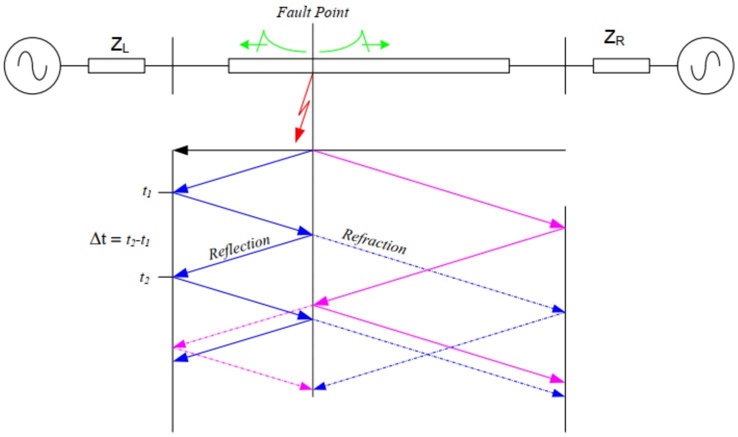

Figure 1 – Bewley-Lattice diagram [6].

Later, in 1951, Lewis classified the traveling wave detection equipment based on its mode of operation as A, B, C and D [8]. Currently, in addition to the methods defined by Lewis, the E method is also used [6].

The fault detection and location methods basically differ in two points: the first is if they have measurement in only one of the substations of the monitored line or in both substations, and the second is if they are passive detectors that are based on the generated traveling waves by the event or have pulse generators for signal injection. Thus, type A is a passive single ended terminal detector, type B is an active single ended detector, type C is an active double ended, and type D is a passive double ended detector [4]. Finally, there is the E method which consists of a single ended detector that is based on the signals generated when a line is re-energized and is used essentially for permanent fault detection [6].

Although studies date back to the 30s, 40s and 50s, applications in protections systems based on traveling waves started only in the late 1970s [9], and since the 2000s there have been several studies to develop and improve the traveling wave detection criteria for protection functions such as distance, directional, differential and for HVDC lines [10]. It is noted in this context that, even though the technique had already been available in protection relays since the late 1970s, there are a very low adoption of this technology in transmission lines in the electrical system that uses traveling wave for protection purposes, and mostly conventional protection relays are applied for this purpose. Traveling wave applications in power systems are mostly related to fault location.

Practical applications of traveling wave fault location, on the other hand, gained strength mainly after the development of synchronized clock technology via GPS (*Global Positioning System*) became available for civil use, as it allowed the TW system to have a unique time base used by the equipment that is generally installed at both ends of the transmission line, that is, far from each other. For double ended fault location methods it is necessary to use the GPS system so that the Traveling Wave records at both ends of the line are synchronized [11].

A more recent study presented in [4] compared different types of traveling wave fault locations applicable in power systems, including GPS based location. Recent studies over the last decade comparing single and double ended impedance fault location methods with traveling wave methods show that errors for a nearly 200 km line can be on the order of kilometers for impedance-based methods and hundreds of meters for methods based on traveling waves [12].

To guide engineers and technicians in the selection of how to perform fault location, the IEEE published the *C37.114 IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines* [6] where several ways to perform the fault location are compared, in which are also listed the advantages and ways of implementation in transmission lines. Finally, the ways to perform the fault location by measuring current or voltage are compared, where it is concluded that, although the initial analysis indicated that the current should be preferred, in practice both ways are applied in fault location and showing good results.

Field experience shows that the accuracy in both methods is similar, making the decision up to manufacturers on how the traveling wave signal is measured in their equipment. To illustrate this relationship, as well as to illustrate the typical behavior of TW signals captured in voltage or current is like, Figures 2 and 3 show an example of a traveling wave signal used for fault location, where Figure 2 shows the signal measured by the secondary voltage of a 500 kV CVT and Figure 3 shows the secondary current measured by the line CT for the same fault.

