Traveling-Wave Based Fault Location

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Traveling Waves (TWs) allow for much more accurate fault location in line protection than possible with impedance-based methods. SDEL CONTRÔLE COMMANDE has developed a new fault location device, which combines impedance-based and TW-based fault location algorithms. Those devices are installed at each end of a power line and are synchronized using GPS (Global Positioning System).

I. INTRODUCTION

The principle of traveling waves on transmission lines is well known in the power industry for decades [1],[2]. Nevertheless, most of the current digital protection devices use phasor-based elements and algorithms based on phasor quantities and impedance for protection and fault location. The progress of technology in signal processing and calculation speed open up new possibilities. The combination of both precise time synchronization of distributed devices and overall power system, brings much more accurate fault location [10].

II. STATE OF THE ART

The most commonly used calculation methods for fault location on high voltage lines are based on current, voltage measurements, and impedance phasers [3]. Many impedance-based algorithms have been implemented over the past 20 years. They are based on feeder's, line's, impedance's zero, positive and negative sequence. But, soil type, weather conditions, earth resistivity, mutual coupling, system load, transformer saturation, tapped lines, fault resistance… are error sources that affect impedance-based algorithms [11].

On one hand, the latest evolution in GPS signal processing has resulted in better resolutions in terms of time synchronizations. It is now possible to synchronize a remote and a local equipment with a precision of a few ns. On the other hand, the behavior of TW is the subject of recent academic research [6] that has made it possible to better understand their behavior.

SDEL CONTRÔLE COMMANDE provides a fault locator dedicated to high voltage lines called "GDS". It integrates impedance based and traveling waves algorithms.

From an electrical grid point of view, fault location is complex [4], [9]. SDEL CONTRÔLE COMMANDE provides its expert software: "FACES". In order to model a network, to analyze information and behavior of different protection relays, to integrate "GDS" disturbances and traveling waves recordings, meteorological data…

III. BASIC PRINCIPLES OF TRAVELING WAVES

A fault on a line, which occurs at any time except at the zero crossing of the voltage, generates a traveling wave, which propagates from the fault location to both ends of the line with speed close to the speed of light. The principle is shown in the Fig. 1 when a fault occurs on a transmission line.

Fig. 1. Basic principle of propagation of traveling waves

TWs can be deduced as result from the solution of the linear differential equation system for transmission lines (telegraph equations). For a lossless transmission line the following equations describe voltages $v(x,t)$ and currents $i(x,t)$:

$$\frac{\partial v(x,t)}{\partial x} = -L' \frac{\partial i(x,t)}{\partial t} \quad (1)$$

$$\frac{\partial i(x,t)}{\partial x} = -C' \frac{\partial v(x,t)}{\partial t} \quad (2)$$

Whereas L' is the conductance of the line in per unit and C' is the capacitance in per unit. This can be combined into the wave equations (equation of d'Alembert) as follows:

$$\frac{\partial^2 v(x,t)}{\partial t^2} = L'C' \frac{\partial^2 v(x,t)}{\partial x^2} \quad (3)$$

$$\frac{\partial^2 i(x,t)}{\partial t^2} = L'C' \frac{\partial^2 i(x,t)}{\partial x^2} \quad (4)$$

The general solution can be expressed as a sum of a traveling wave f in forward and g in backward direction:

$$v(x,t) = f(x-ct) + g(x+ct) \quad (5)$$

$$i(x,t) = \frac{1}{Z_W}(f(x-ut) - g(x+ut)) \quad (6)$$

Whereas $c = \frac{1}{\sqrt{L'C'}}$ is the propagation speed and $Z_W = \sqrt{\frac{L'}{C'}}$ the characteristic impedance of the line.

At the line terminals the TWs can be detected as high frequency surges. Whenever TWs hit a terminal of a line (or the location of a fault), part of the wave is transmitted, a part is reflected, and some is absorbed. Upon reflection the polarity of the traveling wave pulse is inverted. For current traveling waves the polarity of the pulse is depending on the direction in which the wave flows through the current transformer (CT).

