Travelling Wave Fault Locator (TWFL) Technology Applied to HVDC Transmission Line

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Abstract

In order to transmit massive amounts of power generated by remotely located power plants, especially offshore wind farms, and to balance the intermittent nature of renewable energy sources, the need for a stronger high voltage transmission grid is anticipated. Due to limitations in AC power transmission and its cost the most likable choice for such a grid is a high voltage DC (HVDC) grid [1].

The need to detect the fault location in a transmission line as quickly and accurately as possible has increasingly been considered by utilities, and the use of traveling wave-based fault location technology has been implemented in order to improve the efficiency in minimizing the electrical system downtime and thus the application of penalties [2].

The location method consists in measuring the accurate time when the traveling waves (characterized by wave fronts caused by transients that occur on the line) pass through known points, usually substations located at the ends of the transmission line.

Different from fault locators by impedance methods, the location using traveling waves can reach higher accuracy regardless of fault type and line characteristics.

The Travelling Wave Fault Locators (TWLF) currently on the market rely on measurements from inductive CTs or VTs which are not applicable to DC systems. This paper presents a means to acquire the reading of traveling waves in a LCC HVDC system.

In addition, results of the field deployment of a TWLF system on a HVDC transmission line are presented. The proposed system was implemented on IE Madeira HVDC overhead line over a distance of 2375 kilometers connecting Porto Velho to Araraquara II substations from Northwest to Southeast of Brazil and tested for induced faults during the commissioning.

1. Introduction

The first wave of HVDC connected offshore wind power plants (WPPs) has been commissioned and many more are planned in the North Sea, along with other sites around the world. VSC-based HVDC has become the preferred solution for large offshore WPPs, with cable distances typically above 100 km (including both offshore cable and on shore cable to the converter terminal) to the AC grid connection point [3].

In addition, a number of HVDC submarine cable connections for power exchange between countries are being planned, in such a way that is possible to observe that the demand for HVDC power transportation equipment and technology is gradually becoming larger.

In Brazil, due to the large distance from generation and load, HVDC is also deployed as a solution for efficient and flexible power transmission. Since the market regulation, the way power transmission companies are compensated depends on the availability of their transmission systems. When a fault occurs and the transmission line becomes unavailable, such companies are penalized for the time the transmission line is out service. Thus, fault location systems that can reach higher accuracy to estimate the fault location minimize the downtime of the transmission line and, therefore, the application of penalties.

The downtime of a transmission line also influences overall stability of the power system as it becomes less strong and can even reduce the power transfer capability between areas influencing the energy price, reason why there is a pressure to re-establish the transmission line as soon as possible by the National System Operator.

With this in mind, the need to detect the fault location in a transmission line as quickly and accurately as possible has increasingly been considered by utilities, and the use of traveling wave-based fault location technology has been implemented in order to improve the efficiency in minimizing the electrical system downtime and thus the application of penalties.

The location method consists of measuring of the accurate time when the traveling waves (characterized by wave fronts caused by transients that occur on the line) pass through known points, usually substations located at the ends of the transmission line.

Different from fault locators by impedance methods, the location using traveling waves can reach higher accuracy regardless of fault type and transmission line characteristics. In short-circuit faults (usually bolted faults) the traveling wave intensity is higher, and the wave front rise time is quite shorter, thus making their identification easier for the acquiring system. In faults with high-impedance, the traveling waves are less intense and have longer wave front rise time; therefore making their detection and identification tasks more complicated. For this reason, it becomes necessary the use of more complex wave front search algorithms to differentiate, within the records, the correct wave front.

The Travelling Wave Fault Locators currently on the market rely on measurements from inductive CTs or VTs and therefore are largely inapplicable to DC systems. In this paper an alternate form of acquiring travelling wave signal is discussed, allowing the technology to be used on DC systems.

In addition, results of the field deployment of a TWLF system on a HVDC transmission line are presented. The proposed system was implemented on IE Madeira HVDC overhead line over a distance of 2,400 kilometers connecting Coletora Porto Velho to Araraquara II substations from Northwest to Southeast of Brazil and tested for induced faults during the commissioning.

2. Locating faults by using traveling waves

Faults in a transmission line cause transients that travel along the line as a multiple frequency wave in a range of a few kilohertz up to several megahertz. These traveling waves are composed of a "wave front" usually with a short rise time and a long decrease time.

The propagation speed of the waves is close to the speed of light. These waves move away from the fault location towards both ends of the transmission line. By determining the moment when the wave fronts pass through each end, it is possible to estimate the fault location as shown in Figure 1.