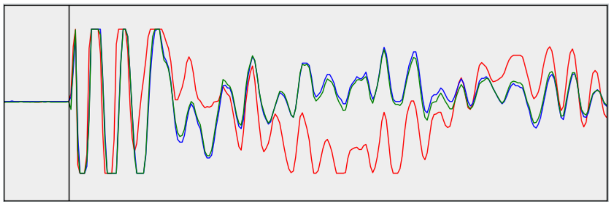

Figure 2 – TW Voltage signal measured during a fault in a 500kV system.

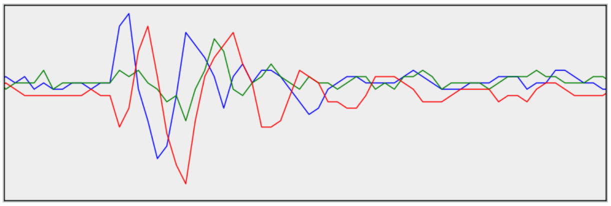

Figure 3 – TW Current signal measured during a fault in a 500kV system.

3 Considerations in the use of Traveling Wave for Power Systems application

Given the intrinsic characteristics of fault location by traveling waves, the assertiveness of its application is established when it provides better fault location accuracy in relation to conventional impedance methods. For short alternating current lines (up to 80 km), for long lines (greater than 240 km), as well as for applications in mixed lines and HVDC lines, the results obtained over time show that its applicability is positive in terms of accurate fault location.

Added to this benefit is the fact that the observed accuracy has little or no relationship with the length of the line, power flow, series compensation or usage of reactors in the busbar or the transmission line. It is noted, on the other hand, that the complexity of determining the fault location when there are elements of compensation, medium or high impedance faults, as well as faults related to lightnings, is greater compared to low impedance faults or faults in uncompensated lines.

In order to locate a fault with the traveling wave method, it is necessary that the system accurately captures the desired signals. Single ended locators must be able to distinguish the wavefronts and reflections from the signals of interest, as well as Double ended locators must distinguish wavefronts when a fault occurs. Traveling wave signals have different characteristics depending on the type and impedance of the fault and are captured differently in HVAC and HVDC systems.

The behavior of traveling wave signals, in general, summarizes the result of the location system: a fault location system is perceived as accurate when, in front of different fault scenarios, it remains accurate in the location within the expected range by the technology, of a few hundred meters, even in situations where the wavefront is low or barely perceptible against the captured noise. High impedance faults, faults with slow wavefront rise, faults caused by lightning or transmission lines in circuits with radial characteristics are examples of situations in which locators can suffer a negative influence on fault location.

However, it is noted that even the fault location accuracy, once the wavefront is accurately determined, is not significantly impacted by factors such as fault impedance or line compensation, the difficulty in determining the wavefront is greater in these situations when compared with the location of low impedance faults. Thus, the accuracy in fault location, whether performed manually or by automatic algorithms, is generally negatively impacted mainly by the impedance of the fault if the operator has not been properly trained or the algorithm used by the fault locator software does not have the necessary robustness for field applications.

To illustrate these differences, the following figures show several TW records captured by traveling wave fault locator recorders for lines with voltages above 220 kV and whose signals are measured by secondary voltage of inductive voltage transformers (IVT) and capacitive voltage transformers (CVT).

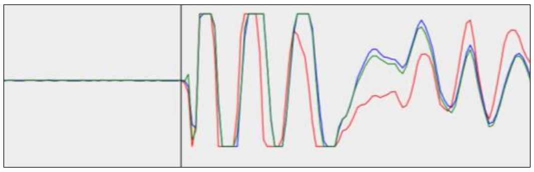

Figure 4 – Example of TW signal measured by a CVT for low impedance fault.

