Application and Results of Travelling Wave Fault Locator (TWFL) technology applied in a 220 kV Line.

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1 INTRODUCTION

The ability to accurately determine the location of faults on power systems lines is important. It facilitates faster inspection and shorter repair times, leading to faster restoration of the faulted lines. At the same time, accurate fault location is a technical challenge because fault location estimation is done based on the limited amount of information gathered at the line terminals. Problems which must be overcome include finite transmission line parameters accuracy, instrument measurement errors, coupling to adjacent transmission lines, unknown and often non-linear fault resistance, and finite duration of faults resulting in short time window opportunity to capture necessary data.

The grid reliability and performance is increased when a problem occurred in HV transmission lines can be located precisely, with a few hundred meters of accuracy, enabling a faster reparation or locating the line weaknesses. The travelling wave fault locator (TWFL) method works on the principle of capturing the step wave generated on a fault, propagating in both directions from the fault point, and measuring its arrival time at both ends of the transmission line. To do so the voltage is sampled at MHz, triggered by external activation such a trip or internal threshold, on each line end and processed with a dedicated high speed algorithm in the main unit that permits the detection of such waves and its localization. This localization can be done in a line up to two sections, i.e. one aerial followed by an underground.

This paper describes a practical case implemented in a 220kV line located in Lleida (north-east Spain), and owned by the Spanish TSO (REE), where an increase on fault rate was noticed. The use of TWFL was decided, due to its special topology, and because the traditional impedance method cannot be able to give an accurate location on the multiple faults occurred, in most of the cases the fault location from both ends are widely overlapped; therefore the equipment was installed as a non-permanent installation to accurately locate the problems, mostly defective isolators. Results of the equipment performance during real faults are also analyzed, showing the advantages of an accurate supervision and its positive impact, resulting in minor costs of the maintenance activities and identification of defective isolators derived from a precise fault localization.

2 THEORY APPROACH

2.1 *Traveling Wave Technology*

A fault at any point on the voltage or current wave other than at zero launches a step wave, which propagates in both directions from the fault location as shown in Fig. 1 (in the unlikely case of a fault at voltage zero, a ramp wave is launched). One method of determining the fault location uses precise measures of the TW arrival times at both ends of the transmission line.

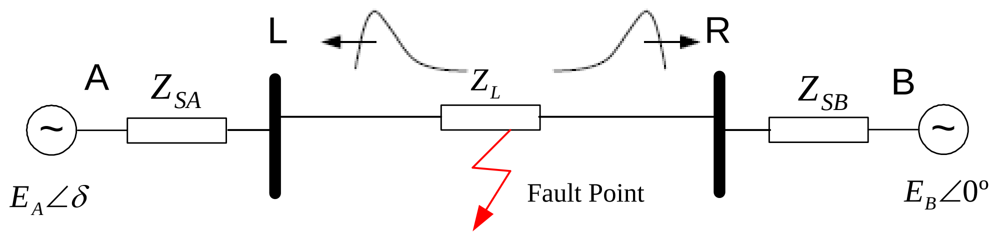

Figure 1. Line Schematic.

Modern TW fault locators using a common time reference for the devices capturing the TWs at the line terminals are, in principle, simple. This TW fault locating approach, shown in Fig. 1 (at L & R terminals), is known as Type D.

In Type D TW fault locating, the required wave arrival times are measured with a common time reference and are exchanged to calculate the fault location as follows:

$$m = \frac{1}{2}[\ell + (t_L - t_R) * k * v] \qquad (1) \qquad [1]$$

Where:

ℓ is the line length.
t_L is the TW arrival time at L.
t_R is the TW arrival time at R.
v is the speed light.
k is a constant that depends on the characteristics of the line (0,95….0,98)