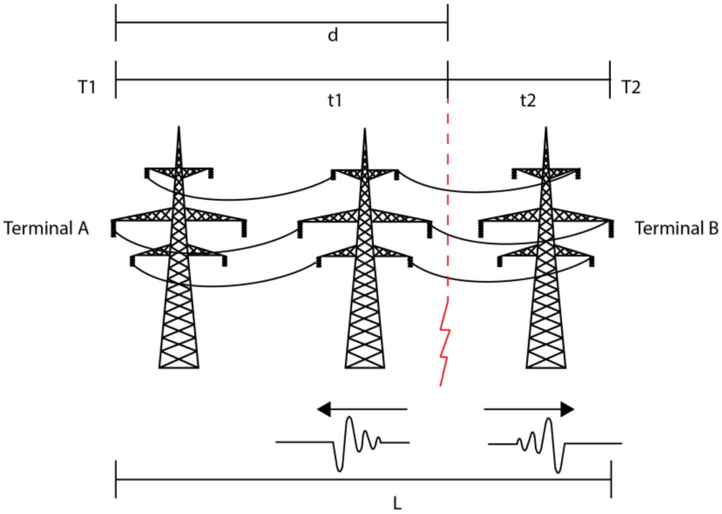


Figure 1: TWFL

Figure 1: Principles for determining the fault location by traveling waves

By knowing the time stamp that wave front reaches ends A and B of the transmission line (T1 and T2) and considering the length of the line "L", it is possible to determine the fault location from end A using the following equation:

Equation 1

$$d = \frac{\mathrm{L} + \mathrm{kc}(T1 - T2)}{2}$$

where *kc* is the propagation speed of the wave, considering that *c* = 299.792.458 m/s is the speed of light and *k* = 0.95...0.99 is the reduction factor that considers some parameters of the overhead line.

The waves are not limited to the transmission line where the fault occurred, spreading to the adjacent electrical system with amplitude decreasing as a result of the combined effects of line impedance and continuous reflections.

The amplitude of these traveling waves is also affected by characteristics of the phenomenon that produced them. Typical bolted or low-impedance faults generate more intense discontinuities in the voltages and currents leading to wave front with higher intensities. However, events related to high-impedance faults also produce wave fronts, however, with lower amplitudes [2].

Because of this it is necessary a different technology to locate faults and also it is important to note the differences in sources of error in relation to traditional methods based on impedance. While traditional methods produce errors originated from electrical phenomena, occurring in the electrical system frequency (60 Hz in the case of Brazil), the traveling waves method is affected by a different phenomena. On the other hand, by simply checking the terms used in the previous equation, it is possible to verify that there are no parameters for currents, voltages, or impedances.

Therefore, the traditional causes, such as mutual impedance, weak infeed, accuracy of CT/VT, high impedance faults, etc, simply are not considered in this method. Moreover, new sources of errors appear, for example, differences in cable length, which occur due to changes in ambient temperature and load variations in the overhead line. However, the impact of such sources of errors is very small when compared to any of the sources of errors in impedance-based methods.

The correct calculation of the fault location lies in the proper detection and identification of the traveling wave caused by the fault. It is known that the conventional CTs and VTs are able to reproduce the traveling wave in their secondary circuit. HVDC measurement systems do not use conventional CTs and VTs, instead, they use sensors and transducers to read the current and voltage of overhead lines. This paper will show a TWFL method that uses the voltage sensors connected to the DC voltage dividers installed at + 600 kV of HVDC overhead line from Coletora Porto Velho to Araraquara II substations.

2.1.Calibration of the TWFL System

The calibration process of the GE Reason TWFL system consists in the determination of 2 parameters: The factor K, each conductor has different physical particularities that influences the speed of the traveling wave. The parameter K is a constant that adjusts the speed of light to match the speed that the traveling wave has in the line conductor; The second parameter is the line length (L), considering the total extension of the conductor. The parameters line length tends to be slightly different from the nominal length given by the customer because it generally does not consider the catenary curves.

These two parameters are adjusted with a linear regression process based on the results of the fault location in relation to the real distance to fault.

3. Power transmission

The transmission and distribution of electrical energy started with direct current (DC) in the late 19th century, but it was inefficient due to the power loss in conductors. Alternating current (AC) offered much better efficiency, since it could easily be transformed to higher voltages, with far less loss of power. AC technology was soon accepted as the only feasible technology for generation, transmission and distribution of electrical energy [4].

3.1. AC Power transmission

The AC power transmission is responsible for carrying the majority of the power generation in the world [5]. It is basically composed of three 3 cables, via which the energy is transmitted in the form of sinusoidal waves, usually oscillating at 50Hz or 60Hz. Each wave is called phase and generally classified as phase A, B and C. This is called a three-phase transmission system. The figure below shows a plot of the three-phase signals along the time.

