Fault Location by Traveling Waves: Application in High Impedance Events

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Abstract

Because the market regulation in Brazil, power transmission companies are paid for the availability of their lines. When a fault occurs and the line becomes unavailable, such companies are penalized for the time the line is off service. Thus, fault location systems that can reach higher accuracy to estimate the fault location minimize the downtime of the line and, therefore, the application of penalties. Impedance-based fault location methods usually are not efficient in high impedance events. Traveling wave-based fault location technology provides good estimation independently of the type of the fault. This article shows the experience of implementing a traveling waves-based fault location system in Eletronorte (Brazil) transmission lines, which because of their geographical location and the climate of the region, have a large incidence of high-impedance faults. After a large number of events, the results show the reliability of fault location by using traveling waves, even if the wave fronts are shown with higher attenuation compared to those produced by low-impedance faults.

1. Introduction

The need to detect the fault location in a transmission line as quickly and accurately as possible has increasingly been considered by companies in the electric power sector. Market deregulation has changed the way transmission utilities manage their lines as they are not paid by the amount of power transmitted, but rather by the availability of their lines. The reason for that is that the concept of free energy market (generation prices) requires the transmission system to be always available for large energy block transfers. In this new model, the transmission utilities are penalized for the time a line is off service to the system after a permanent fault. The time needed for restoring the line to the system is mostly lost in locating the exact place of the fault. 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 the accurate time when the traveling waves (characterized by wave fronts caused by transients that occur in 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. In short-circuit faults (usually low-impedance 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.

This article shows the experience of implementing the proposed traveling waves system in the Eletronorte (Brazil) transmission lines which, due to their geographical location and local climate, have a large incidence of high-impedance faults.

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 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.

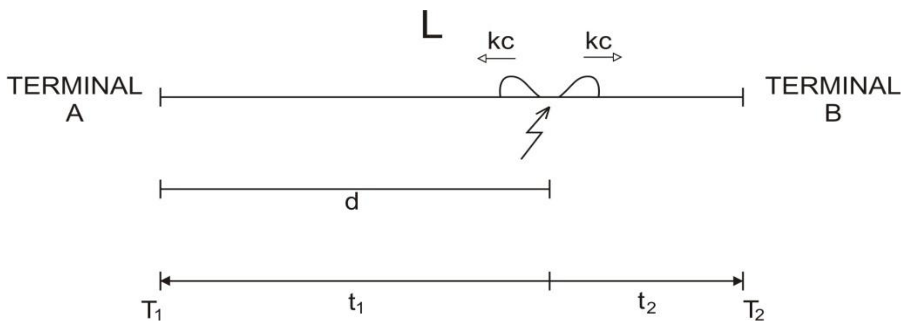

Figure 1: Principles for determining the fault location by traveling waves

By knowing the time stamp the 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:

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

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 peculiarities of the transmission 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 countinuous reflections.

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

Because it is a different technology to locate faults, 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 (60Hz in the case of Brazil), the traveling waves method is affected by different phenomena, 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 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.

Additionally, it is important to note that the traveling waves-based method always estimates the location of the fault, even in the case of high impedance faults. This type of faults often has errors when using impedance-based methods. A further advantage of the traveling waves method is that, conceptually, even in high impedance faults it estimates the fault location with the accuracy equivalent to that of a fault caused by a short circuit.

3. The Reason Traveling Wave-based Fault locator

Considering that traveling waves propagates all over the grid, the identification of the wave front related to the event in the line being monitored is critical in order to make the estimation of its location possible.

In order to read and record the wave front associated with the event, this system is based on the Multifunction Digital Fault Recorder, RPV-310 model, developed by Reason Tecnologia S.A. And to be able to record the traveling waves, specific modules related to the traveling waves acquisition (T31 – high speed acquisition module and U30 - traveling waves conditioning module) are added to the DFR.

The acquisition module has three independent channels, with an A / D converter for each channel. The acquisition is performed every 200 nanoseconds, synchronized with PPS (pulse-per-second). The voltages of the line to be monitored are applied to the traveling wave conditioning module. This module has efficient filters that limit the bandwidth frequency within the frequency spectrum of traveling waves to capture the desired signals.

The fault location system considers 2 units, one on each end of the line, connected to the voltage transformers. It is mandatory that these units be synchronized by GPS-based time references to provide RPV310-TW the accurate time stamp for recording the traveling waves when they reach each of the ends of the line.