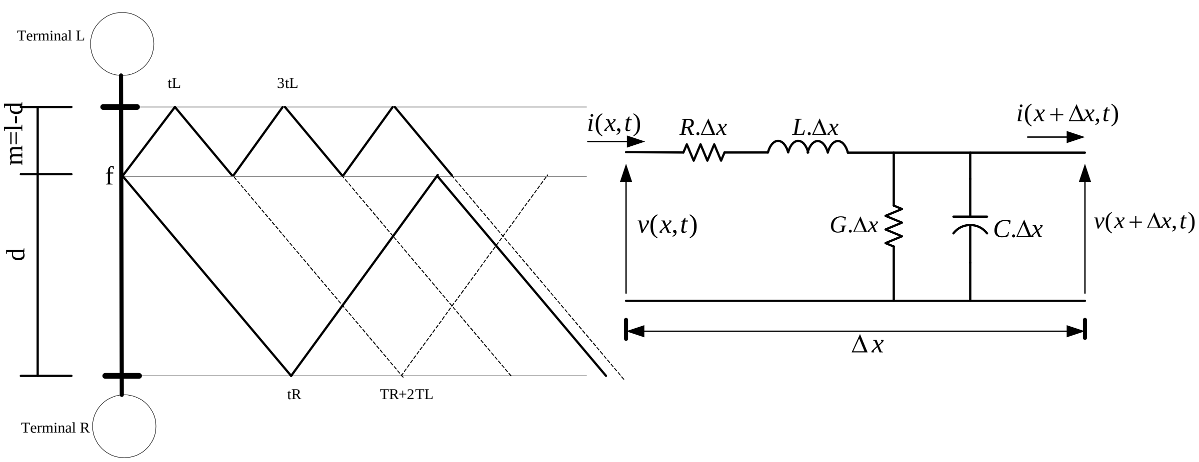

Figure 2. Electrical system, Lattice drawing and circuit for analysis.

2.2 Basic Theory

Fig. 2 shows also the equivalent circuit of a segment with length Δx of a two-conductor transmission line. The circuit includes the resistance R, inductance L, conductance G, and capacitance C of the line in per unit of line length.

$$v(x,t) - v(x+\Delta x,t) = R * \Delta x * i(x,t) + L * \Delta x \frac{\partial i(x,t)}{\partial t} \qquad (2)$$

$$i(x,t) - i(x+\Delta x,t) = G * \Delta x * v(x+\Delta x,t) + C * \Delta x \frac{\partial i(x+\Delta x,t)}{\partial t} \qquad (3)$$

We can divide both sides of (2) and (3) by the line segment length Δx to obtain the rate of change of the voltage and current for a change in location Δx. If we assume the change in location Δx approaches zero, we will obtain derivatives of the voltage and current with respect to the position x. These equations determine the voltage and current as a function of location (x) and time (t) for the two-conductor transmission line. The negative signs indicate that the amplitudes of the waves decrease as x increases.

$$\frac{\partial v(x,t)}{\partial x} = -R * i(x,t) - L * \frac{\partial v(x,t)}{\partial t} \qquad (4)$$

$$\frac{\partial i(x,t)}{\partial x} = -G * v(x,t) - C * \frac{\partial v(x,t)}{\partial t} \qquad (5)$$

We substitute the operator $s = \frac{\partial}{\partial t}$

And transform (4) and (5) equations from time domain to frequency domain (Laplace), obtaining equations (6) and (7).

$$\frac{\partial v(x,s)}{\partial x} = -(R + sL) * i(x,s) \qquad (6)$$

$$\frac{\partial i(x,s)}{\partial x} = -(G + sC) * v(x,s) \qquad (7)$$

We further introduce Z = R + sL and Y = G + sC and use them to obtain (8) and (9).

$$\frac{\partial v(x,s)}{\partial x} = -Z * i(x,s) \qquad (8)$$

$$\frac{\partial i(x,s)}{\partial x} = -Y * v(x,s) \qquad (9)$$

Our goal is to have two separate equations that would involve only the voltage and only the current, but not both. We can accomplish this if we take the derivative of (8) and (9) with respect to x to obtain (10) and (11).