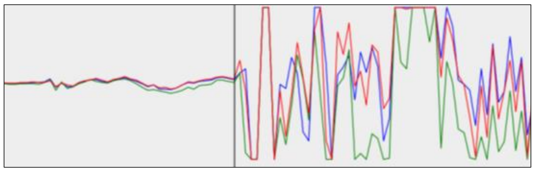

Figure 5 – Example of TW signal measured by a CVT for low impedance fault in a compensated line.

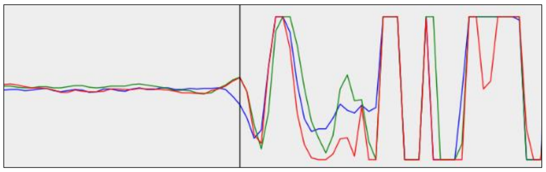

Figure 6 – Example of TW signal measured by a IVT for low impedance fault.

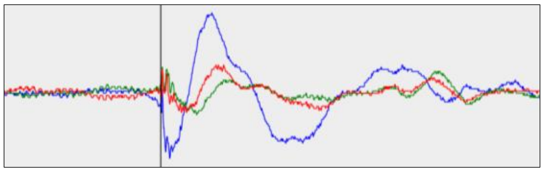

Figure 7 – Example of TW signal measured by a CVT for medium impedance fault.

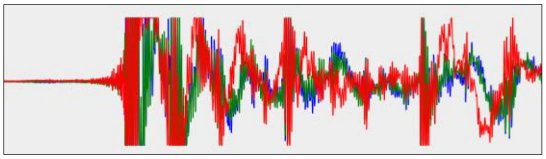

Figure 8 – Example of TW signal measured by a CVT for a lightning strike in a line with reactors.

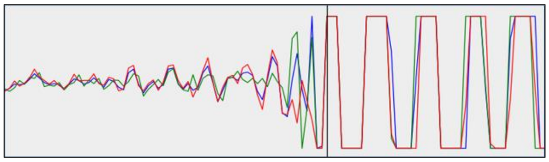

Figure 9 – Wavefront detail of Figure 8.

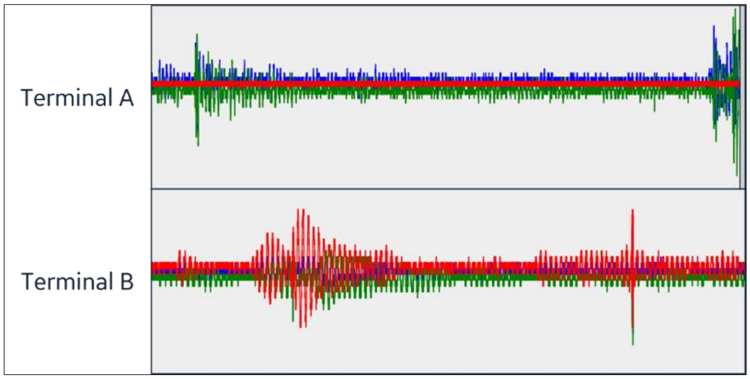

Figure 10 – Traveling wave signals in both terminals of a radial transmission line during a fault, measured by an IVT.

For faults with high or very high impedance, as in cases involving faults with trees, the level of the signal to be captured from the wavefront, in general, is superimposed by noise related to the fault, but the noise is not interesting to the fault locator. In these situations, the locator must be able to distinguish the signals of interest from the measured noises. Figure 11 shows a typical example of a high impedance fault with the details of the correct point to be used by the fault locator and the time reference range of the record in the different time scales used.