When a fault is detected by crossing some thresholds set in the RPV310-TW (such as overcurrent, undervoltage, level of negative sequence, circuit breaker open, etc), a traveling wave record is created. The records, which have the wave fronts related to the fault, of each end of the line are used to make the location by the software called *TW Fault Locator* which is part of the *RPVTools* package.

4. High impedance faults

The transmission line is the part of the electrical system most susceptible to failure due to weather conditions, fires, vandalism, current leakage in the chain of insulators, vegetation growth, etc..

In faults caused by short circuits, with a clear discontinuity of the voltage or current signals, it is possible to detect wave fronts whose profile is a short rise time with high amplitude range. With the acquisition system presented in this paper, these phenomena will in most cases lead to saturation of the acquisition system. An example of that is shown in Figures 2 and 3.

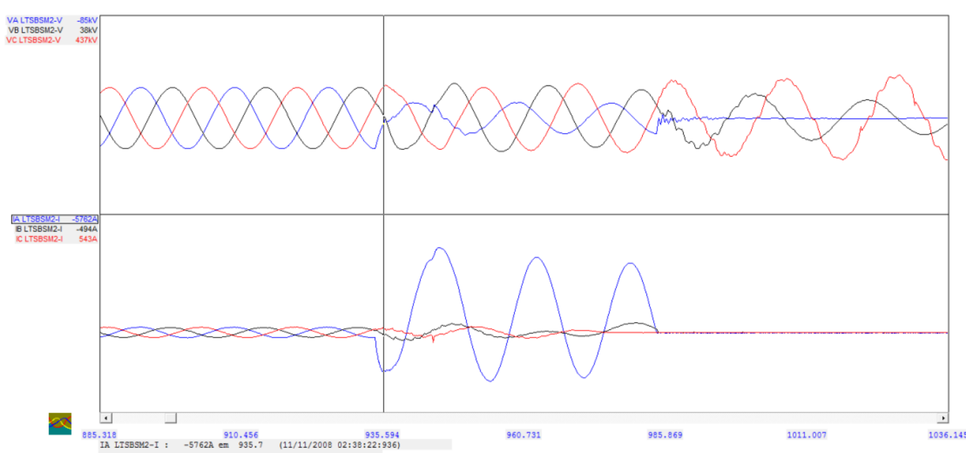

Figure 2: Short-term record of a low impedance fault

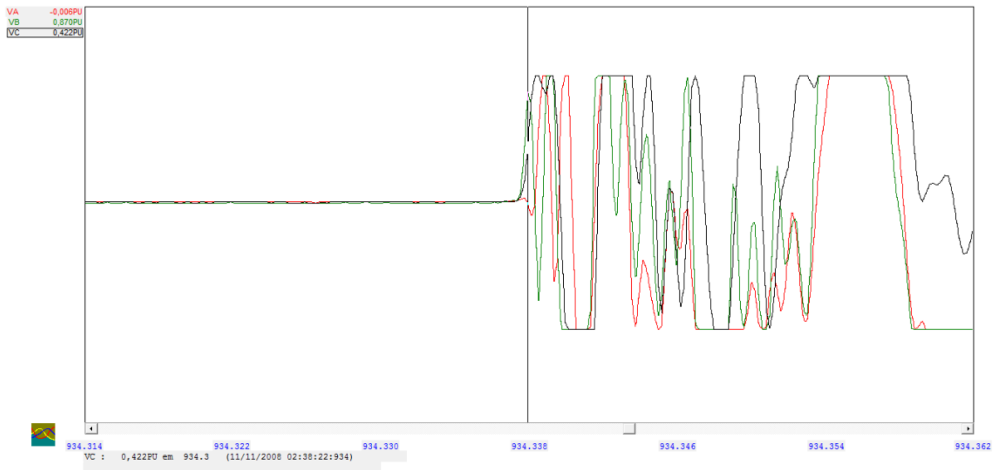

Figure 3: Traveling wave record of a high impedance fault

Since the object of the acquisition system is to create traveling waves records where the time stamp of the beginning of the wave fronts can be identified, the fact that the acquisition system saturates does not interfere in the fault location.

But in faults where there is not a clear discontinuity (as events related to high impedance), it is possible to note that the wave fronts are much smaller than the amplitudes of wave fronts from short circuits. Figure 4 shows a short-term record with a small discontinuity in the signal and Figure 5 shows the traveling waves related to the such fault.