Propagation of traveling waves including their reflections are commonly visualized using Bewley lattice diagrams (Fig. 2). For different media, e.g. in mixed overhead line and cable topologies, different velocities can be shown in the same diagram.

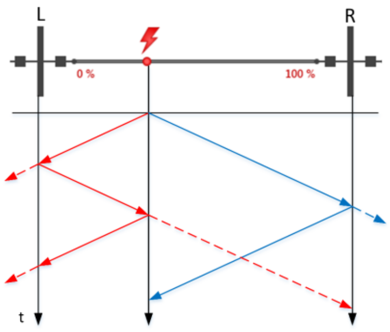

Fig. 2. Bewley lattice diagram showing the propagation of TWs

If the topology of the power system gets more complicated, e.g. with multiple buses, adjacent lines and parallel lines, the algorithms in the devices need to discriminate the reflected traveling waves from the various points with discontinuities in the topology.

For secondary equipment the detection of TWs is possible on the secondary terminals of CTs and voltage transformers (VTs). Common CTs have a sufficiently high bandwidth to allow reliable detection of TWs on the secondary.

Fault location elements based on TW have some advantages over phasor-based elements. Since the calculation of the fault location is based on the measurement of time differences between the arrival times of different TW pulses, a high precision for the fault location is possible. Nowadays precise time measurements within digital substation equipment is possible, even among different distributed devices, which can be time-synchronized using a common global time reference.

IV. Using Traveling Waves for Fault Location

By using traveling waves, a more accurate estimation of the fault location is possible compared to impedance-based principles. All the algorithms based on the apparent impedance measured from the line have a limited accuracy and are influenced by a lot of factors, which are difficult to eliminate.

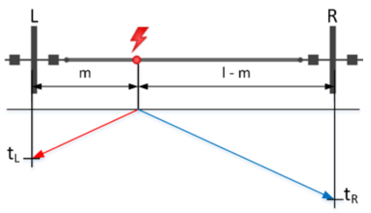

Fig. 3. Two-ended fault location based on time difference of first arrival times

The arrival times of the TWs on both ends of the line are compared and the fault location m is calculated according to the following formula:

$$m = \frac{1}{2}(l + (t_L - t_R)v) \quad (7)$$

Where l is the length of the line, t_L and t_R are the arrival times of the TWs at the local and remote end respectively and v is the propagation velocity. The calculated location depends on the precise arrival time stamps of the detected TW fronts and a correct length of the line.

The principle can even be extended to three-terminal lines or multi-ended topologies.

It is also possible to locate faults on a line using a single ended TW algorithm [7]. Because of reflections in the substations and at the fault point, the location can be computed with the first and the second TW arrival time at the substation:

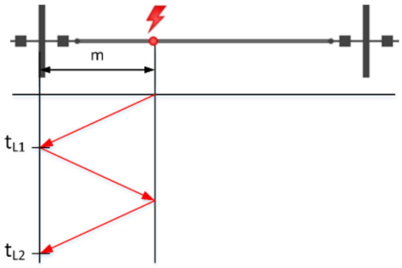

Fig. 4. Single-ended fault location

The fault location m is calculated according to the following formula:

$$m = \frac{t_{L2} - t_{L1}}{2} v \quad (8)$$

V. "GDS" Location Accuracy

Traveling Waves fault locators require the following accurate parameters: the line length, the positives sequences line's impedances for each section and a correct device synchronization.

The line's length and its positives sequences impedances are often accurate and given by Distribution System Operators (DSOs) and Transmission System Operators (TSOs).

For the "GDS" devices, the synchronisation is based on GPS information's. The synchronization accuracy is measured by generating a pulse every 6.2548 seconds to 2 "GDS" devices for 64 hours and by measuring the time stamps difference registered for each pulse (Tab 1).