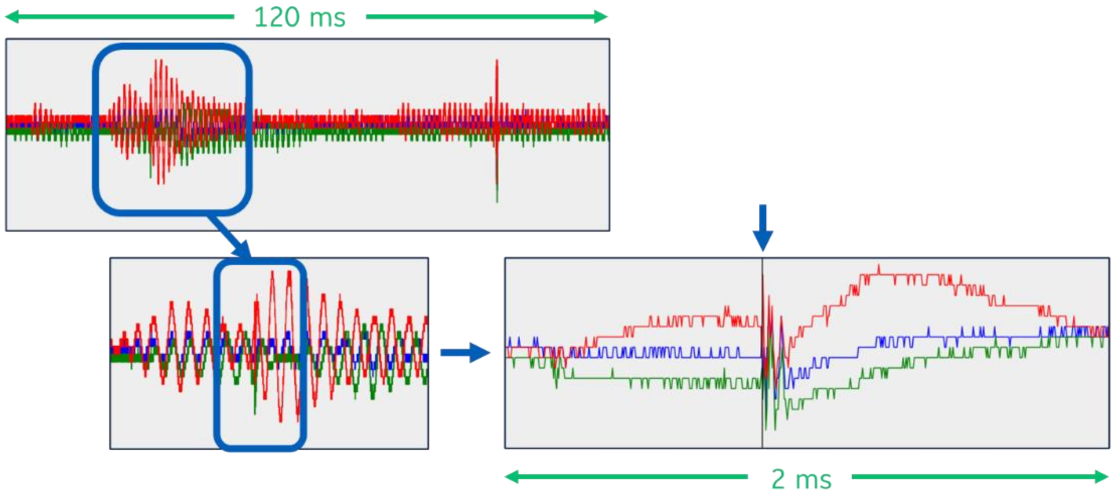

Figure 11 – Example of the determination of wavefront for a high impedance fault.

Mainly in cases of high impedance faults, the traveling wave record shows that, although the wavefront behavior is visually perceptible, the same cannot be said to the automatic fault location algorithms since the magnitude, the duration and the behavior of the traveling waves is not easily modeled in these situations. While it is possible to evaluate only the traveling wave record in these cases, in general these situations require additional tools from the operator or algorithm in order to determine a time zone smaller than the record as a whole, a tool that works as a guide to perform a more in-depth filtering in a smaller time interval.

One possibility in this case is the use of the records triggered by a Fault Recorder synchronized in the same time base as the fault locator, where the oscillography record is used as an additional tool to evaluate the time instant when the fault occurs, then the traveling wave record is used with the same time base. Figure 12 shows, as example, the use of this technique to define the time range – three-phase voltage signals at the top, three-phase current signals at the middle and traveling wave signals at the bottom.

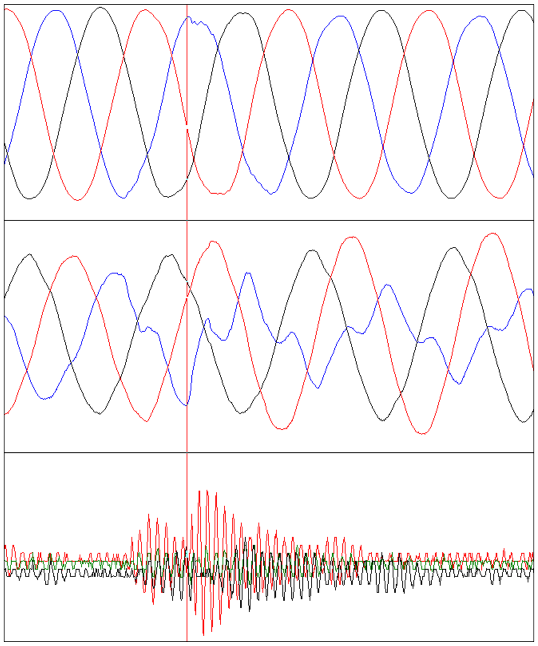

Figure 12 – Fault and Traveling Wave records combination to wavefront peak determination.

4 Traveling Wave Fault Location examples with confirmed location

Currently, there are several applications of global scope using traveling waves and the vast majority are related to fault location. Despite having a clear improvement in the accuracy of fault location with the traveling wave technique, it is generally perceived that its use globally is more widespread or is more consolidated in electrical systems and countries that have a significant number of long transmission lines, mainly due to the fact that the relative error on short lines can, in general, result in absolute errors with values acceptable to local utilities.

