

The Furnas line was selected because it has a high number of protection actuations per year. It is a long, series compensated line, presenting a significant challenge to precise location of faults using traditional impedance-based methods.

Another major cause of faults on the line, are the droppings of a local bird - “Curicaca” - on the towers isolators (Figure 3). The constant re-closing and high temperatures from electric arcs can create small cracks on insulators and eventually produce a permanent fault.



Fig. 3. Curicaca Bird Standing on a Tower

Eletronorte has a total of 59 substations with a transformation capacity of 26.562 MVA, 10,573 km of transmission lines from 138kV to 500 kV and 11 power plants (9787 MW total).

Two different sources of fault occurred on the Eletronorte lines: one was caused by vegetation fires around the transmission lines and the other one by approximating a thin wire on transmission line and causing a short-circuit, as shown in Figure 4.



Fig. 4. Induced Short-Circuit on Transmission Line

This test was conducted during a maintenance of the line.

II. TRAVELING WAVE FAULT LOCATOR

The Reason TW system is composed of two fault locator devices and two GPS-based clocks. The traveling wave devices are connected to the line potential transformers on each end of the line. The GPS clocks are used to synchronously record the precise time that the traveling wave reaches each terminal of the line.

The TW method only needs to know the cable length of the line (l), the line attenuation speed of the traveling wave (k), and the time difference between the times of arrival of the traveling waves at each end of the line ($t_a - t_b$), as shown in Equation 1.

$$d = \frac{l + kc(t_a - t_b)}{2}$$

Equation 1 – TW Fault Location Computation

Compared to impedance methods, a significant difference is the absence of reliance on information regarding line parameters at the nominal frequency of 60Hz or 50Hz. In fact, traveling wave fault locators remove the nominal frequency content using a high pass filter in order to completely eliminate it.

It is important to distinguish between line and cable length. The length of the line is usually calculated as the geographical distance between the towers (Figure 5). This is valid for impedance methods, since distance is proportional to the impedance of the line. It is also valid for distance protective relays that are designed to work by zones and not by the exact distance to the fault.

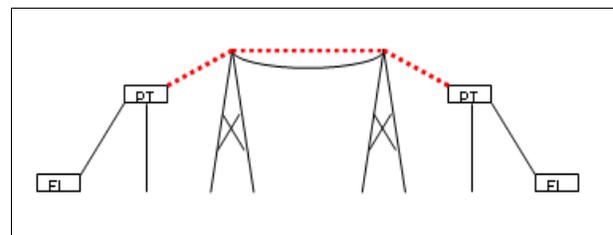


Fig. 5. Cable Length for Impedance Methods

However, the traveling wave method is based on the total cable length between the fault locator devices, including the cables from potential transformer to the terminals of the fault locator, as shown in Figure 6. It is not unusual having cable longer than 500 meters (1,500 feet) from the PT to the fault locator device installed in the cabinet.

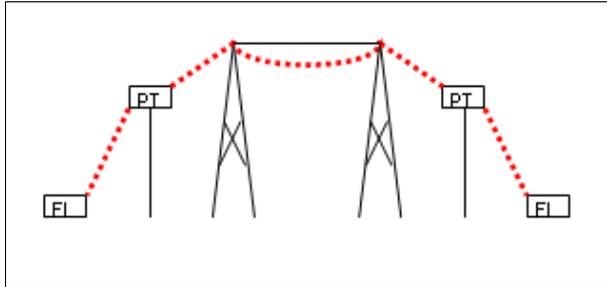


Fig. 6. Cable Length for Traveling Wave Methods

Considering that TW precision is in the range of few hundred meters (yards), failing to include the length of cables in calculations can produce large fault location errors.

Information about the propagation speed of the traveling wave is also required to compute the fault location using the TW method. Cable speed is usually around 98% of the speed of light for overhead transmission lines and close to 50% on underground cables.

Cable wave speed can be calculated using line parameters, or measured using TW fault locators. Calculated values are often similar to measured ones. However, the propagation speed should ideally be measured, since even a small difference can have a significant impact on the precision of fault location.