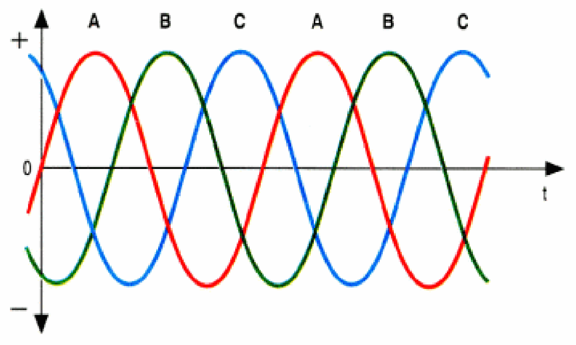


Figure 2: Three phase system

The main reason for using AC in power systems is that it allows raising and lowering the voltage by means of transformers [6].

Figure below exemplifies AC power trasmission from the power plant, passing through the step up transformer straight then AC transmission lines, then through step down transoformers, AC distribuition lines and finally the end customers.

Figure 3: AC power transmission

3.2. DC Power transmission

A simple representation of a HVDC interconnection is shown in Figure 4. AC power is fed to a converter operating as a rectifier. The output of this rectifier is DC power, which is independent of the AC supply frequency and phase. The DC power is transmitted through a conduction medium; be it an overhead line, a cable or a short length of busbar and applied to the DC terminals of a second converter. This second converter is operated as a inverter and allows the DC power to flow into the receiving AC network [7].

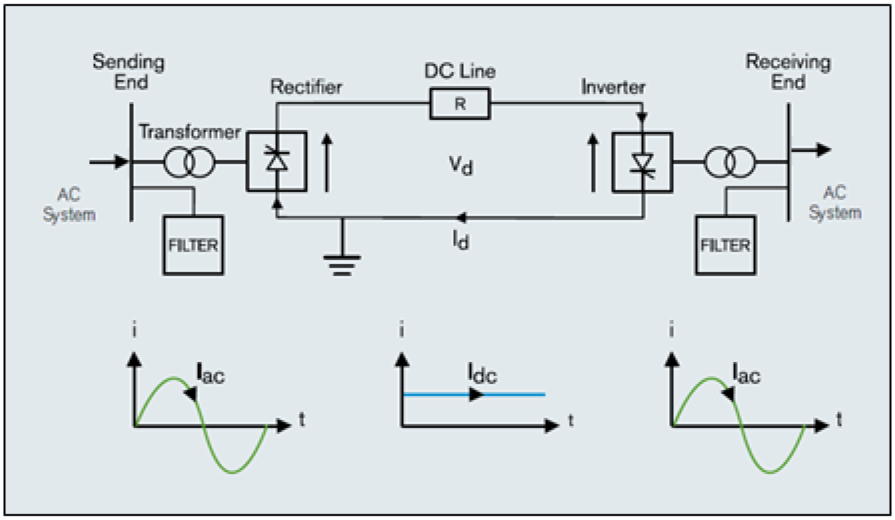


Figure 4: DC power transmission

4. Traveling waves measurement

As mentioned previously, the success of the TWFL methods lies in the proper measurement and detection of the traveling wave.
Since the AC and DC transmission lines count on different technologies for voltage and current measurements the TWFL equipment must be capable to extract the information in both systems. Below the main differences in AC and DC traveling wave acquisition is described.

4.1. TWFL in AC transmission lines

In an AC system the characteristics of the waves are monitored using Instrument Transformers. These transformers have their primary circuitry connected to the transmission lines at the power substation and they reproduce in their secondary circuitry an identical waveform as in the primary but with lower levels of magnitude so it can be measured by the IED installed in the substation.
The TWFL IED acquires its reading from the secondary circuitry of either the voltage transformers or the current transformers. Those readings are registered and processed to extract the necessary information for the fault location.
Below is a single line diagram representation of conventional bays and their CTs and VTs.

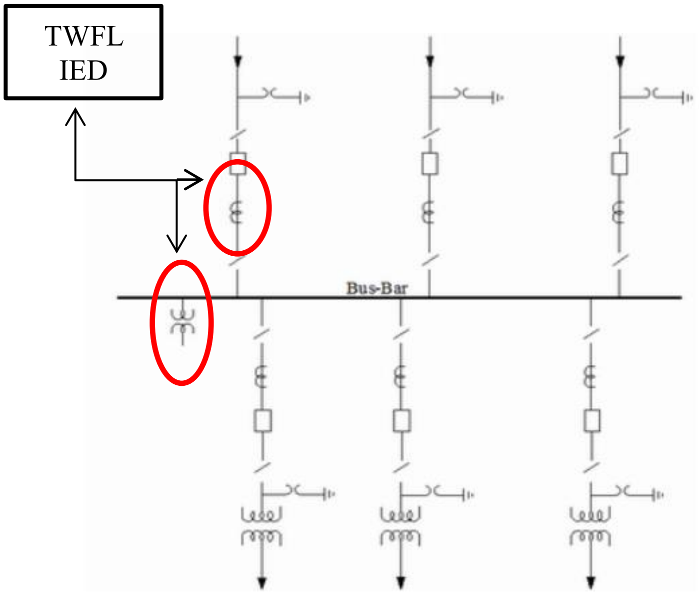


Figure 5: Regular connection to CT and VT

4.2. TWFL installation in DC transmission lines

Instrument transformers are not applicable to DC measurement. To do so, the following approaches are taken.