Parameter	Value	unit
mean absolute error	12	ns
standard deviation error	113	ns
median error	8	ns

Tab 1. Synchronization accuracy

The median error for time synchronization is 8ns. It was performed on 37406 measurements. By considering a TW velocity close to 3.10^8m/s, the median location error generated is less than 3 meters.

Tests and faults simulations including TW are now available with the TWX1 OMICRON equipment [4], [5]. TWX1 is a field-testing solution to test all functions of traveling wave protection relays and fault locators. The voltage and current travelling waves are superimposed on the transient signal with nanosecond accuracy allowing precise verification of all relay functions. It is possible to set the line characteristics (length, sections, impedances), the fault position, the faulted phase, the fault type, the fault angle, the fault resistance. TW monitoring works for single-, double- and multi-ended TW systems. TWX1 generates the arrival TW and the first reflected TW at each end.

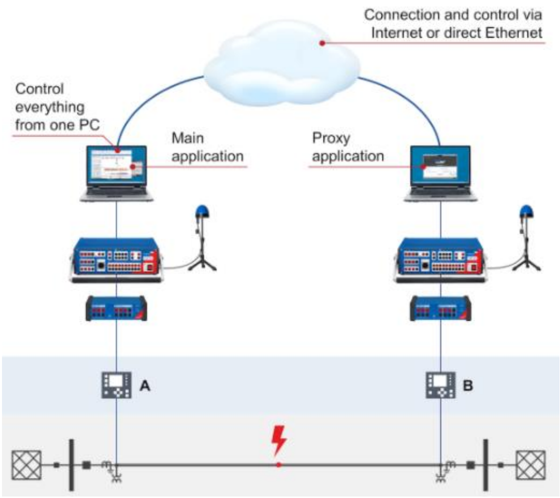

Fig. 5. TWX1 Omicron test tool

In the following example, simulations have been performed on a 100 km / 400kV line by varying :

- fault resistance (0,1Ω - 1 Ω - 10 Ω - 100 Ω),
- fault type (A-G, B-G, C-G, AB, AC, BC, AB-G, AC-G, BC-G, ABC),
- fault angle (90°, -90°),
- fault position (every 10km)

The location accuracy regarding TW and Impedance Based algorithm with the “FACES”/“GDS” solution is given in the Tab 2

FACES / GDS average location error			
Impedance based single Ended	Impedance based double Ended	TW single Ended	TW double Ended
666m	**528m**	**7m**	**6m**

Tab 2. Fault location accuracy

“FACES” Impedance based algorithm locates the fault position with an accuracy close to 1%.

The location precision calculated with TW algorithms is better than 10m and does not depend from the fault resistance.

VI. Advanced Cases

For single lines, or small network topologies (fig 6), TW fault locators can discriminate and locate faults coming from the protected line, from the parallel line and from the outside’s lines.

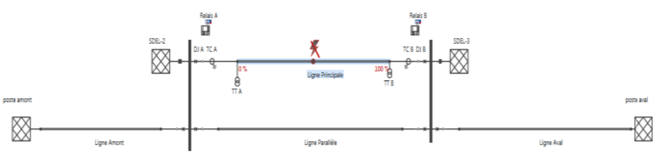

Fig. 6. Parallel and outsides lines

The TW pulse polarity compared to the phase angle allows to determine the faulted line. The location can be calculated by using a single- or a double- ended TW algorithm.

In this configuration, impedance-based algorithms require more current and voltage measurement to discriminate the faulted line and locate the fault.

For more complex networks (Fig7), including TAP, parallel lines, many substations…, an advanced networks analysis software is required.

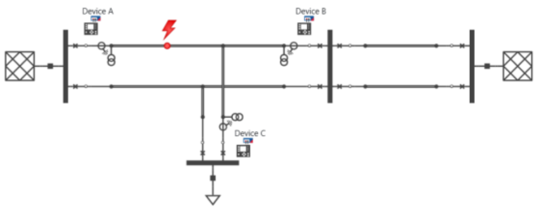

Fig. 7. Fault on an advanced power system topology

Discrimination of the faulted line and location is possible by computing more informations coming from different substations.

