Traveling Wave Fault Location on HVDC Lines

Alberto Becker Soeth Jr - GE Grid Solutions LLC, Brasil
Paulo Renato Freire de Souza - GE Grid Solutions LLC, Brasil
Diogo Totti Custódio - Interligação Elétrica do Madeira S.A, Brazil
Ilia Voloh - GE Grid Solutions LLC, Canada

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 reliable high voltage transmission grid is anticipated. Due to power transfer limitations by AC transmission lines and its cost, the most attractive choice for such a power transfer is a high voltage DC (HVDC) lines [1].

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

The location method consists from measuring accurate time, when the traveling waves (generated by wave fronts caused by transients during line fault) pass through known measurement points, usually substations located at the ends of the transmission line.

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

The Travelling Wave Fault Locators (TWFL) currently available on the market rely on measurements from inductive CTs and inductive/capacitive VTs, which are not applicable to DC systems. This paper presents a means to acquire the readings of traveling waves in a HVDC transmission system.

In addition, results of the field deployment of a TWFL system on a HVDC transmission line are presented. The described system was implemented on the *longest in the world* 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 stage faults during 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. A voltage-source converters (VSC) technology HVDC system 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, many 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 system operation. Due to 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, utility which owns this line is penalized for the time the transmission line is out service. Thus, fault location systems that can reach higher accuracy to estimate the fault location, can vastly help utility to minimize the downtime of the transmission line and therefore minimize penalties.

The downtime of the transmission line also affects overall stability of the power system as it becomes less reliable and can even reduce the power transfer capability between areas. This would impact the energy price, which is the main reason why there is a tremendous pressure from the National System Operator to re-energize transmission line as soon as possible.

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

During bolted line faults, the traveling wave intensity is higher, and the wave front rise time is much shorter, thus making their identification easier for the acquisition system. During high-resistance faults, the traveling waves are less intense and have longer wave front rise time; this 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.

2. Locating faults by using traveling waves

Faults in a transmission line are causing transients, that travel along the line as a multiple frequencies waves 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.

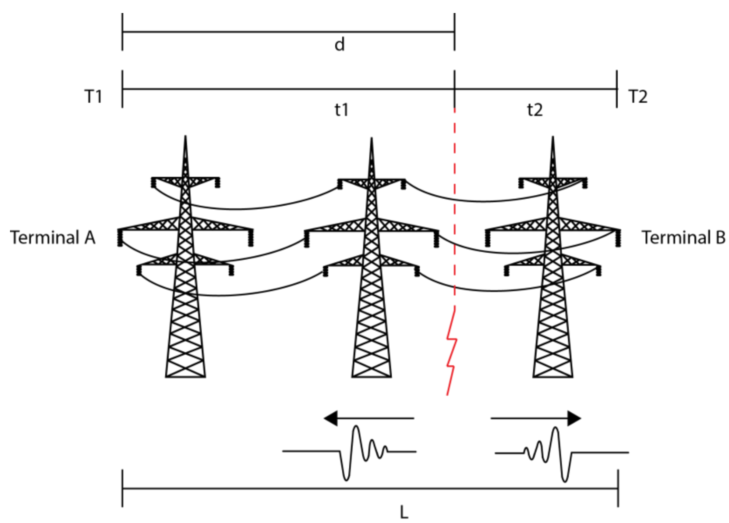

Figure 1: Principles for determining the fault location by traveling waves

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.

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:

$$\mathbf{d} = \frac{\mathbf{L+k \cdot c \cdot (T1-T2)}}{\mathbf{2}} \qquad \textbf{Eq. 1}$$

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 faulted transmission line only, spreading to the adjacent electrical system with amplitude gradually 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 travelling waves signatures in the voltages and currents leading to wave front with a higher intensities. However, events related to high-impedance faults also produce wave fronts, but with a lower amplitude [2].

Because of this, talking about different technology to locate faults, it is also 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 phenomenon. 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 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 using direct current (DC) started in the late 19th century along with a development of the AC transmission and distribution system. The famous War of Current between DC system of Thomas Edison and the AC system of George Westinghouse ended with an AC being preferred solution. Depending on the amount of energy to be transferred, distances causing power loses and available voltage level technology, either AC or DC system can be more economical.

Alternating current (AC) offered much better efficiency, since it could be easily transformed to higher or lower 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

Today the AC power transmission is used for carrying the majority of the energy in the world [5]. It is basically composed of three 3 conductors, 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 A, B and C along the time.