$$\frac{\partial^2 v(x,s)}{\partial x^2} = -Z * \frac{\partial i(x,s)}{\partial x} \qquad (10)$$

$$\frac{\partial^2 i(x,s)}{\partial x^2} = -Y * \frac{\partial v(x,s)}{\partial x} \qquad (11)$$

We then substitute (8) and (9) into (10) and (11) to obtain the voltage and current wave equations (12) and (13).

$$\frac{\partial^2 v(x,s)}{\partial x^2} = Z * Y * v(x.s) \tag{12}$$

$$\frac{\partial^2 i(x,s)}{\partial x^2} = Y * Z * i(x.s) \tag{13}$$

Equation (14) defines the propagation constant γ, and (15) and (16) are the wave equations that include γ.

$$\gamma = \sqrt{Z * Y} \tag{14}$$

$$\frac{\partial^2 v(x,s)}{\partial x^2} = \gamma^2 * v(x.s) = 0 \tag{15}$$

$$\frac{\partial^2 i(x,s)}{\partial x^2} = \gamma^2 * i(x.s) = 0 \tag{16}$$

Solving these equations requires assuming a disturbance, such as a step change in voltage caused by a fault, and a set of boundary conditions, such as an open line terminal (current is zero) or a transition point to a bus.

Equations (17) and (18) are the general solutions for the second-order partial differential equations (12) and (13). The voltage and current are the sum of two components; these components are referred to as the incident wave: $v_I e^{-\gamma X}$, $i_I e^{-\gamma X}$ and the reflected wave $v_R e^{\gamma X}$, $i_R e^{\gamma X}$.

$$v(x,y) = v_I e^{-\gamma X} + v_R e^{\gamma X} \tag{17}$$

$$i(x,y) = i_I e^{-\gamma X} + i_R e^{\gamma X} \tag{18}$$

3 SIMULATIONS IN EMTP

Figure 3 shows a computer simulation in EMTP of the first incoming and first reflected traveling waves.

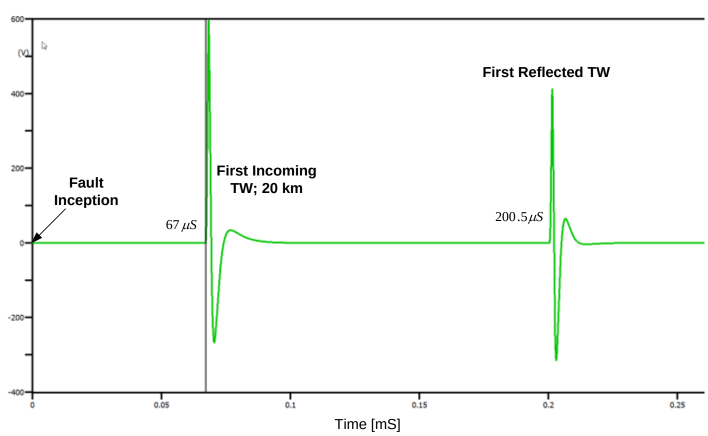

Figure 3. Impulse wave simulated

Fault location can be determined in two ways:

- By taking synchronized time measurements at two line ends (terminals) by GPS and calculating the fault location from the time difference in received signals from the GPS. Method used in the present paper.
- Calculate fault location from the time difference between the first and second TW pulses.

4 FAULT LOCATION REQUIREMENTS FOR HV TRANSMISSION LINES IN REE

The main requirement on fault location is, obviously, accuracy and easiness on installation. REE has a focus on this technology for maintenance purposes on lines that have increased their tripping trends, and consequently their operation costs, because of the lack of availability of the circuit, and lines located on places with difficult access, where the costs of line check are high and a reliable data from the location system is relevant to repair and restore service of the line as soon as possible.