By evaluating the intensity of traveling waves, it is possible to note that the signal intensity of traveling waves generated by high impedance faults could be less than 10% of that generated by low impedance faults.

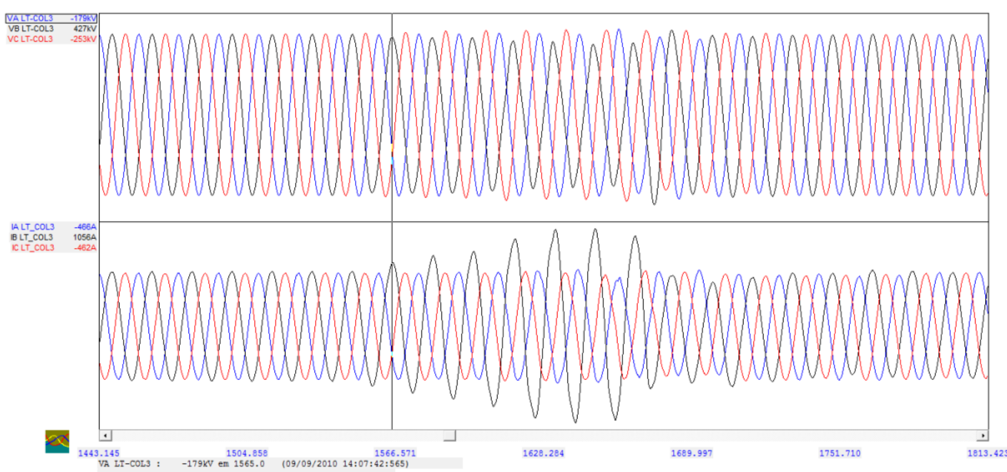

Figure 4: Short-term record of a high impedance fault

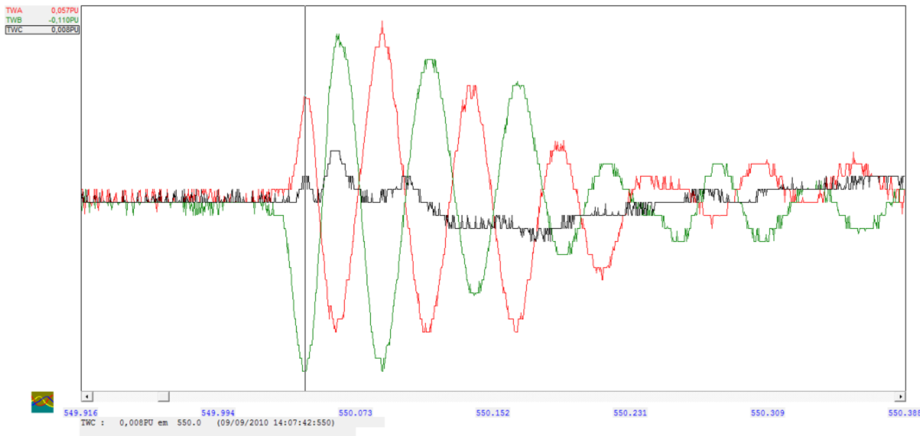

Figure 5: Traveling wave record of a high impedance fault

Considering that the DFRs are constantly monitoring both ends of the line, when an event occurs and each DFR is properly configured, both devices are triggered and create traveling waves records. Independent of the intensity, it is possible to note that the wave fronts related to the fault are present in these records and their time stamps can be identified to estimate the location of the fault.

As shown in Section 3, Reason´s traveling wave-based fault locator considers that the records with wave fronts are obtained from the monitoring of quantities at low frequency, i.e., from measurements of voltages, currents, or digital channels (electrical inputs or GOOSE messages) or by the derived quantities. Thresholds are created considering these measurements and grouped to form a trigger logic to enable the recording of traveling waves.

In high impedance faults, the time for a threshold to be triggered is usually greater. In this case, a suitable trigger logics for the line being monitored allows the wave fronts to be recorded properly.

Once the records of traveling waves are created, they are uploaded to the analysis center (operator computer or a server) to run the algorithms for fault location. These algorithms seek the time stamp of the beginning of the wave front and, based on such time stamps, estimate the location of the fault. Even when the wave front has low intensity, the algorithms allow to locate the fault location with great accuracy. When using impedance methods, the results for this type of fault commonly produce large errors which can make their use unfeasible.