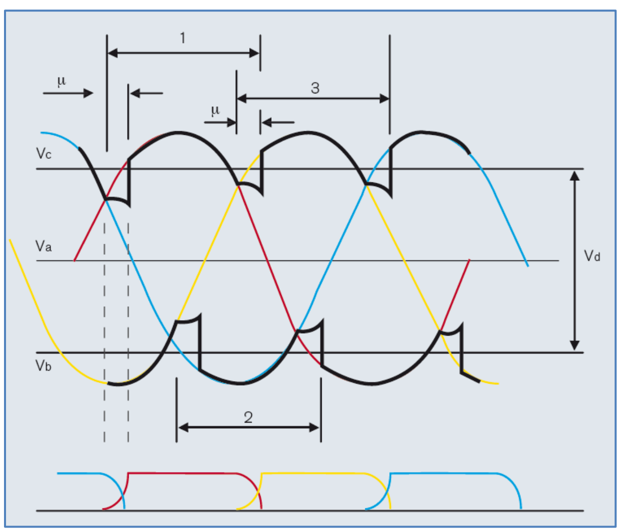

Figure 2: Three phase system signal AC conversion to DC

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

Figure 3: AC power system

Figure 3 above demionstates conventional AC power trasmission system from the generating power plant, passing through the step up transformer straight through AC transmission lines, then through step down transoformers, AC distribuition lines and finally to the end customers.

3.2. DC Power transmission

A simple representation of a HVDC interconnection to AC system is shown in Figure 4 below.

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 the second converter. This second converter is operated as an inverter and allows the transferred DC power to flow into the receiving AC network [7].

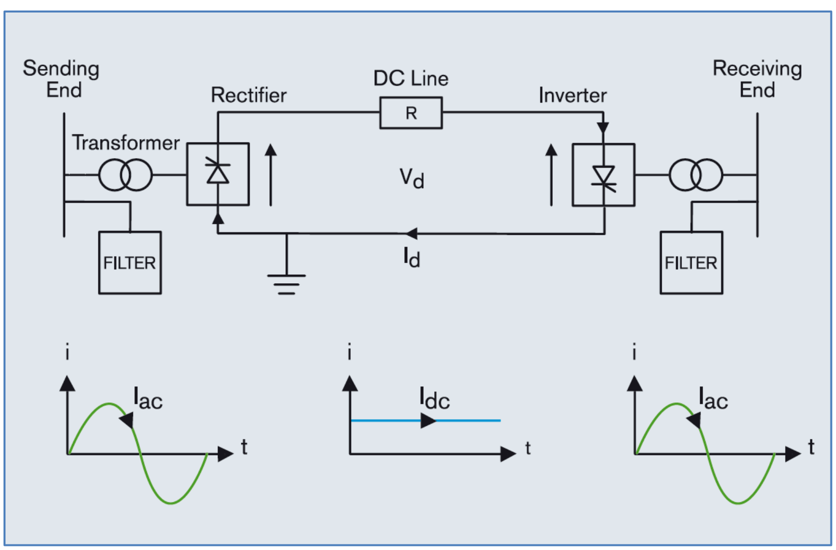

Figure 4: HVDC line connection to the AC power system

In the Figure 2 above, the process of converting AC signal to DC is shown. It can be seen that DC signal is not very smooth because of conversion-inversion commutation process. The AC/DC converter is a source of harmonics. This is because the converter only connects the supply to the load for a controlled period of a fundamental frequency cycle and hence the current drawn from the supply is not sinusoidal. Seen from the AC side, a converter can be considered as a generator of current harmonics, and from the DC side a generator of voltage harmonics. To reduce harmonics, heavy filtering is applied at both AC and DC sides.

4. Traveling waves measurements

As mentioned previously, the success of the TWFL methods is dependent on 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 are 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 much lower levels of magnitude so it can be measured by the IED installed in the substation.