Line propagation speed can be measured by generating a traveling wave by opening a breaker, switching a shunt reactor, or protection of a series capacitor, since they are in a known location.

Reason TW fault location devices capture the traveling wave using a circular buffer with a 5 MHz sampling rate synchronized with the GPS clock.

The fault locator band-pass filter is designed to capture signals from 1 kHz to 1 MHz, thus eliminating all known voltage and current signals at nominal frequency. In other words, TW records are not stored in normal line operating conditions.

Figures 7 and 8 show the captured records of a fault that occurred in 22/04/08 on both ends of the transmission line at Furnas.

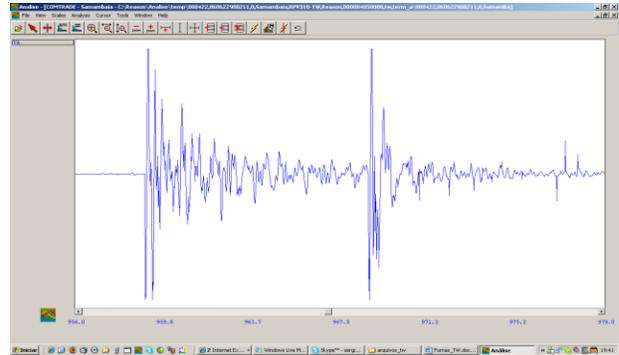


Fig. 7. Traveling Wave at Samambaia Terminal

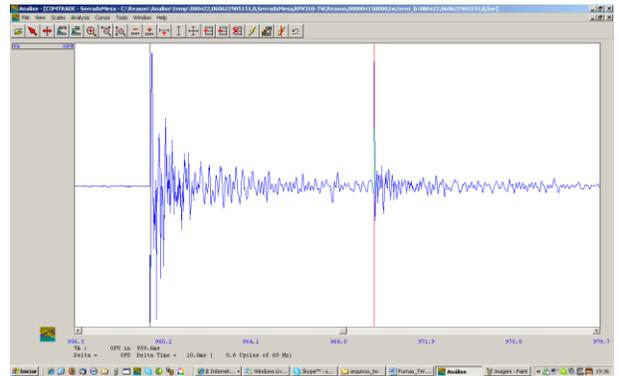


Fig. 8. Traveling Wave at Serra da Mesa Terminal

It is possible to see that actually two traveling waves were captured spaced 10ms from each other. This is due the activation of the gap from the series capacitor protection 10 ms after the beginning of the fault to avoid an over voltage in the series capacitor.

Figure 9 shows a zoom of the waveform captured where is possible to see that the waveform of the traveling wave is smaller than the waveform of the fundamental wave. But, the most important information is the timestamps of the traveling wave arrival at the terminals of the line.

Figure 10 depicts the standard fault recording from the moment of the fault, where is possible to see that the two discontinuities in the voltage occurred in less than one cycle.