DC voltage measurement is made by either a resistive DC voltage divider or an optical voltage divider. The resistive voltage divider comprises a series of connected resistors and a voltage measurement can be taken across a low voltage end resistor which will be proportional to the DC voltage applied across the whole resistive divider assembly. Optical voltage transducers detect the strength of the electric field around a busbar with the use of Pockel cells.

The DC current measurement for both control and protection requires an electronic processing system. Measurement can be achieved by generating a magnetic field within a measuring head which is sufficient to cancel the magnetic field around a busbar through the measuring head. The current required to generate the magnetic field in the measuring head is then proportional to the actual current flowing through the busbar. Devices using this method are commonly known as Zero Flux Current Transducer (ZFCT).

Optical current measurement makes use of, amongst others, the Faraday effect in which the phase of an optical signal in a fibre optic cable is influenced by the magnetic field of a busbar around which the cable is wound. By measuring the phase change between the generated signal and the signal reflected back from the busbar, the magnitude of the current can be found.

The simplified diagram below shows the location of the DC transducers in the installation.

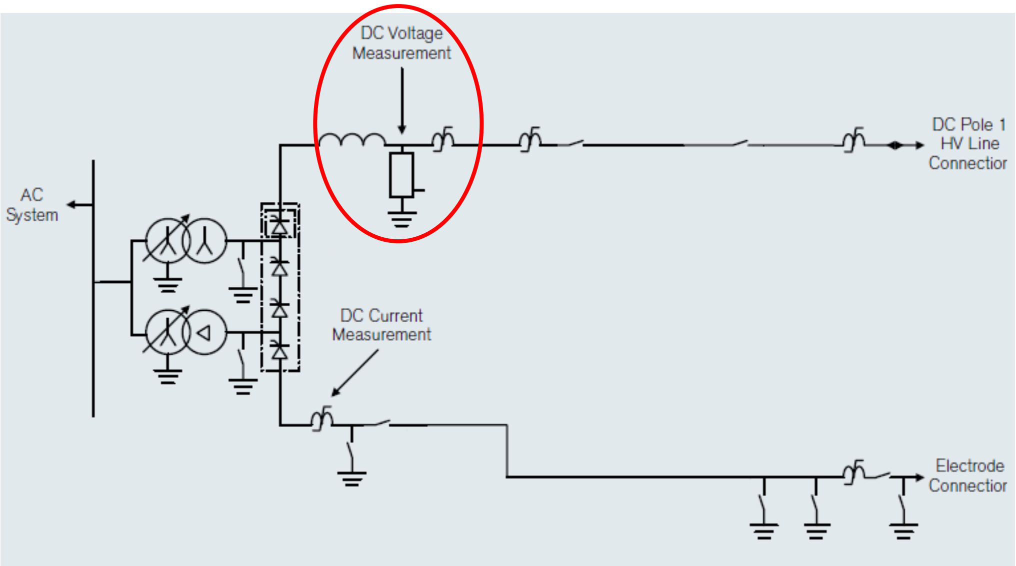


Figure 6: HVDC transmission line installation and measurement point

3. Real Installation: Coletora Porto Velho – Araraquara II ± 600kVdc Bipoles installation

The Madeira Complex is composed of the hydro power plants of Santo Antônio and Jirau, in Rondônia, which have a total power around 6,500 MW. In order to transmit such amount of power, a DC transmission system is composed of 2 HVDC bipoles in ± 600 kVdc, which cover a distance of 2375 km up to São Paulo, and two Back-to Backs converters of 2 x 400 MW, installed in Porto Velho, were designed. [8]
The TW fault location IED is installed in the bipole 2 both in Coletora Porto Velho substation as in Araraquara II.

The installation uses the resistive divider method for DC voltage measurement where the TWFL IED is connected to capture the TW information. As the TW is severely damped as a result of the overhead line length and resistive divider, the AD converter in the TWFL IED is design to have a greater gain than the usual AD for TW in AC overhead lines.

The voltage measurement is done through a ± 6 V DC transducer, where 100000 Vdc in primary circuitry represent 1 Vdc in the secondary.

In the figure below the black dashed line show the extension of the overhead line.