Numerous applications have been established around the world with the traveling wave fault location tool and some are brought here for this article in order to show its applicability for different voltage levels and types of faults.

Table 1 shows some results from locations in different regions with low and high impedance faults, different operating voltage levels and line lengths, as well as compensated lines up to 765 kV. Additionally, the estimated fault locations by the traveling wave fault locator, the actual fault location determined by line inspection and the calculated error in relation to the line length are shown too.

Table 1 – Examples of results of Traveling Wave Fault locations compared to real fault location according to maintenance personnel team.

System Voltage	Date (mm/aa)	L (km)	Confirmed Location (km)	Calculated Location (km)	Error (km)	Relative error based on line length (%)
765 kV	04/20	231.40	32.436	32.390	0.046	0.020
765 kV	06/20	231.40	40.365	40.240	0.125	0.054
765 kV	07/20	240.00	239.100	239.010	0.090	0.038
765 kV	07/20	240.00	239.100	239.140	0.040	0.017
765 kV	08/19	361.00	0.000	0.000	0.000	0.000
765 kV	07/19	342.00	270.000	270.068	0.068	0.020
765 kV	08/20	240.00	238.700	238.760	0.060	0.025
765 kV	04/21	334.46	0.300	0.300	0.000	0.000
500 kV	05/08	248.28	206.000	206.220	0.220	0.089
500 kV	04/08	248.28	206.000	206.150	0.150	0.060
400 kV	04/21	216.00	47.750	47.180	0.570	0.264
400 kV	05/17	262.41	1.902	1.920	0.018	0.000
230 kV	20/09	325.73	122.430	122.560	0.130	0.040
230 kV	27/09	325.73	325.680	325.690	0.010	0.003
230 kV	10/09	325.73	99.510	99.550	0.040	0.012
230 kV	22/09	325.73	194.620	194.650	0.030	0.009
230 kV	09/09	325.73	156.960	156.990	0.030	0.009
230 kV	09/18	64.72	48.000	46.260	1.740	2.689
230 kV	06/21	140.59	40.000	39.920	0.080	0.057
220 kV	08/15	16.40	14.960	14.959	0.001	0.000
220 kV	08/15	16.40	13.098	13.160	0.062	0.378

Fault location results are based on 765 kV and 400 kV transmission lines in India, 220 kV from Spain, 230 kV in Mexico and 230 kV and 500 kV in Brazil, using some of the results from lines in Brazil that are shown in [3]. Most of the events are single-phase-to-ground faults, where about 3 to 4 cycles later there is a single-pole breaker opening operation. One second later, an Automatic Reclose attempt is made by sending the circuit breaker closing command for the faulted phase. In cases of temporary faults, a single breaker opening is sufficient to eliminate the disturbance. For cases of persistent faults, the line is opened again after an Automatic Reclose attempt. For faults where the Automatic Reclose attempt was not successful, the protection system performs the three-phase opening of the transmission line circuit breakers.

The TW fault location is performed with the records of the first TW event, which is the Trip event. The use of the Trip event records ensures greater reliability in the fault location compared to the reclose or three-phase opening records, as the wavefront peaks are better defined, and it eases the positioning of the timestamp reference for fault location calculation.

Regarding the results shown in the table, it can be seen that the system has an accuracy with relative errors below 0.5% for the majority of cases. It is noteworthy that this precision is achieved with the refinement of the parameters involved in the location of faults by traveling waves, notably the line length (*L*) and the wave propagation speed, in general related to the attenuation factor *k* that indicates the percentage of the speed of light at which the wave travels on the line.