The main application for an accurate location system as the TWFL is in "special circuits" as mixed lines, complex lines with different voltage levels on the same electrical tower, teed feeders, direct current interconnections that will need to be covered by the fault location systems. Also of importance are applications where the line is shared by another company, like international connections, and consequently, due to shared maintenance costs, an accurate fault location can determine, without doubt, which company is affected by the fault. Also a side application of TWFL is to determine in mixed lines where is located the fault, with the purpose of restoring the service quickly by reclosing the breakers in case of location on the aerial section or avoiding autoreclose in underground/underwater section of the mixed line.

The accuracy drives to an exact fault location, or a closer range, that is very helpful, and cost reducer, when accessibility problems is a key factor during line check, also this translates to a quick determination of the faulty component (usually an insulator) that, without the correct identification, can drive to repetitive faults on the same line, degrading its availability and, more important, degrading as well the electrical hardware on the line due to electrical and electrodynamic stress by the fault circulating currents. Furthermore, this has an environmental side effect, a fire or an oil leak on underwater cables could happened by the repetitive faults and the stress related before.

When the accuracy in the fault location is trusted and reliable, the reparation time decrease significantly, because the line check time is reduced to a maximum of two days, on worst conditions, when this time is usually, at least, a week, with traditional fault locations.

Considering that the costs of line check on aerial lines in case of using a helicopter (exceptional situation) is from 3k€ to 4k€ per day, and for underwater cables this cost is increased from 15k€ per day, in case of cables at 50m deep maximum, to 25k€ per day when the cables are deeper, the economic influence of reducing the time on line check is significant. In underwater cables, the cost reduction is approximately 54%, and with only one fault detected, the investment is completely paid-back.

The following tables show the costs incurred on line check stage, due to works to localize the origin of the fault and unavailability of the line during this period, these days are estimated by company experience. For the aerial line this unavailability cost is regulated by Spanish law and is produced by the reduction on grid performance, when this line is out of service. This concept is different for underwater cable, where the cost increases significantly, because the cable unavailability is traduced in a lack of power on affected island (future TWFL installation), and needs to be supplied by other means. In this comparison, we have assumed an accuracy of 150 m in fault detection.

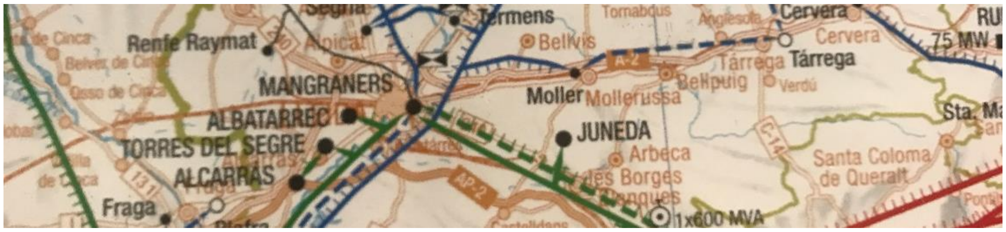

Figure 4. Mangraners – Juneda line.

		Traditional locator		TWFL	
Item	Cost	Days	Total	Days	Total
Helicopter	4k€/day	1	4k€	0	0k€
Line unavailability	1’43k€/day	2	2’86k€	1	2’86k€
		Total	6’86k€	Total	2’86k€

Table 1. Line check costs on aerial line.

		Traditional locator		TWFL	
Item	Cost	Days	Total	Days	Total
Underwater check	25k€/day	5	125k€	3	75k€
Line unavailability	30k€/day	6	180k€	3	90k€
		Total	305k€	Total	165k€

Table 2. Line check costs on underwater cable.

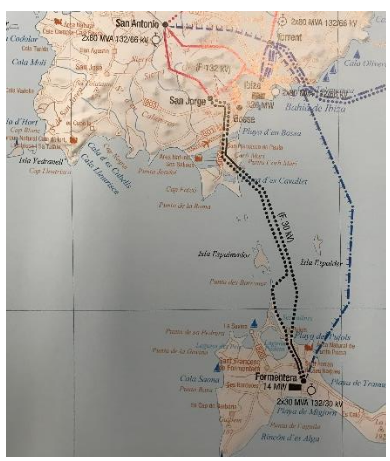

Figure 5. San Jorge - Formentera underwater line.