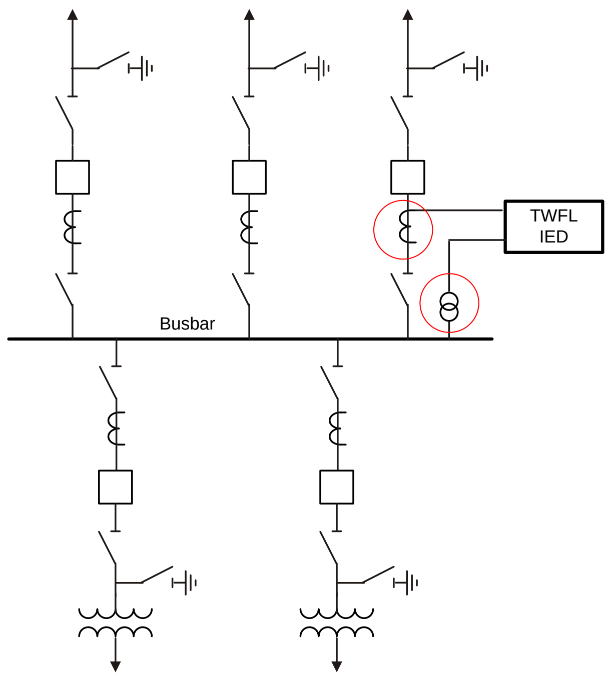

Figure 5: TWFL connection to CTs and VTs in AC system

The TWFL IED acquires its reading from the secondary circuitry of either voltage transformers or the current transformers. Those readings are registered and processed to extract the necessary information for the fault location.

Figure 5 above illustrates is a single line diagram representation of conventional AC bays and their CTs and VTs locations.

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. Pockel cells are voltage-controlled wave-plates, modulating the polarization of the light passing through.

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 fiber optic cable is modulated by the magnetic field of th busbar around which the fiber optic cable is wound. By measuring the phase change between the generated signal and the signal reflected from the busbar, the magnitude of the current can be found.

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

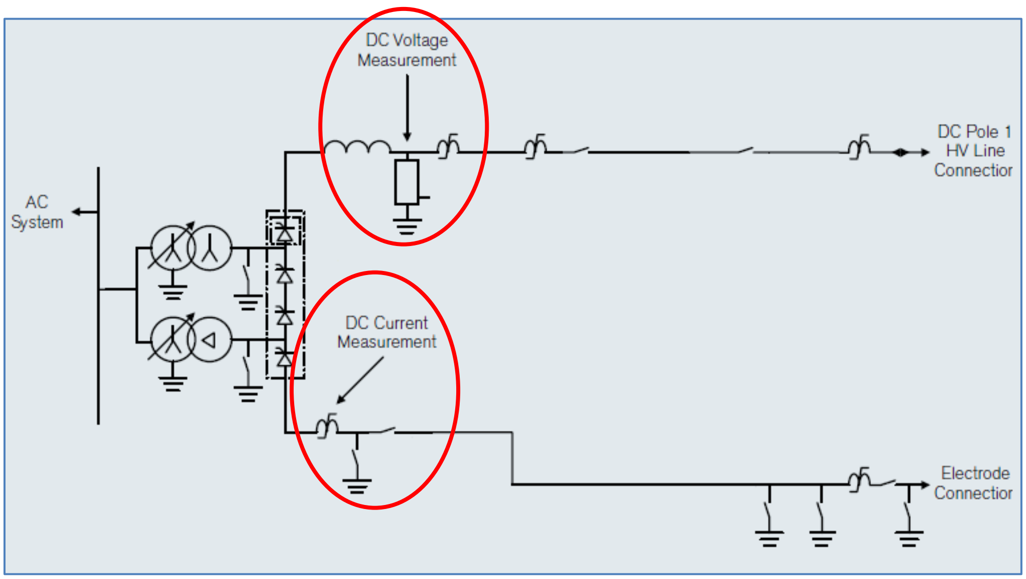

Figure 6: HVDC bipolar transmission line installation and measurement point

Figure 6 above presents a simplified diagram showing the location of the DC transducers in the installation.

5. 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 bipole HVDC ± 600 kVdc line, 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 pole 2 in Coletora Porto Velho substation same 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 data. 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 designed to have a higher 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.