To provide the accuracy shown in the fault location examples, notably applicable to the Double-ended method with synchronized measurements, it is necessary to carry out a previous calibration of the transmission line parameters. These factors are usually refined during commissioning or through regression methods after the first events. These events make possible to calculate the wave propagation coefficient on the transmission line (k factor) and the real line length of the line. Given the unavailability of the traveling wave parameters commissioning, the fault location system must use real fault data to ensure greater accuracy. If the system is not calibrated and standard parameters are used, the fault location error is generally within 1 km for every 100 km of line length. The confirmation of the location of faults is carried out through the field maintenance team that travels along the lines and certifies the result of fault locations.

The fault in Table 1 where there is an error greater than 1% in relation to the size of the line, refers to a high impedance event where the wavefronts do not have a discontinuity as clear as a low impedance fault, thus being more difficult to determine the time instant of the wavefront accurately. Despite the error from the actual fault location, the calculated location provides comparatively a better estimate of the region where the fault may have occurred compared to impedance-based location.

Figure 13 and Figure 14 show the Waveform and the Traveling Wave records for both transmission line ends for the second fault shown in Table 1, a typical fault for the 765kV line. This event occurred in June 2020 and it was a low impedance fault on phase A. The single-pole circuit breaker of phase A received the opening command and, around 3,3 cycles after the fault, the phase A is deenergized. The uppermost part of the graph show the three-phase currents, the middle of graph shows the three-phase voltages and in the bottom part are the high frequency TW signals.

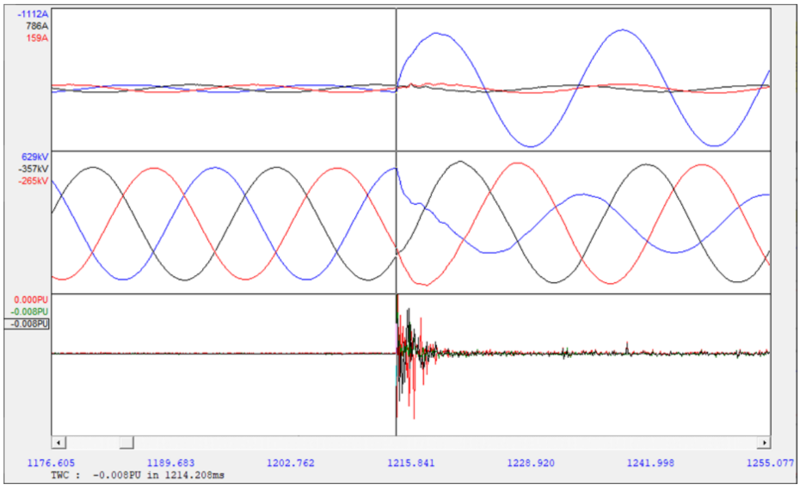

Figure 13 – Waveform record and TW record for terminal A.

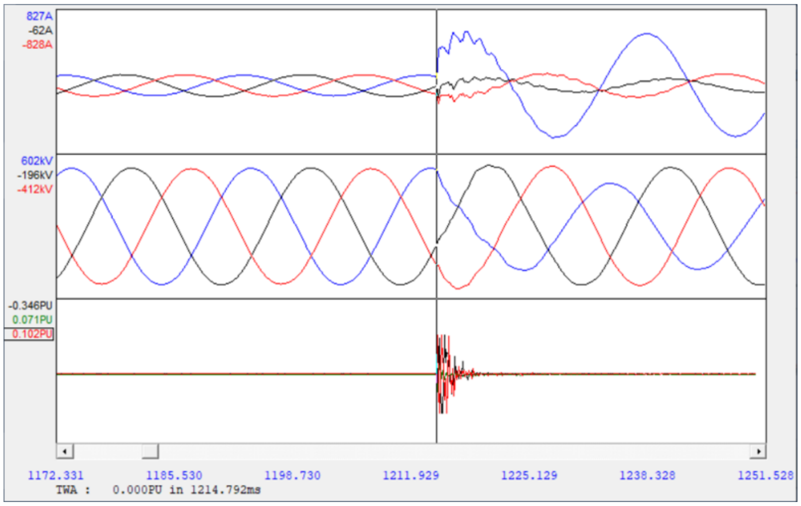

Figure 14 – Waveform record and TW record for terminal B.