5. Eletronorte cases

Because the climate in Northern Brazil is tropical, there are a dry season and a rain season well defined. In dry season it is common to have incidences of fires caused by farmers clearing vegetation to cultivate the land (queimadas), by natural events or by human imprudence. These fires can be of such high proportions that in some cases they cannot be easily controlled. Because the burned area can be quite large, it is possible for these fires to reach areas close to transmission lines, and thus, cause faults.

Since the area covered by Eletronorte is located in or very close to the Amazon region, it is not always possible (because environmental laws) to carry out preventive trimming of the trees along the transmission lines and the growth of such trees could generate faults in the system.

Eletronorte is the power utility in charge of supplying energy to the nine states that make up the “Legal Brazilian Amazon”. Through the SIN (National Integrated System), Eletronorte also provides power to other areas. It has a total generating capacity of around 10,000 MW (comprehending the fourth largest hydroelectric plant in the world - Tucuruí) and almost 10,000 km (6250 mi) of transmission lines. This power is transmitted through long lines that are part of the North-Southeast interconnection. These lines provide energy for large industrial centers in southeastern

Brazil through basic power transmission lines (500 KV lines) making them essential for the proper functioning of the electrical system in the country. Figure 6 shows the area covered by Eletronorte.

Inspecting lines in a region where the faults must be seek is a hard task for the field staff. Such lines cross forests, rivers, pass along areas not provided by good roads, etc. Thus, for Eletronorte, locate faults with good precision is mandatory to reduce the time to solve problems. Because of that, traveling wave-based methods could help the field staff to go to the exact point where the fault occurs using the best route to arrive there.

Figure 6: Area covered by Eletronorte

In Brazil, the power transmission companies are penalized by the downtime of the line, this means that if faults that open the line occur, depending on the time the line stayed off, the company has a discount of the profits that would be earn.

In the dry season there is a large quantity of fires that occasionally reach transmission lines, and thus, leading them to open. Knowing the exact location of these faults contributes to a more rapid identification of the phenomenon that generated them and consequently to a faster to action to solve them in order to avoid future occurrences. Moreover, in situations where it is possible to give a justification, the company may not be penalized.

Faults caused either by fires or by vegetation growth are usually of high impedance and fault locators based on impedance methods are not efficient. Therefore, the Reason RPV310-TW units have been installed in some lines which historically have had higher incidence of failures in order to identify more precisely the location of faults.

After some events have occurred, the results were verified to evaluate the performance of the proposed system.

6. Results

Two transmission lines were evaluated. They were chosen because of their specific characteristics. They are:

- 230 KV transmission line between the Tucuruí hydroelectric power plant and the Altamira substation which has a nominal length of 325.73 km and is part of the Western region interconnection. Figure 7 shows the location of such line. It is important to note that there is a three terminal line monitored by travelling waves only in two terminals (Ruropolis-Altamira).
- Circuit 3 of the transmission line that connects the Miracema and Colinas substations. This line is a part of the “North-Southeast interconnection” that provides power to the most industrialized region of Brazil. Figure 8 shows the location of such line. Its length is of 174 km. it belongs to INTESA but it is operated by Eletronorte.

Both transmission lines use series capacitors and phase-shifting to improve stability. Therefore, the location of the fault becomes difficult when using traditional impedance-based methods.