Focusing on maintenance, the fault locators must be easy to install. For that purpose, an installation that only requires the line voltage to work is preferred in front of systems with operation requirements with line currents. The reason is simple, line currents secondary loops are not possible to operate without an important change on the circuit, that needs to be retested again, this feature is solved using voltage, then the fault location device is installed in parallel with existing circuits without a change on existing voltage circuit. Taking into consideration that the current could be used to trigger a TW, i.e. by monitoring the negative sequence current, the system that provides a method to include the current without changing the current loop is convenient, this can be done by using calibrated current clamps.

5 CHARACTERISTICS OF PILOT SYSTEM INSTALLED

The TWFL is installed in a line that interconnects two transmission substations, this line is going to be monitored by two TW units located in each substation and composed by a TW acquisition unit, central process unit and GPS/IRIG-B clock system, these last two with Ethernet connection to substation, first one for managing and obtain remotely records or change configuration and GPS for remote managing.

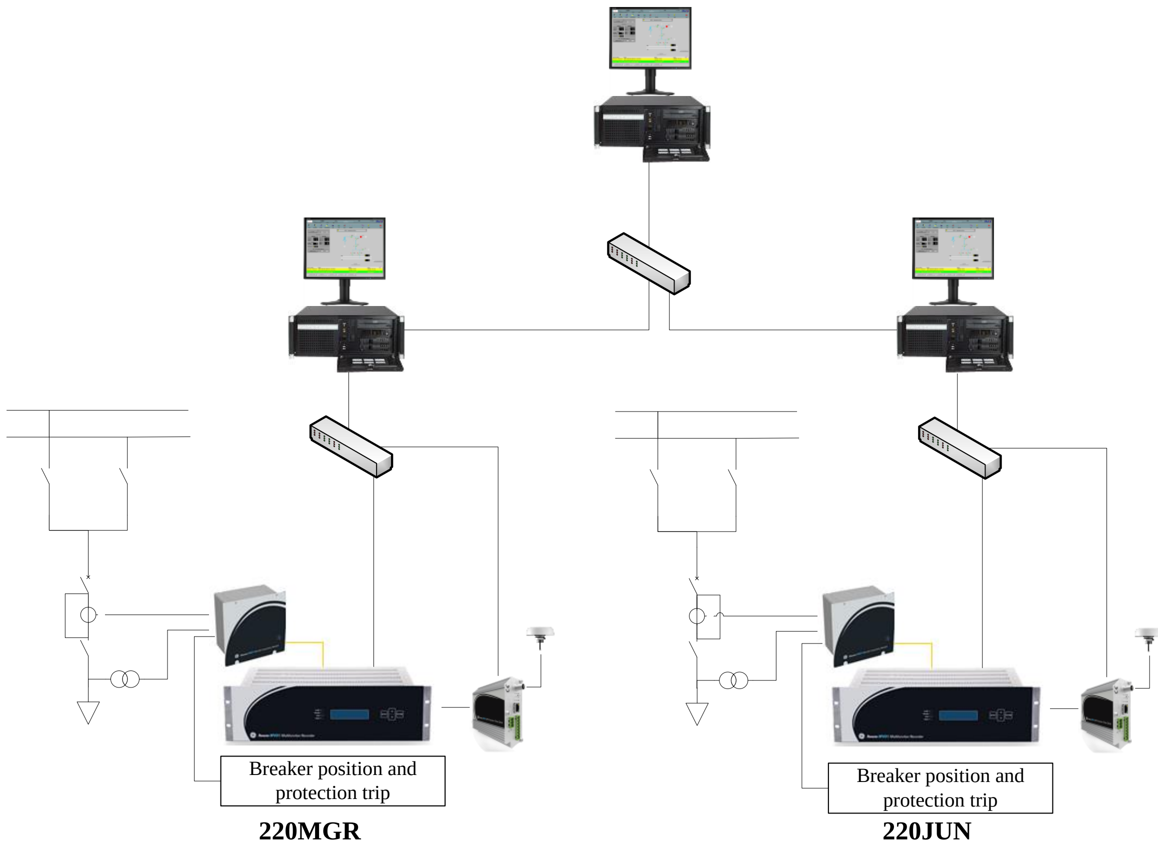

Figure 6. Architecture.