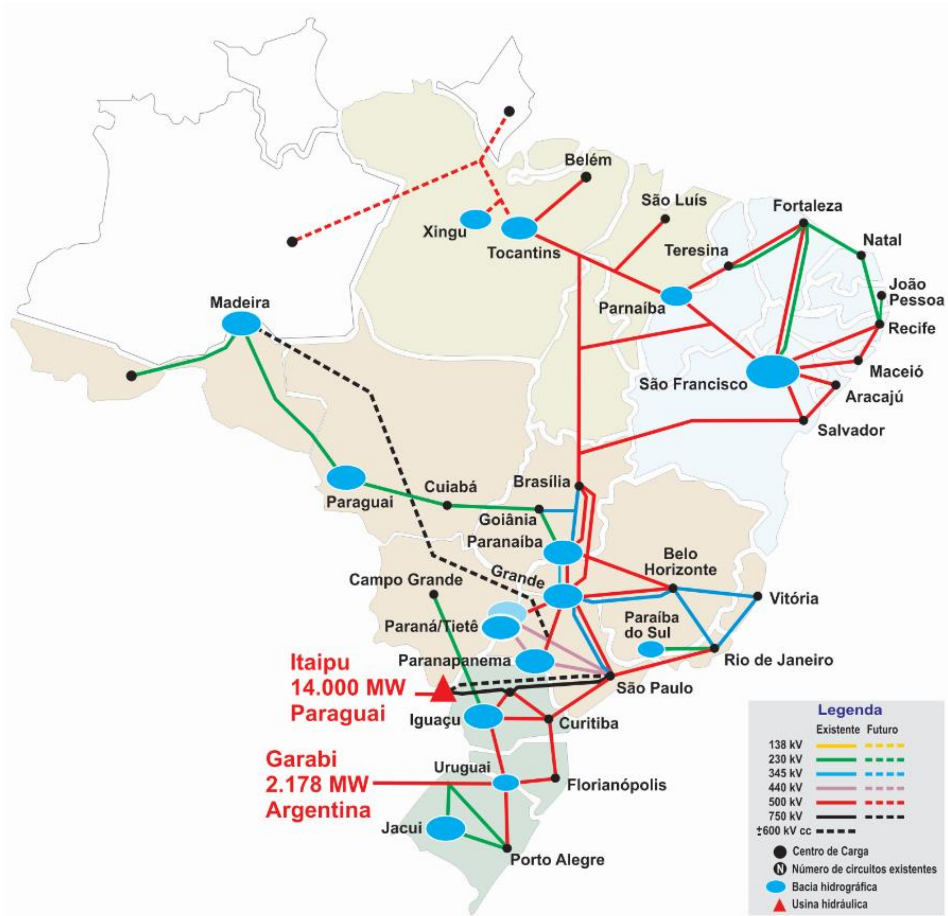

Figure 7: Interconnected National Power Transmission System [8]

Figure 7 below shows the HVDC line in the Brazilian National power system as a black dashed line.

5.1.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 equation 1 presented in section 2 to determine the fault location.

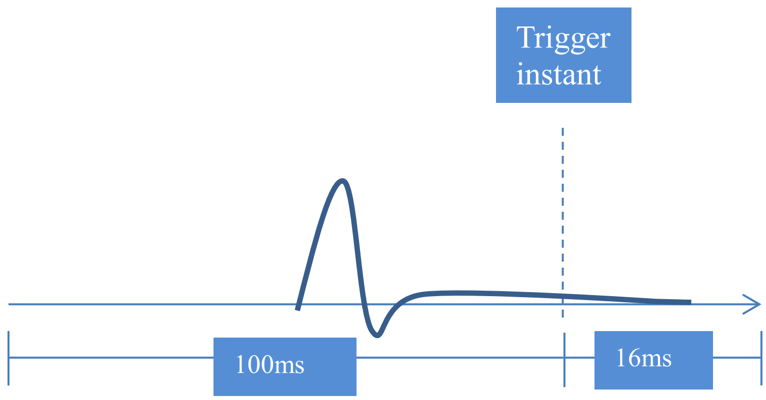

Figure 8: Travelling waves capture trigger

To initiate the traveling wave COMTRADE register capture, the device uses configurable thresholds to trigger the COMTRADE file recording, when thresholds are exceeded. The register creates records with 100 ms length prior to the trigger instant and 16 ms after trigger instance as shown in the Figure 8 above.

As explained 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 with a 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 captured in the first 100 ms of the register.

The above mention statements are the basis for the TWFL threshold choices, that's why 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 force the trigger of the TW record. DC Line Fault Protection trip for high-impedance faults depends on the setting of DC undervoltage only and it can take some time to be exceeded, therefore using the trip signal there is some risk to lose the first wave front.

b) **Analog threshold**

   HVDC Undervoltage: Triggers the TW record when the DC voltage measure by TWFL IED is below an undervoltage setting. For this case, the register triggers when $V < 500$ kV.