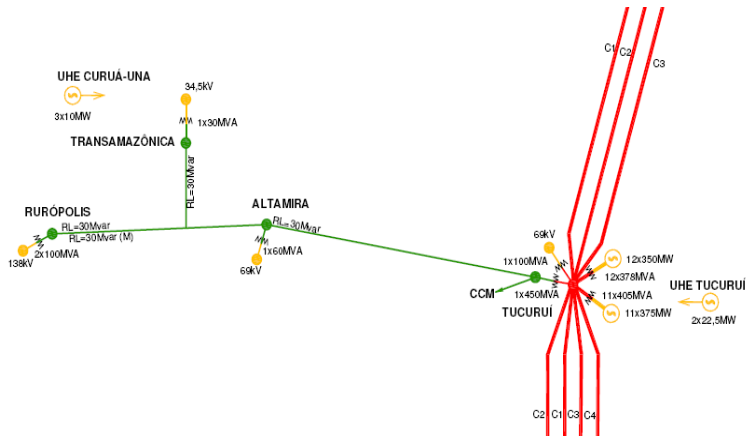

Figure 7: Map of Tucuruí - Altamira transmission line

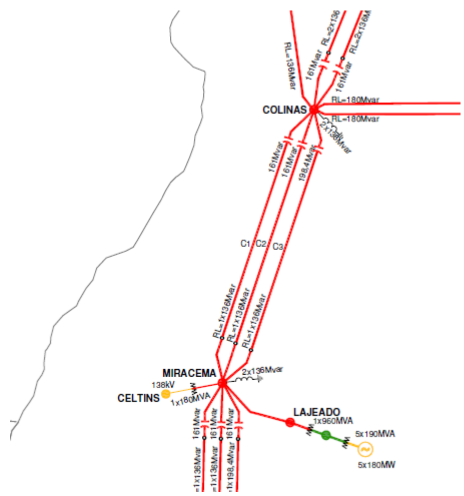

Figure 8: Map of Colinas - Miracema transmission line

A RPV310-TW was installed in each substation being monitored. These devices were connected via Ethernet network to an operation center where operators could have access to the records of traveling waves and could run the software for estimating the location of the fault.

6.1 The Tucuruí - Altamira transmission line

During the period under analysis, many faults have been verified. Most of them were related to high impedance events, mainly caused by fires or by vegetation growth. Figures 9 and 10 show the short-term records, from both ends of the line, of a typical occurrence. Such event occurred on May 10, 2010 at 12:40 pm.

It is possible to note that the current in phases B and C slowly increases while the current in phase A decreases, which is characteristics of a high impedance fault and not a short circuit (which would have caused an immediate drop of voltage in phases B and C).

In that fault, algorithms for fault location based on impedance methods (provided by the protective relay or by the Reason Analise software) are not able to estimate the location of the fault.