Due to Ethernet architecture, it is not possible to connect directly both central process units to the same switch, then is necessary to go through substation PC to get TW information from both substations and get the fault location on a third PC connected on upper level.

The main unit to monitor, as stated before, is line voltage, where is extracted the TW to locate accurately the fault, also, as checked on Figure 5, is monitored line current, then, in this way, it is possible to start a TW record, among others, with any current unbalance detected by the TW acquisition unit. The others records, and concretely the disturbance fault record is helpful when the fault is weak and is difficult to determine exactly, the moment when the fault occurs.

5.1 Characteristic of the Transmission Line

REE reported problems with fault locator in a 220kV line, with 16’4km length, between SE Mangraners (220MGR) and SE Juneda (220JUN) substations, that has a special configuration, by-passed on several points and some electrical towers with different circuits. Those special characteristics have influenced the location in impedance terms, giving most of the time inaccurate fault locations, and hindering the correct line healing.

From the equation (1) we can determine the unique element that changes from one line to another, that is, the k parameter, because all the other elements can be stated, once the line information is obtained, and then clearing the variable k, it can be determined before field tests. This value is stated in 0’988921.

5.2 Tests and Results

The main test carried out on commission is determine practically the k variable, then is needed that the whole length of the line must be travelled by a TW, to do so is provoked a disturbance (breaker closing for i.e.) on each end one by one, then the time obtained for the TW to reach each side is 0 in end with the disturbance and t in opposite end. The expected fault location in these scenario is the entire line length, by this way the k variable is determined.

Figure 7 shows, in red, the line where the TWFL system is placed.

Once the system was commissioned a fault on the line occurred, having a location by TWFL, on 3’31km from 220JUN and 13’09km from 220MGR, determining by this that the fault has happened on very close nearby electrical tower number 52. The maintenance team was send to check the line and discover a fault on 3’269km from 220JUN and 13’098km from 220MGR in electrical tower 52. In Figure 7, a flashover on recently installed isolator base could be observed.

By the means of having the feedback from real faults location, is done a linear regression calculation to confirm the k variable value.

Fault	Dist. from JUN220 (m)	Dist. from MGR220 (m)	TW arrival on JUN220 (s)	TW arrival on MGR220 (s)	Real dist. from JUN220 (m)
24/07/2015 02:55	0’03	16370	02:55:46.733169	02:55:46.733224	0
02/08/2015 23:35	3310	13090	23:35:59.205040	23:35:59.205074	3269
20/08/2015 12:43	0	16400	12:43:35.773014	12:43:35.772957	0
20/08/2015 13:07	0’06	16340	13:07:33.373651	13:07:33.37376	0
28/08/2015 02:37	1480	14920	02:37:32.781329	02:37:32.781375	1440

With this data, doing a linear regression, it is obtained the value of k = 0’973213.

6 CONCLUSIONS

For the operation of transmission lines, an out of service line can result, in worst cases, in a lack on power supply to a city or essential place. At any rate, in all the cases a downed line has a daily cost as an asset which is not working as designed. The downed time is composed by line check time and reparation time. Therefore an accurate fault location can significantly reduce the line check time, in which TWFL systems are key to deterministic reduce the nonoperating time.

The advantages of a fast and reliable fault location on transmission lines with difficult access and in underwater submarine cables, are not only economic (operational availability together with operational cost reduction), but also Environmental friendly due to reduced number of issues (oil spill in submarine cables or fire caused by faults in transmission lines as the most relevant examples).