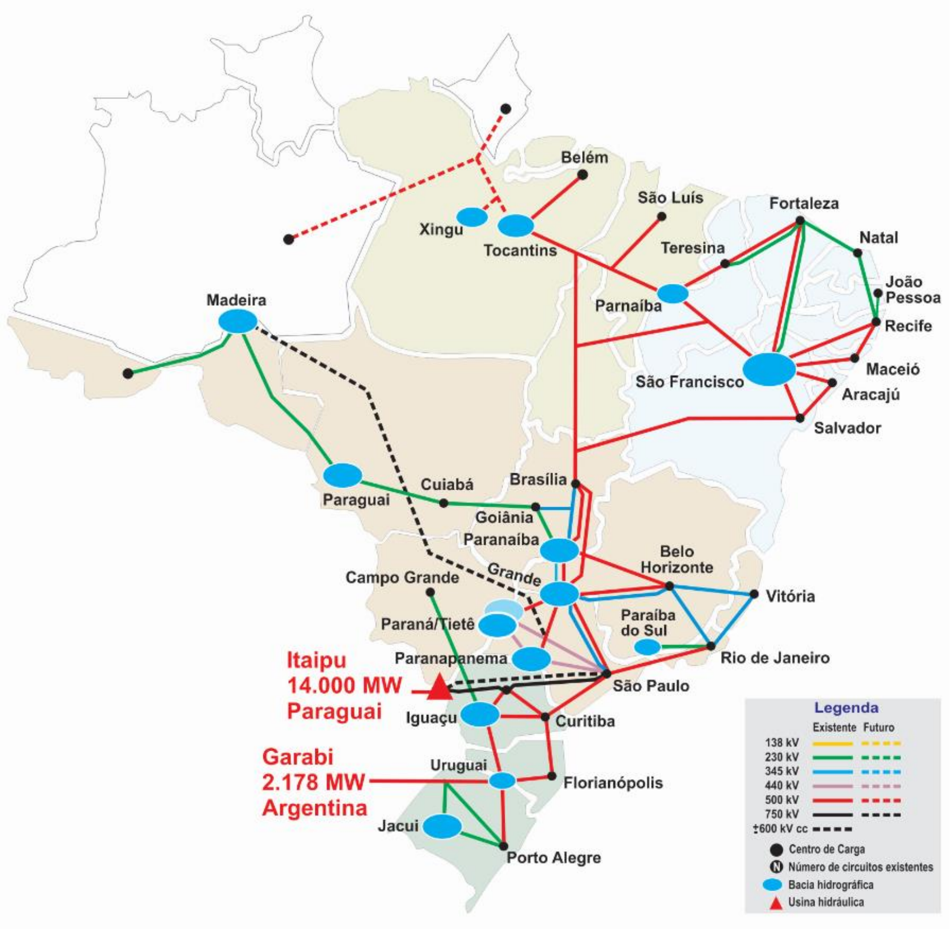


Figure 7: Integração Eletroenergética do Sistema Interligado Nacional [9]

Thresholds

The Traveling Wave Fault Location (TWFL) method uses the high frequency traveling wave COMTRADE register in order to identify the exact moment the waves reach the terminals, then, those time values are used in the formula presented in Chapter 2 to determine the fault location.
To initiate the traveling wave COMTRADE register, the device uses configurable thresholds that once violated trigger the COMTRADE file recording. The register creates records with 100 ms prior to the trigger instant and 16 ms after as shown in the figure below.

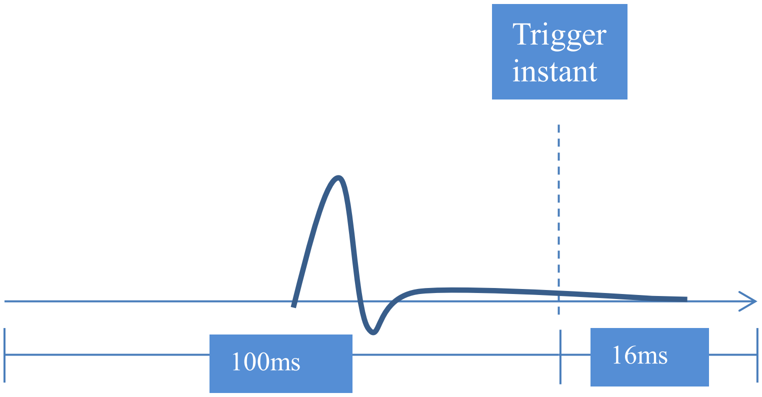


Figure 8: Traveling wave

As exemplified above, the traveling wave reaches the substation before the trigger instant, that's the reason why the threshold choice is critical in the TWFL process. The threshold can be associated to binary inputs, values violation (magnitude of voltage, current, frequency, sequence components and others) and cross-trigger (a first device commands the recording trigger of a second device whenever the first device triggers), therefore the beginning of traveling wave must be accommodated in the first 100 ms of the register.