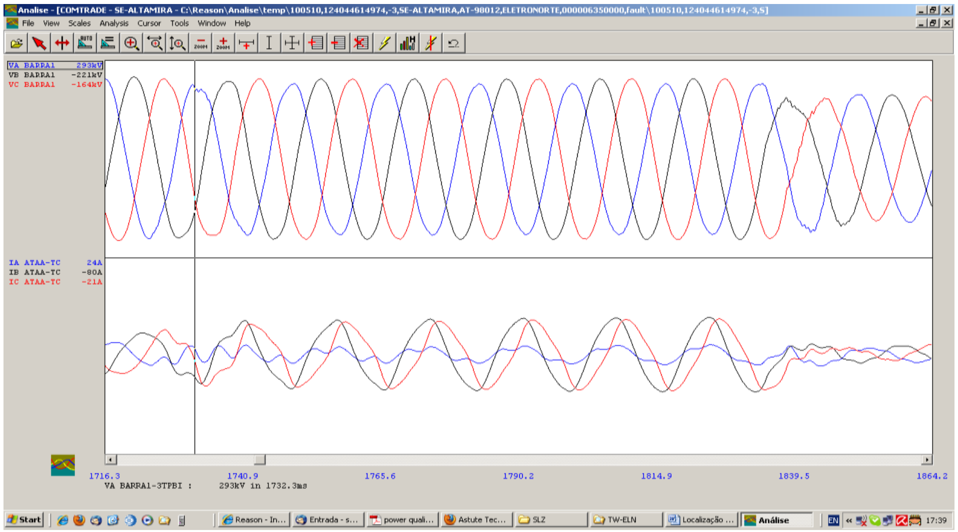

Figure 9: Short-term record of the Altamira substation

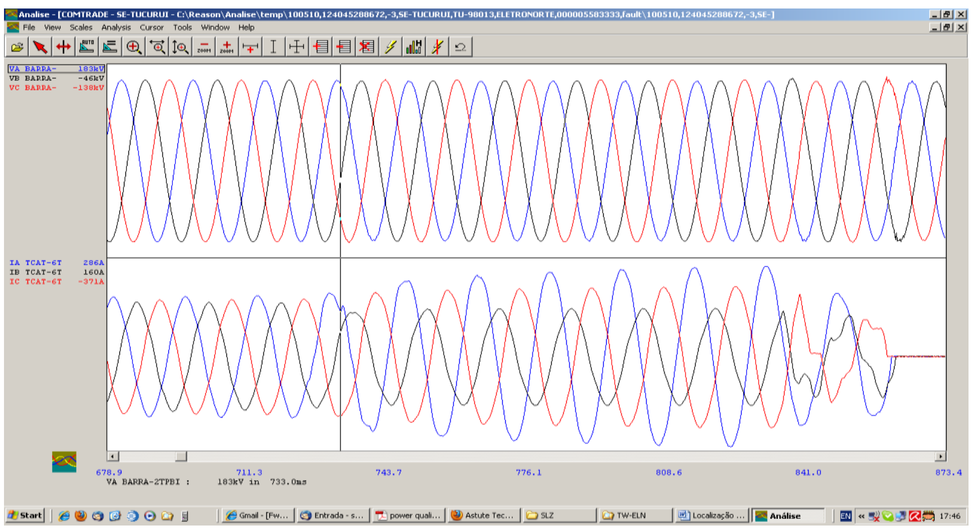

Figure 10: Short-term record of the Tucurui substation

Figures 11 and 12 show the traveling waves and the voltage measurement recorded on both ends of the line.

Because the fault was related to a high impedance event, the intensity of the traveling wave was lower. By making the relationship between Traveling wave records and the short-term records, it is possible to visually correlate the wave front with the instant the fault begun.

Thus, either by visual analysis of the records or by using the Software TW Fault Locator (which runs automatic algorithms based on traveling waves to locate the fault), the location of the fault was estimated in 290,986 meters from the Tucuruí power plant. The field staff inspected the line and detected that the fault was caused by a palm tree located between towers number 746 and number 747 (291,043 m and 291,361 m, respectively) which means an error between 57 and 372 meters, or 0.01% and 0.1% of the length of the line.

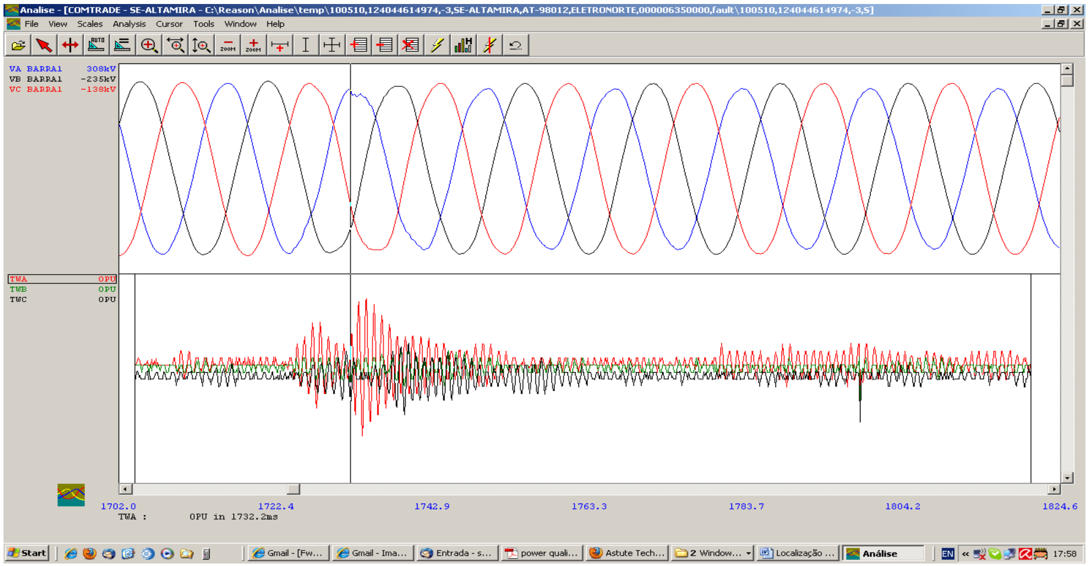

Figure 11 – Voltage measurement and traveling waves recorded from the Altamira substation