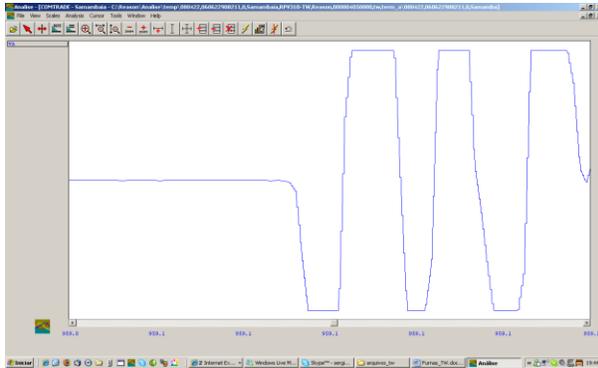


Fig. 9. Details of the Waveform Captured

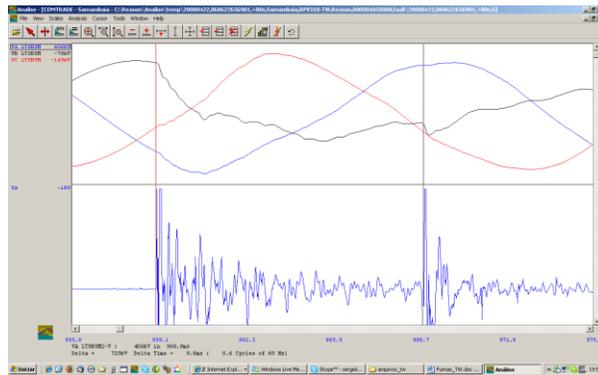


Fig. 10. System Voltage Waveform and Discontinuity

Another important point related to fault location device based on traveling waves is that they cannot be tested with standard test sets as usually the maximum frequency that they can reproduce is around 1000Hz, below the frequencies generated by traveling waves.

This means that the devices cannot be tested during commissioning using standard tests. The only way is to actually measure a traveling wave generated by equipment installed in a known position on the transmission line, like a breaker, switch or reactor for example.

III. TRIGGERING APPROACH

Although the traveling wave capturing for fault location is not a new technology and being on the market for some time, the innovation used here makes it unique and solves the problems of missed faults.

Usually the fault location device capture the time of arrival of the traveling waves on each terminal when a threshold level is violated in the high frequency sampling.

This approach has been used with some success but from time to time the device does not record the traveling wave on one terminal, making it impossible to calculate the position of the fault.

The main cause for this missed fault is that the device does not record the correct traveling wave, that is, the first traveling wave caused by the fault itself.

This equipment work with a concept of triggering not on the high frequency content of the fault, but on the nominal system frequency (50Hz or 60Hz) by starting the high frequency recorder when an over current, under voltage or other phenomena is detected in the nominal system frequency as a standard digital fault recorder (DFR) uses to capture a fault.

Once a fault is detected in the nominal system frequency and recorded with the 5 MHz recorder, it is processed in order to locate the traveling wave and locate the fault.

The advantage of this approach is that always the traveling wave will be recorded and no fault condition will be missed, as can occur with the traveling wave fault locators that trigger based only on the high frequency content of the signal.

The main disadvantage of this method is the additional disk/memory storage necessary to keep the pre-fault data.

IV. RESULTS

A. FURNAS TRANSMISSION LINE

Impedance based fault location is the most known technology used today to find the position of a fault in a transmission line. There are two different methods that can be used to locate a fault based on impedance: one end algorithms and two ends algorithms.

There are a number of papers in the literature that describe the disadvantages of one end fault location due the fact that part of the information, the contribution of the other end to the fault is, by different ways not considered in the equation in order to make possible the fault location using voltage and current information from just one end of the line.

Two ends fault location on the other hand is less prone to errors as it actually uses all information available. Although this do not significantly improves the precision, it will make the solution much more stable than one end fault location, as the main reason to errors are PT, CT and line parameters errors.

However, on both cases, the precision is still a percentage of the line length, desired to be $\pm 1\%$ but actually around $\pm 5\%$ in most cases. For a transmission line as the one presented in this paper, with 248 km this represent almost 25 km that the line patrol personnel will have to inspect in order to find the fault.

Table I lists the real and measured positions recorded by four different fault location solutions for the first fault located after installing the traveling wave system at Furnas.

The algorithms used on the commercial software for impedance fault location from Reason and Furnas are identified as Takagi [5], [6] for the one terminal algorithms and Johns and Jamaly [7] for the two terminal algorithm and probably have minor implementation differences as the software from Reason and Furnas show slightly differences

in the results for the same fault.

For example, in Table I, the error with the traveling wave equipment is of 0.2% of the line, and using the software the utility has, this same fault has errors from 3.9% up to 9.2% of the line length.

It is important to notice that although the transmission line is series compensated and this causes sub synchronous frequencies during faults, the protection device of the series compensator capacitor actuated very fast and the phasor information used to locate the fault with impedance methods was obtained just from the waveform after the bypass of the series compensation [3]. Also, the small errors of Table I for impedance methods are the result of a “best choice” of the instant to extract the phasors in order to lower the errors.