The above mention statements are the basis for the TWFL threshold choices, that's why DCLF (DC line fault) protection and DC voltage threshold violation are used as inputs to trigger the COMTRADE recording. That guarantees that the waveform will fit into the register and that the fault event occurred between the monitored terminals and not in the HVDC converter stations. Based on that the below settings were chosen to trigger to TW records.

a) **Digital threshold**
   DC Line Fault Protection: Uses the pickup of the protection relay to speed up the trigger in the TW record. DCLF trip for high-impedance faults depends on the setting of DC undervoltage only and it can take some time to be violated, therefore using the trip signal there is a risk to lose the first wave front.

b) **Analog threshold**
   HVDC Undervoltage: Triggers the TW record when the DC voltage exceeds an undervoltage setting. For this case, the register triggers when V < 500 kV.

c) **Cross-trigger**
   Whenever a particular device triggers a record it sends an Ethernet message commanding the receiving device to trigger the record as well. This feature ensures that both ends will trigger in the occurrence of any device triggers.

5. Results

In order to verify the performance of the fault location system, short-circuit tests were performed in the HVDC line on the early hours of November 7 to 8, 2017. Eight low-impedance short-circuits were performed at predetermined points along the line in order to validate and calibrate the GE fault locating system. The location of each short circuit was only disclosed after verification of the location results of the GE TWFL system.

Below is presented the waveform records of 5 tested scenarios where the short circuit were positioned at both ends and in the middle of the transmission line.

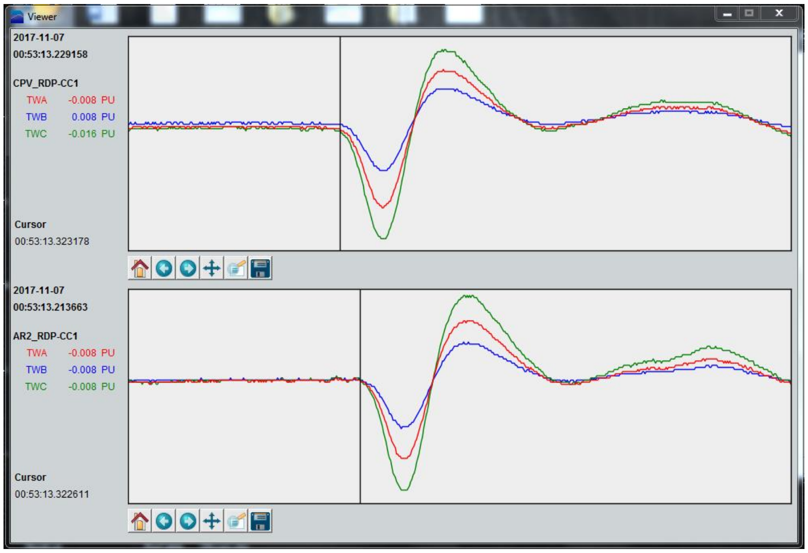
The fault location is carried out by applying the timestamp of the moment the traveling wave reaches each terminal of the transmission line to the Equation 1 (section 2).

It is possible to notice that even after traveling a distance of more than 2,300 km, the traveling wave still presents enough energy to be clearly capture by the acquisition system.

Test 1 - 07/11/2017, 00:53

Fault location:

- 1292.34 km from substation Coletora Porto Velho
- 1124.55 km from substation Araraquara II



2017-11-07
00:53:13.229158

CPV_RDP-CC1
TWA -0.008 PU
TWB 0.008 PU
TWC -0.016 PU

Cursor
00:53:13.323178

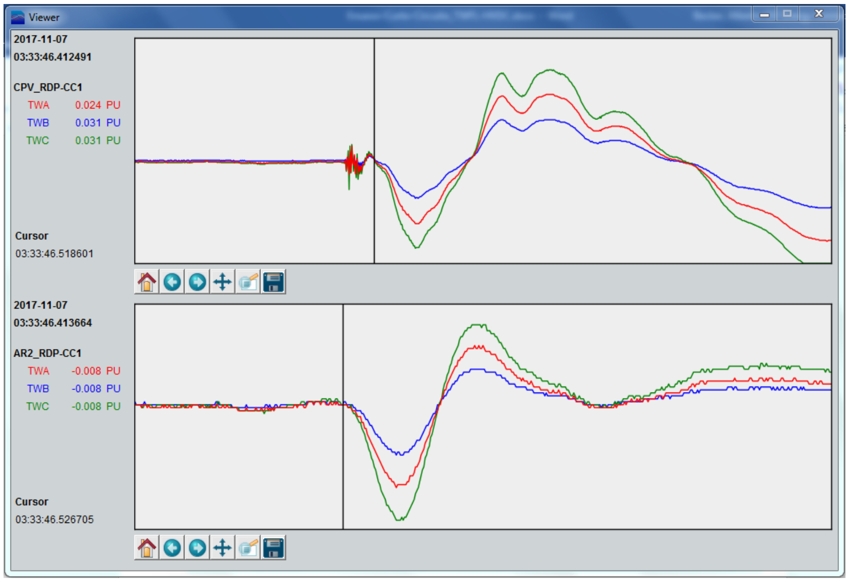
2017-11-07
00:53:13.213663

AR2_RDP-CC1
TWA -0.008 PU
TWB -0.008 PU
TWC -0.008 PU

Cursor
00:53:13.322611

Test 2 - 07/11/2017, 03:33

- 8.90 km from substation Coletora Porto Velho
- 2407.99 km from substation Araraquara II