It is possible to notice for the fault that, due to its low impedance characteristic, the current waveform quickly goes high, and the voltage waveform suffers an abrupt drop. The intensity of the TW wavefront for low impedance faults (bottom of the figures) is clear enough to identify the timestamps to be used to locate faults.

Another aspect to be analyzed is the way in which the accuracy of fault location methods by TW is compared. For example, the absolute fault error is based on the absolute difference between the actual location and the software-calculated location. When the line length is taken into account for the error calculation, the percentage error in relation to the actual fault location is drastically reduced [6].

It is always important to have confirmation of the actual fault location by field personnel to feed back the system and ensure better accuracy of the TW fault location method for future events. The more data with confirmed real location, the more the method becomes adherent to the real model of the line and, thus, offers better accuracy in the locations. It should be noted that an accuracy of ±150 meters with respect to the actual fault location is generally considered good enough to accurately alert field personnel to repair.

Another point is the certainty of how the field personnel confirmed the actual location of the fault. When the short circuit is close to the substation or is in easily accessible areas, for example, the location confirmed by the maintenance team occurs faster and more accurately (up to meters), but when it comes to more remote parts or in places with difficult access, this confirmed location is sometimes estimated and has errors of up to hundreds of meters. However, this error becomes tolerable once the distance between towers on average is sufficiently accurate for the line inspection team, and this distance is usually greater than 400 m.

In other cases, when there is no real confirmation of the fault location provided by the line maintenance team, the fault location compared to the traveling wave system, as a way of consolidating the result, is usually given by single or double ended impedance methods. However, attention should be paid to these cases because the actual location of the fault confirmed in this way inherently has the imprecision of the impedance methods [13], [14], and this should not be a method to calibrate the locator by traveling waves. The fault impedance, fault distance to the measurement terminals and the type of modeling implemented in the equipment can negatively affect the result provided by the impedance location method, therefore, negatively affecting the performance of the TW fault location system when the actual fault location is provided by impedance methods.

Fault location using TW methodology is based both on software and user experience when the fault location software have manual location mode. Each fault event has a unique characteristic in the behavior of TW wavefronts. A solid short-circuit, for example, will result in a much more defined TW wavefront than a high impedance fault. It is in this aspect that the user experience comes in to identify cases where greater attention is required to define the best timestamp points within the TW record, as well as cases in which the field team should consider a bigger inspection range. The analyst's ability, in these more complex cases, is a vital part of determining the most appropriate timestamps for location and consequently ensuring better accuracy.

There are tools that perform traveling wave fault location automatically based on fault records of the fundamental frequency (50/60 Hz) and high frequency components (traveling wave records), once they are available. These tools save the user time by performing automatic location based on a pair of TW records and a pair of Waveform records at each end of the transmission line. For more complex cases where location does not occur automatically due to the fault characteristic, an analyst must be assigned for analysis. On the other hand, it is recommended in systems that have manual tools that the analyst performs a critical analysis of the automatic location, thus ensuring that the inspection team is directed to the correct location of the failure and is already aware of the possibility of the inspection range being greater or smaller, depending on the analyst's difficulty in locating it.

5 Conclusion

The article, in addition to presenting a brief review and history of fault detection by traveling waves, showed considerations, experience and practical examples accumulated in the last 13 years of the use of this technique in fault location, having applications in several transmission companies in Brazil and several countries in the world, mainly in Latin America, Europe and Asia. With this history of application in different parts of the world, quite diverse, it is possible to have a relevant history of the behavior of traveling waves in different types of faults, in different electrical systems and at different voltage levels.