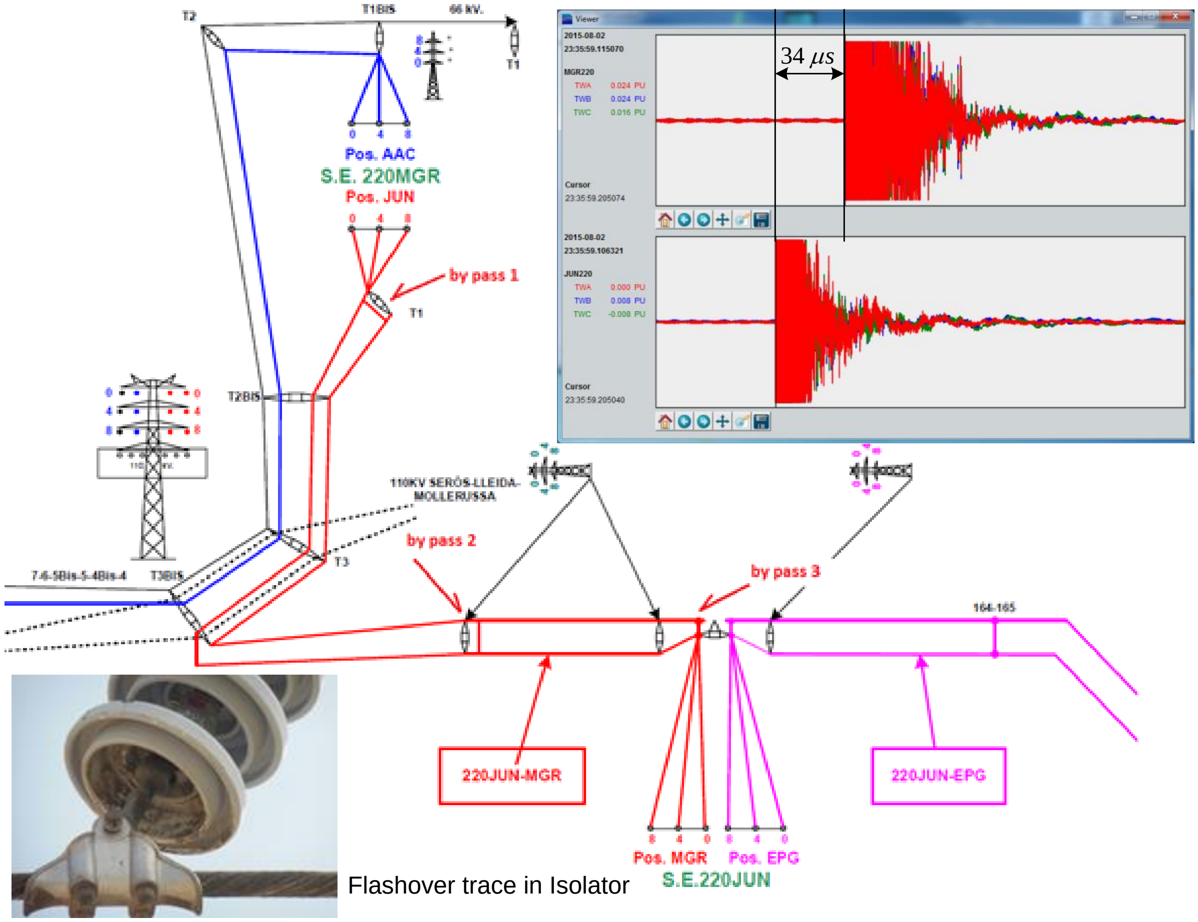

Figure 7. Characteristics of the Installation and results of fault location.

7 FUTURE WORK

From 220JUN-220MGR installation has been planned more installations on lines with high fault rate or sensitive ones. In the first case is the line 220JUN-220EPG and on second cases is a mixed line (aerial+underwater+aerial) that interconnects Mallorca with Menorca, this installation will be carried out in a 2+1 sections configuration, one of this section will be composed by a mixed line fault location, finally, in a complete underwater circuit, that interconnects Ibiza with Formentera, will be installed a system with TWFL on two parallel lines.

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