2017-11-07
03:33:46.412491

CPV_RDP-CC1
TWA 0.024 PU
TWB 0.031 PU
TWC 0.031 PU

Cursor
03:33:46.518601

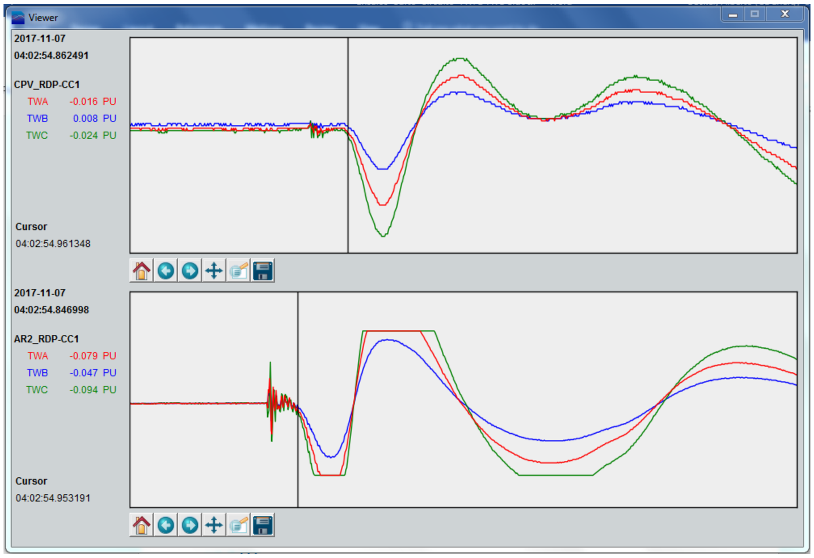
2017-11-07
03:33:46.413664

AR2_RDP-CC1
TWA -0.008 PU
TWB -0.008 PU
TWC -0.008 PU

Cursor
03:33:46.526705

Test 3 - 07/11/2017, 04:02

- 2415.93 km from substation Coletora Porto Velho
- 0.96 km from substation Araraquara II



2017-11-07
04:02:54.862491

CPV_RDP-CC1
TWA -0.016 PU
TWB 0.008 PU
TWC -0.024 PU

Cursor
04:02:54.961348

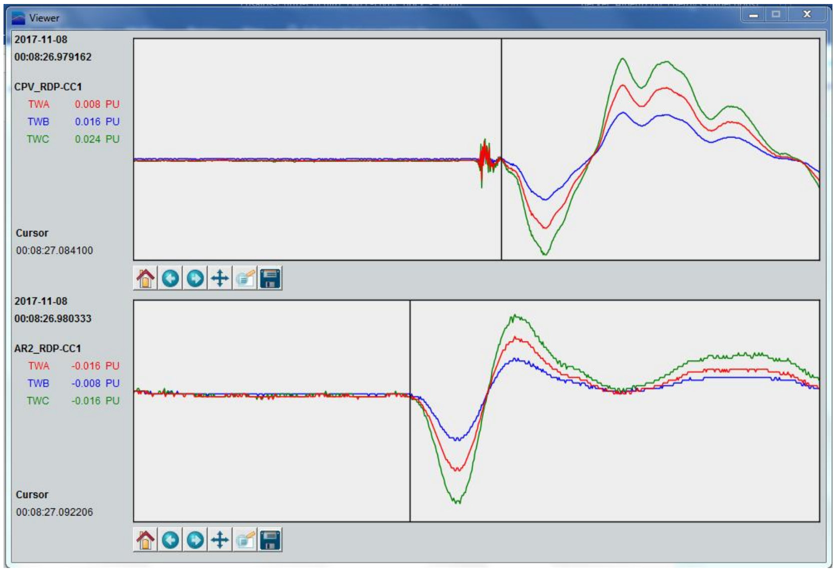
2017-11-07
04:02:54.846998

AR2_RDP-CC1
TWA -0.079 PU
TWB -0.047 PU
TWC -0.094 PU

Cursor
04:02:54.953191

Test 4 - 08/11/2017, 00:08

- 8.48 km from substation Coletora Porto Velho
- 2408.41 km from substation Araraquara II