Some practical examples of traveling waves records in different types of faults were shown, where it is explored how the protection engineer can obtain important information through these records to determine the precise location of a fault and, depending on the situation, the expected assertiveness for the location including in situations with fault location performed automatically by location algorithms. In these examples it was possible to observe the variability of the behavior of the traveling wave signals, which is a relevant topic to be considered and analyzed when applying technologies in the field, especially when applying automatic algorithms to detect these signals.

Practical examples of the technology in operation show that, for different types of faults, high or low impedance, line lengths of hundreds of kilometers, with or without reactive compensation, etc., the accuracy of the locations can range from hundreds to tens of meters – this being the result often obtained by the traveling wave fault location system. This is verified even in situations of automatic location, which is limited to factors that are normally under the control of the utilities, such as the correct selection of the signal to trigger the locators, correct calibration of the equipment, as well as the analyst's capacity in more complex cases to understand the traveling wave signals through the records to determine the most appropriate timestamp for the fault location.

6 References

[1] L. B. de Oliveira, C. Dutra, R. Matos, P. de Souza and S. Zimath, "Predictive Maintenance with Travelling Wave Fault Location," *CIRGÉ - Study Committee B5 Colloquium,* no. PS3-316, pp. 20-26, 2015.

[2] S. H. H. Kazmi, J. Wang and Y. Li, "Comparison of High-Speed Transient-based Pilot Directional Protection Algorithms for Distribution Grids," *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe),* pp. 1-5, 2018.

[3] S. L. Zimath, C. A. Dutra, R. R. Matos, O. L. B. de, R. J. H. M. de and M. J. A. P., "Traveling wave fault location applied to high impedance events," in *12th IET International Conference on Developments in Power System Protection (DPSP 2014)*, 2014.

[4] P. Gale, Crossley, P.A., X. Bingyin, G. Yaozhong, B. J. Cpry and J. R. G. Barker, "Fault location based on travelling waves," *Fifth International Conference on Developments in Power System Protection,* pp. 54-59, 1993.

[5] A. Deshpande and G. S. Shah, "Transmission line protection based on travelling waves," *WSEAS Transactions on Circuits and Systems,* pp. 423-441, 2011.

[6] IEEE, "IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines," *IEEE Std C37.114-2014 (Revision of IEEE Std C37.114-2004),* pp. 1-76, 2015.

[7] L. V. Bewley, Traveling Waves on Power Electric Ssytem, New York: Wiley, 1941.

[8] L. J. Lewis, "Traveling Wave Relations Applicable to Power-System Fault Locators," *Transactions of the American Institute of Electrical Engineers,* vol. 70, no. 2, pp. 1671-1680, 1951.

[9] M. Chamia and S. Liberman, "Ultra-Highspeed Relay for EHV-UHV Transmission Line - Development Design and Application," *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-97, pp. 2104-2116, 1978.

[10] K. Glik, Rasolomampionona, , D. Dauphin and K. Ryszard, "Detection, classification and fault location in HV lines using travelling waves," *Przegląd Elektrotechniczny (Electrical Review),* vol. 88, 2012.

[11] M. a. I. Gilany, D. Khalil, T. Eldin and E. Sayed, "Traveling-Wave-Based Fault-Location Scheme for Multiend-Aged Underground Cable System," *IEEE Transactions on Power Delivery,* vol. 22, no. 1, pp. 82-89, 2007.

[12] S. Zimath, C. Dutra, C. Seibel, M. A. Ramos and J. E. S. Filho, "Furnas Experience with Traveling Wave," in *IEEE International Conference on Grounding and Earthing & 3rd International*, Florianópolis, 2008.

[13] Dalcastagne, A. L. and S. L. Zimath, "A study about the sources of error of impedance-based fault location methods," *IEEE/PES Transmission and Distribution Conference and Exposition: Latin America,* pp. 1-6, 2008.

[14] S. L. Zimath, M. A. F. Ramos and J. E. Filho, "Comparison of impedance and travelling wave fault location using real faults," *IEEE PES T D 2010,* pp. 1-5, 2010.