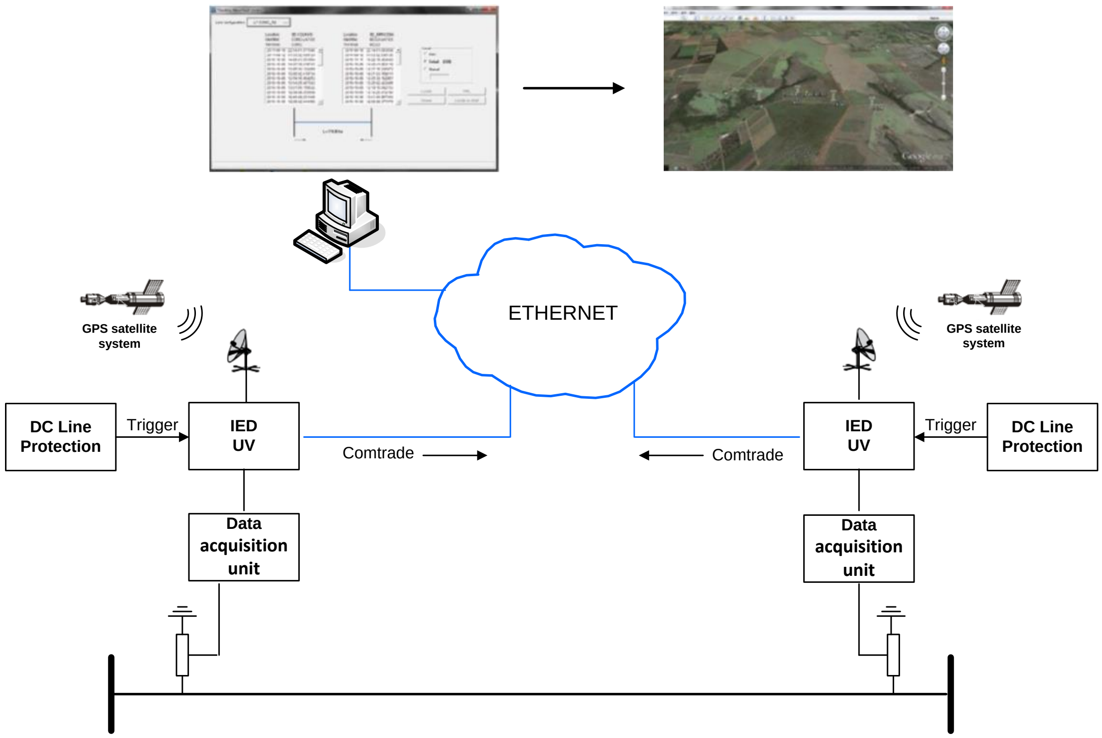

Figure 9: TWFL system arrangement

c) **Cross-trigger**

Whenever a particular device triggers a record it sends an Ethernet message requesting the receiving device to trigger the record as well. This feature ensures that both ends will trigger in the occurrence of any command to trigger record.

5.2. Operation

Data acquisition unit is continuously acquiring data from voltage sensor at 5mHz sampling rate, filtering at 1kHz to 1mHz and then buffering data to be always ready for the trigger. Once trigger happens, IED is instantly sending waveform acquisition request and waveform recording is started. It takes approximately 2 minutes to capture, prepare and transfer Comtrade file to the TWFL IED. Computer, where TWFL software resides in the system control center, is continuously checking if new records are available. Once new record is detected, it's uploaded visa Ethernet. Comtrades from both ends are time aligned and high frequency wave rising edge is detected automatically by the TWFL s/w and time stamp from both ends allows to calculate fault location automatically and display on the Google map.

There is a possibility to visualize TWFL records, check and manually adjust the rising edge of the high frequency to make sure is detected by the s/w correctly. Whole process of obtaining fault location takes 5-10 minutes and result of the fault location is available to system operator and sent via Modbus to all users.