2017-11-08
00:08:26.979162

CPV_RDP-CC1
TWA 0.008 PU
TWB 0.016 PU
TWC 0.024 PU

Cursor
00:08:27.084100

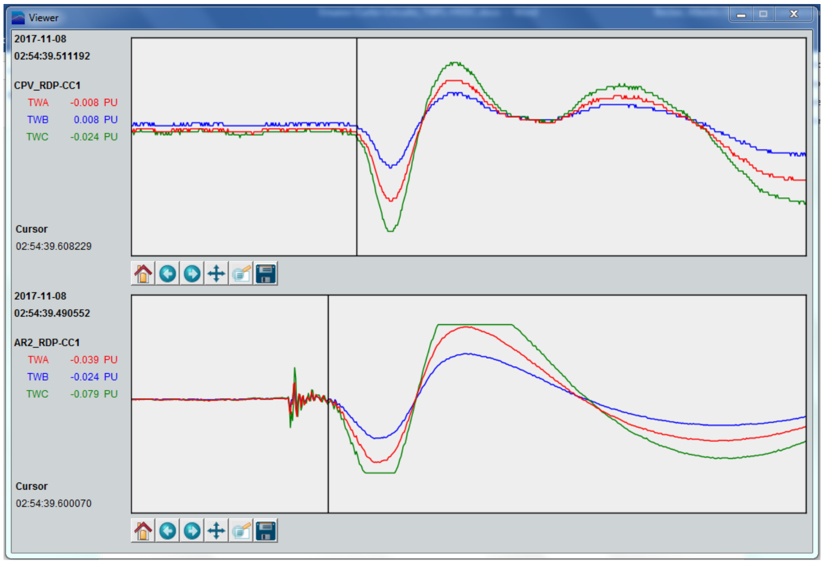
2017-11-08
00:08:26.980333

AR2_RDP-CC1
TWA -0.016 PU
TWB -0.008 PU
TWC -0.016 PU

Cursor
00:08:27.092206

Test 5 - 08/11/2017, 02:54

- 2416.21 km from substation Coletora Porto Velho
- 0.58 km from substation Araraquara II



2017-11-08
02:54:39.511192

CPV_RDP-CC1
TWA -0.008 PU
TWB 0.008 PU
TWC -0.024 PU

Cursor
02:54:39.608229

2017-11-08
02:54:39.490552

AR2_RDP-CC1
TWA -0.039 PU
TWB -0.024 PU
TWC -0.079 PU

Cursor
02:54:39.600070

5.1.Fault Location Results

The real distances to the fault were informed by the customer immediately after the disclosure of the result of the localization calculation performed by the GE TWFL. The table below shows the real distance to fault, the fault location of the GE TWFL and the respective errors.

The minimum error found was 61 meters or 0.003% of the line; and the maximum error was 412 meters or 0.017% of the line and the average error is 215 m or 0.009% of the transmission line.

Test	Description	Real distance to fault (km)	Fault Location GE TWFL (km)	Error (m)	Error in % of the line
1	07/11/2017 - 00:53 - Low impedance	1292.052	1292.38	**328**	**0.014%**
2	07/11/2017 - 03:33 - Low impedance	8.717	8.778	**61**	**0.003%**
3	07/11/2017 - 04:02 - Low impedance	2416.17	2415.957	**-213**	**-0.009%**
4	08/11/2017 - 00:08 - Low impedance	8.717	8.482	**-235**	**-0.010%**
5	08/11/2017 - 02:54 - Low impedance	2416.17	2416.253	**83**	**0.003%**
6	07/11/2017 - 02:01 - Low impedance	1292.052	1291.64	**-412**	**-0.017%**
7	07/11/2017 - 03:00 - Low impedance	1292.052	1292.38	**328**	**0.014%**
8	08/11/2017 - 02:22 - Low impedance	8.717	8.778	**61**	**0.003%**

**** The reference for distance to fault is the Coletora Porto Velho substation***

After the second event, the linear regression method was used to determine the best value of K and L for the set of samples obtained. At the end of the tests the following results were reached:

K factor	**0.98758**
Line length, L (meters)	**2416889**

6. Conclusions

The tests showed that it is possible to locate faults with high accuracy in HVDC transmission lines by capturing the traveling waves from the line resistive voltage divider without the need for additional investments with switchyard equipment.

It is clearly demonstrated that the traveling wave, even after traveling over 2300 km, does not suffer attenuation that would preclude the fault location from working properly.

The GE TWFL technology located the faults with average accuracy of less than 0,01% of the line length. Such accuracy allows the customer to drastically reduce outage time and costs with line inspections and maintenance. This technology is especially significative in transmission lines like the Coletora Porto Velho – Araraquara II, with long extension and crossing terrains with difficult access as forest and rivers.

7. References

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Biografy

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