VII. Experience of Fault Location with “GDS” and “FACES”

SDEL CONTRÔLE COMMANDE propose on its offer for global supervision of High Voltage Electrical Grid a complete system which includes a new IED (Intelligent Electronic Device), called “GDS”, monitored by the software FACES (Fault Analysis Classifying Expert System).

The “GDS” IED is a surge type fault locator mostly installed on HV (high voltage) transmission lines in substations. But, because traveling waves do not occur in AC transmission lines only, the “GDS” has also been designed to monitor High Voltage Direct Current (HVDC) lines.

TW are detected on CT’s secondary circuit using Rogowski coils. These sensors have several advantages. They have sufficient bandwidth for accurate TW detection and timestamping unlike other opening current sensors [8]. Rogowski probes do not require complex signal processing. Those probes can also be used to measure current on a primary circuit of a distribution network. They do not require the opening of the measured circuit. The installation and the commissioning are simplified.

In the field, each “GDS” device records transients and detects faults by measuring currents and voltages on the secondary circuit from substations Current Transformers (CTs) and Voltage Transformers (VTs). The recordings are sent in standard COMTRADE file format to a fault location server running the “FACES” software, which performs the calculation of the fault location.

“FACES” includes many location methods: impedance-based, traveling wave based algorithms, protection relay information… When a fault is detected, it is first analysed to determine its type (single-phase-to-ground, two-phase, three-phase or two-phase-to-ground). In the field, there are many traveling waves or parasitic information. Impedance based analyse is used to confirm the fault and avoid false positive events. Fault location is then calculated according advanced impedance-based and traveling waves algorithms.

The following example is a 63kV protected line (without mutual coupling). This line (16.5 km) is monitored at each end (substation D and substation I) with a “GDS”.

Events (disturbance recordings, TW) are detected by each “GDS” and collected with (“FACES”) (fig 8).

☑ Phase A ☑ Analogique ☐ Double Extrémité ☑ Autotest
☑ Phase B ☑ Onde Incidente ☐ Simple Extrémité ☑ GDS Dettwiller
☑ Phase C ☑ Réflexion ☑ TW ☑ GDS Ingwiller

Liste des défauts :

	Φ			Date	Heure	ms µs ns	C1(m) →	← C2(m)	ΔT(ns)	Sat1	Sat2	Zapp1(Ω)	Zapp2(Ω)
304	C	---	+	jeu 17 septembre	06:54:52	993 320 979	--- ---	--- ---	---	9			
305	B	---	+	jeu 17 septembre	06:54:52	966 761 635	--- ---	--- ---	---		9		
306	A	---	+	jeu 17 septembre	06:54:52	966 751 723	--- ---	--- ---	---	9			
307	B	---	+	jeu 17 septembre	06:54:52	966 748 031	--- ---	--- ---	---	9			

Fig. 8. Events detected and collected

The currents and voltages waveforms are sent from each “GDS” to “FACES” in a standard IEEE C37.111-2014 Comtrade file (Fig 9 & 10).