6. Staged Testing

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

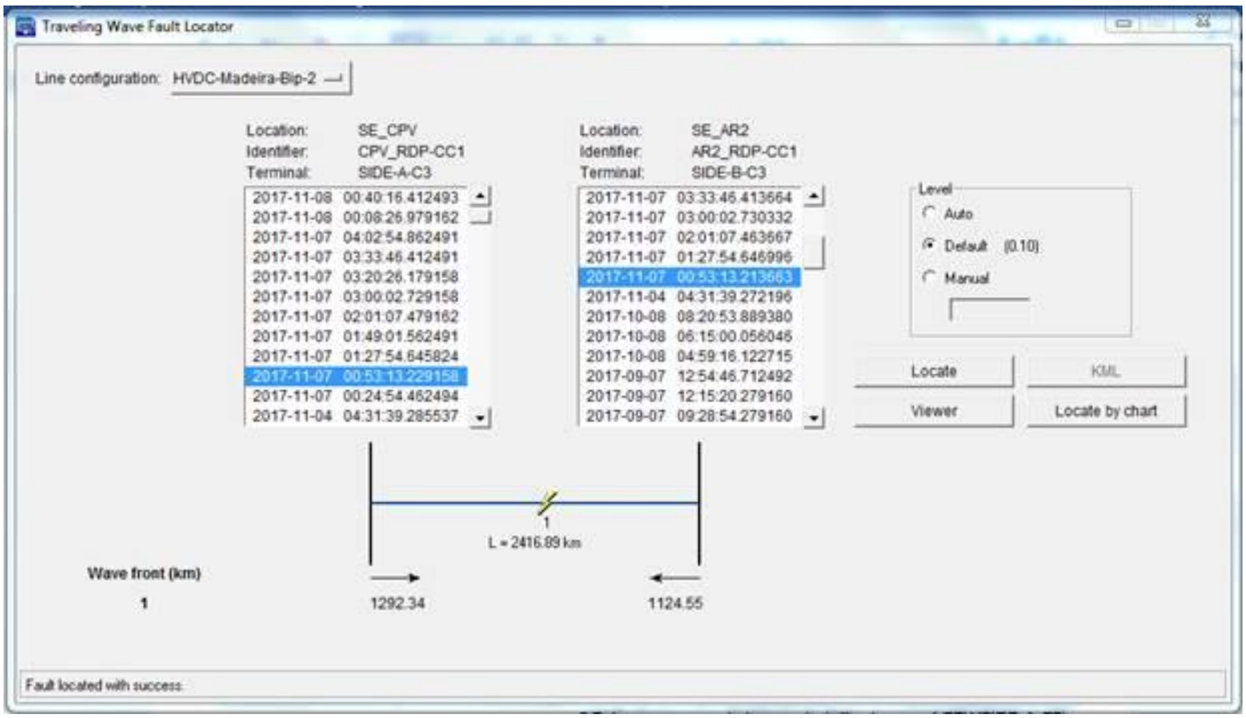

Figure 10: TWFL software reporting fault location

It is possible to notice that even after traveling a distance of more than 2300 km, the traveling wave still presents enough energy to be clearly capture by the acquisition system.

6.1. Staged short circuit tests results

There were 10 staged short circuit tests performed at different locations to validate performance, calibrate TWFL system and get confidence that TWFL system will provide operate adequately at this extra-long HVDC line. It has to be noted that span between line towers is 490m average, therefore error within 400m would be considered acceptable.

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

Fault location:

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

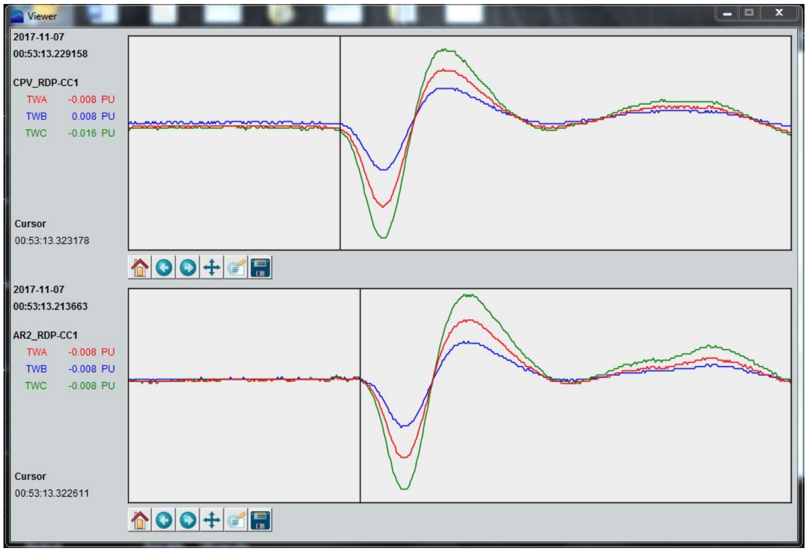

Figure 11: Test 1 waves capture

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

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

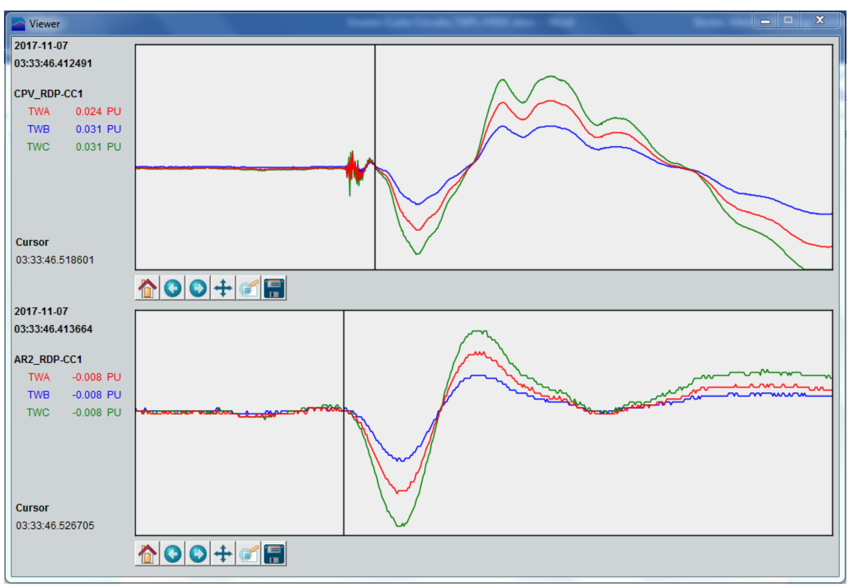

Figure 12: Test 2 waves capture

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

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

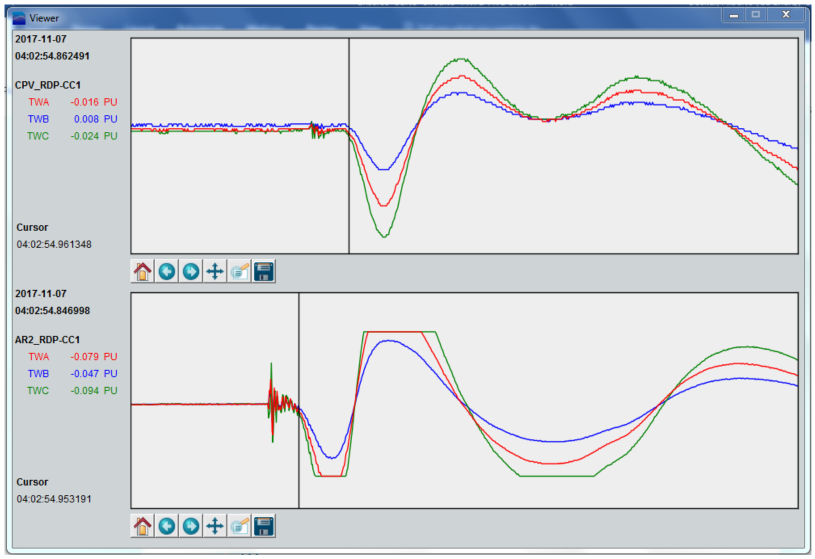

Figure 13: Test 3 waves capture

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

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

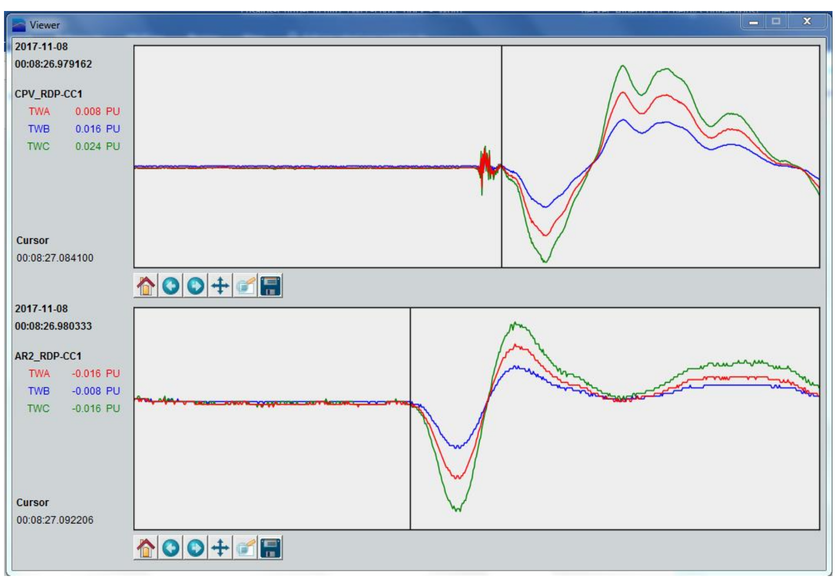

Figure 14: Test 4 waves capture

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

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

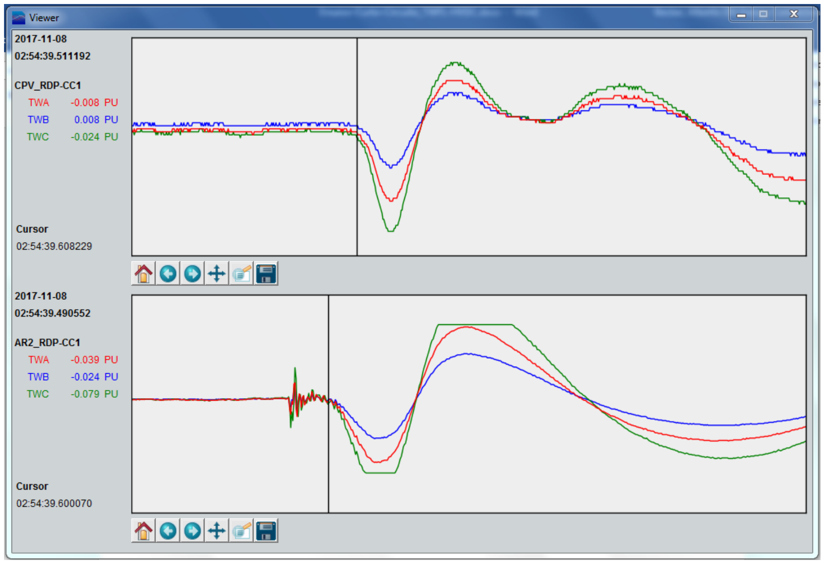

Figure 15: Test 5 waves capture

6.2.Fault Location Staged Tests 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 DC TWFL. The table below shows the real distance to fault, the fault location of the DC 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***

Table 1 Accuracy for DC TWFL for staged tests

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 calibration values were applied:

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

Table 2 Calibration of DC TWFL after staged tests

7. Conclusions

The tests demonstrated that it is possible to locate faults with a high accuracy in long 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 operating properly.

The DC 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 critical in very long transmission lines like the Coletora Porto Velho – Araraquara II, with long extension and crossing terrains with a very difficult access due to forests and rivers.

7. References

[1] "HVDC SuperGrids with modular multilevel converters — The power transmission backbone of the future". Ahmed, Noman; Stockholm, Sweden ; Norrga, Staffan.