TABLE I
COMPARISON BETWEEN DIFFERENT ALGORITHMS
FOR SAME FAULT

| Algorithm | Samambaia | | Serra da Mesa | |
|---------------------------|-----------|-------|---------------|-------|
| | km | Error | km | Error |
| Real position | 41,9 | - | 206,6 | - |
| TW device | 42,3 | 0,2% | 206,2 | 0,2% |
| One end impedance Reason | 32,2 | 3,9% | 183,7 | 9,2% |
| One end impedance Furnas | 31,5 | 4,2% | 188,9 | 7,1% |
| Two ends impedance Furnas | 30,4 | 4,7% | 218,2 | 4,7% |

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order to lower the errors.

Table II shows the results from the first faults that occurred on the transmission line after the traveling wave fault location system was installed.

There were several faults where the line patrol personnel only found the fault after the second fault on the same position. The first actuation of each fault had a successful re-closing of the line and the line patrol was only sent to locate the fault after the second fault on the same position.

TABLE II
REAL AND MEASURES LOCATION FOR THE FIRST FAULTS

| Date | Location (km) | | Error |
|----------|---------------|--------|-------|
| | Measured | Actual | |
| 22/04/08 | 206.26 | 206.64 | 0.18% |
| 21/05/08 | 206.26 | 206.64 | 0.18% |
| 03/06/08 | 121.90 | 121.60 | 0.25% |
| 07/06/08 | 122.04 | 121.60 | 0.36% |
| 27/09/08 | 213.25 | 213.68 | 0.20% |
| 01/10/08 | 197.45 | 197.50 | 0.02% |
| 07/10/08 | 196.19 | 197.50 | 0.66% |
| 20/10/08 | 140.58 | 140.07 | 0.35% |
| 30/10/08 | 145.51 | 144.35 | 0.80% |
| 01/11/08 | 145.48 | 144.35 | 0.78% |
| 01/11/08 | 201.27 | 201.14 | 0.06% |
| 01/11/08 | 138.26 | 137.53 | 0.53% |

B. ELETRONORTE TRANSMISSION LINES

Table III indicates the locations measured by the TW-based fault locator system and short circuits actual position.

TABLE III
REAL AND MEASURED POSITION FOR INDUCED SHORT-CIRCUITS

| Date | Location (km) | | Error |
|----------|---------------|--------|-------|
| | Measured | Actual | |
| 09/20/09 | 122,43 | 122,52 | 0.07% |
| 09/27/09 | 325,73 | 325,68 | 0.02% |

Table IV displays the recorded values by the

TW-based fault locator and the real location of the short circuits caused by fires under the transmission line.

TABLE IV
REAL AND MEASURED POSITION FOR FIRE SHORT-CIRCUITS

| Date | Location (km) | | Error |
|----------|---------------|--------|-------|
| | Measured | Actual | |
| 10/10/09 | 99,58 | 99,51 | 0.08% |
| 22/10/09 | 194,22 | 194,62 | 0.20% |
| 11/11/09 | 157,07 | 156,96 | 0.07% |

V. CONCLUSIONS

This paper shows a comparison of different algorithms for fault location, including traveling wave, for actual faults in a transmission line. The accuracy obtained using the traveling wave method was far greater than using impedance-based methods. Faults that occurred after the installation of the traveling wave device were located with a high degree of precision.

The total time needed to fix the problem on the line was greatly reduced because line patrol personnel were able quickly find the fault location by going directly to the point indicated by the traveling wave device. The system's accuracy was consistent throughout the tests, even in complex transmission configurations, including parallel lines with series compensation.

These results demonstrate that the Reason traveling wave fault location solution can greatly reduce the time it takes to identify and correct a fault on the line, significantly minimizing the financial consequences of a power outage, and voiding faults altogether by providing utilities with a cost-effective way to find problems in their transmission lines before they cause a permanent fault.

VI. REFERENCES

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VII. BIOGRAPHIES

Sergio Luiz Zimath, earned his B.S. degree in Automation and Control Engineering from Federal University of Santa Catarina in 1997. He works for Reason Tecnologia since 1995. He is involved in technical sales and product development, including GPS clocks and digital fault recorders. He has participated in several research projects and presented in numerous national and international conferences.

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