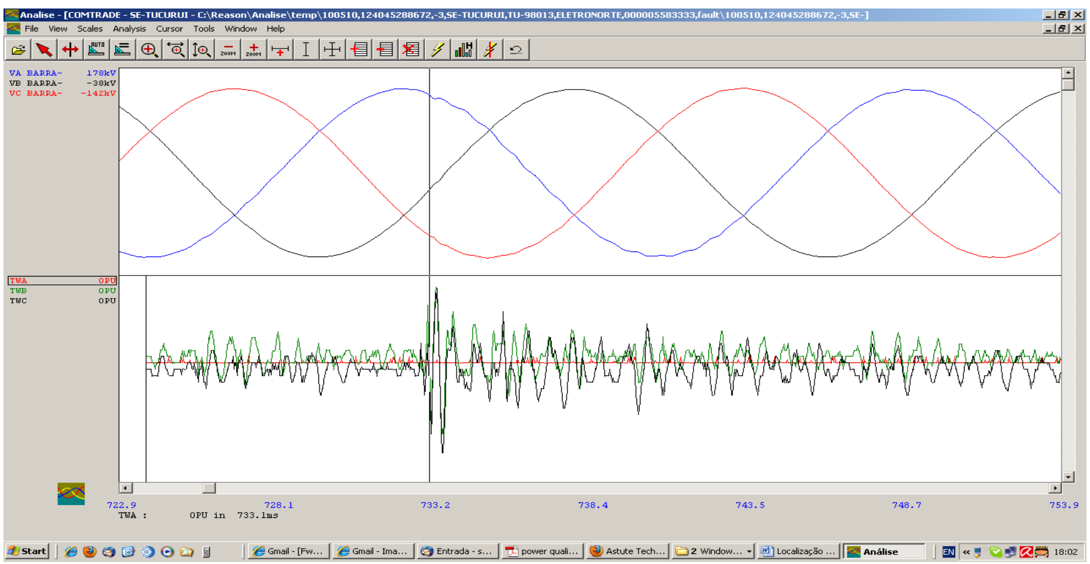

Figure 12 – Voltage measurement and traveling waves recorded from the Tucurui substation

Other faults related to high impedance events have happened and the estimation of the location was verified by the field staff. Table 1 shows a comparison between the location estimated and the place determined through the inspection of the line for such events.

Date	Location estimated	Location inspected	Error (meters)	Error (%)
2009/09/20	122520	122430	90	0.028
2009/09/27	325680	325730	50	0.015
2009/10/10	99510	99585	75	0.023
2009/10/22	194620	194221	399	0.122
2009/11/09	156960	157077	117	0.036

Table 1: Comparison between location estimated and the place determined through inspection the line

6.2 The Colinas - Miracema transmission line

Over a period of 45 days, more than 70 events were counted in the circuit being analyzed. Most of these events were related to fires. The short-term and traveling waves records have the typical behavior for such occurrences. However, it is possible to note that in a short period of time, the location of the fault estimated for a sequence of several events was related to the same place. Table 2 shows some of these estimations.

Date	Estimation (m)
2010/09/03 04:38:28	173402
2010/09/04 10:44:32	173402
2010/09/07 15:23:49	173550
2010/09/07 16:45:12	174143
2010/09/20 12:49:10	76181
2010/09/20 12:52:41	76774
2010/09/20 13:30:11	76626
2010/09/20 13:33:02	76477
2010/09/20 14:27:35	77366
2010/09/20 14:37:43	77070
2010/10/06 12:09:54	62270
2010/10/06 12:35:02	62547
2010/10/06 12:58:08	62843
2010/10/06 13:14:25	62695
2010/10/06 13:19:16	61806

Table 2: Sequences of the fault location estimations

Considering the repeatability of the fault location estimated in a short period of time, the field staff performed the inspection of the line and, as estimated, verified the presence of areas burning near the transmission line.

Therefore, based on the estimations of the fault locator, it was possible to identify the location of the faults, their reasons, and to take actions to resolve them. Additionally it was possible to show to the regulatory agencies that the operation was not viable, thus, avoiding penalties related to unavailability of the line.

7. Conclusions

Because of regulations that make the relation between the payment to the power transmission companies and the availability of the line, the rapid and accurate identification of the location of a fault becomes an effective tool for a line to be reestablished as soon as possible and consequently losses that may reach thousands of dollars due to the unavailability could be minimized by such companies.

In general, impedance-based fault location methods have very large errors when the failure was related to high impedance. Traveling waves-based fault location technology made it possible to locate faults with high accuracy and excellent reliability, independently of the type of fault. For Eletronorte it was a very important issue because performing the inspection of the line in the Amazon region generates high costs and demands time.

The system presented shows the efficiency in locating faults when using the traveling waves records. The results showed a good estimation for fault location in events which traditional methods are not able to estimate. This leads to a quick recovery of the line since the difficulty of the field staff in getting to the exact place of the event is reduced.

8. References

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Biografy

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