[2] CIGRÉ TB 619 2015 HVDC CONNECTION OF OFFSHORE WIND POWER PLANTS.

[3] "Transmission and Distribution Networks: AC versus DC", D.M. Larruskain

[4] IEEE Smart Grid Experts Roundup: AC vs. DC Power, Retrieved from

http://smartgrid.ieee.org/resources/interviews/368-ieee-smart-grid-experts-roundup-ac-vs-dc-power.

[5] "Electric Power Systems", Alexandra von Meier. 2006.

[6] Alstom GRID. HVDC for beginners and beyond, Alstom Grid.

[7] Magazine of Operador Nacional do Sistema Elétrico, #04, Year 3.

[8] ONS. Mapas do SIN – Mapa de integração Eletroenergética. Retrieved from http://www.ons.org.br/conheca_sistema/mapas_sin.aspx

[9] GE publication RPV311-TM-EN-8A, RPV311Distributed Multifunction Fault Recorder - Technical Manual, 2017

Biography

Paulo Renato Freire de Souza

Received his graduation degree in Electrical Engineering from UFSC (Federal University of Santa Catarina) in 2011. He has been working in GE Reason since 2012, worked in several field projects applying Reason's products and is, currently, a product manager of the measurement products.

Alberto Becker Soeth Jr

Received his graduation degree in Technology Industrial Automation from College of Technology SENAI Florianopolis in 2005 and was post postgraduate in the MBA course of Business Planning and Management Systems from UFSC (Federal University of Santa Catarina) in 2009. He has been working in GE Reason since 2006, worked in several field projects applying GE Reason's products and as Technical Coordinator from several contracts. Currently in GE Grid Automation, he is Technical Support Coordinator from Latin America region.

Diogo Totti Custódio

B.S. degree in Electrical Engineering from Pontifical Catholic University of Minas Gerais, 2005 and M.S. degree from State University of Campinas, UNICAMP, 2009, Brazil. He has been working in Interligação Elétrica do Madeira since 2014 in protection and control of HVDC system.