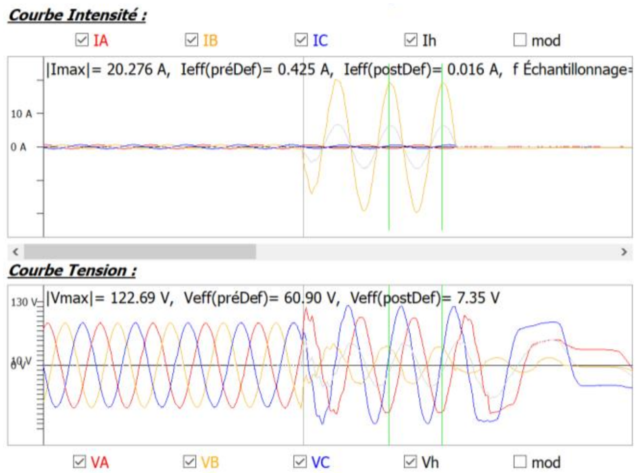

Fig. 9. Currents and voltages from subtation D

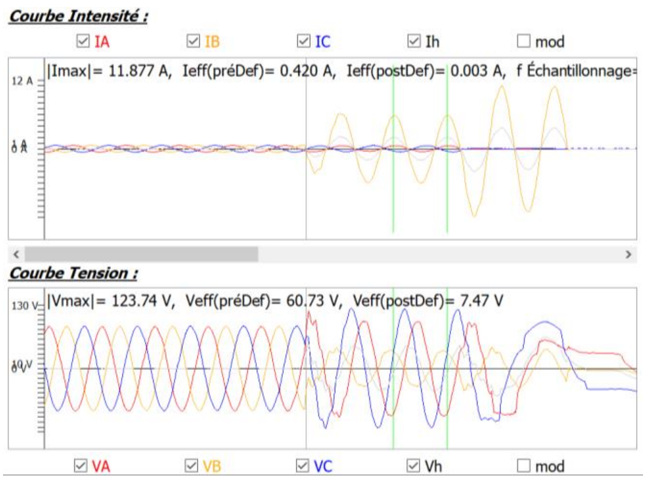

Fig. 10. Currents and voltages from subtation I

In a first step, an impedance based analysis eliminates parasitic information. It determines the fault type, and a location is computed from each end : 3.980km from substation D, 10.050km from substation I (Fig 11).

☑ Phase A ☑ Analogique ☑ Double Extrémité ☐ Autotest
☑ Phase B ☐ Onde Incidente ☐ Simple Extrémité ☑ GDS D
☑ Phase C ☑ Réflexion ☐ TW ☑ GDS I

Liste des défauts :

	Φ			Date	Heure	ms µs ns	C1(m) →	← C2(m)	ΔT(ns)	Sat1	Sat2	Zapp1(Ω)	Zapp2(Ω)
42	H	B	ana	jeu 17 septembre	06:54:52	966 349 488	--- 0	--- 10050	---		9		19
43	H	B	ana	jeu 17 septembre	06:54:52	965 962 518	--- 3980	--- ---	---	9		6	

Fig. 11. Impedance based analysis

In a second step, “FACES” agregates informations from each end, and a more accurate fault location is computed regarding TW arrival times at each substation : 4.229km from substation D, 12282km from substation I (fig 12).

☑ Phase A ☑ Analogique ☑ Double Extrémité ☐ Autotest
☑ Phase B ☑ Onde Incidente ☐ Simple Extrémité ☑ GDS D
☑ Phase C ☑ Réflexion ☐ TW ☑ GDS I

Liste des défauts :

	Φ			Date	Heure	ms µs ns	C1(m) →	← C2(m)	ΔT(ns)	Sat1	Sat2	Zapp1(Ω)	Zapp2(Ω)
81	B	B	- -	jeu 17 septembre	06:54:52	966 651 079	4229 3980	12282 10050	27391	9	9	6	19

Fig. 12. TW based analysis

The “GDS” application provides to the user a summary of the fault detected (fig 13).

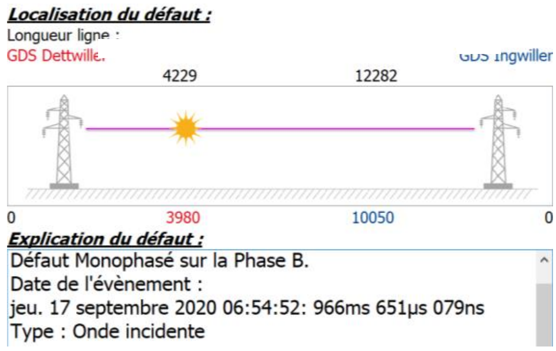

Fig. 13. “GDS” fault summary

“FACES” correlates the fault location with additional information delivered by different relays in the substations and with storm lightning positions from meteorological services in the Internet. All this information improve he consistency and quality of fault analysis and location accuracy. The position of the fault is indicated on a map (Fig 14).

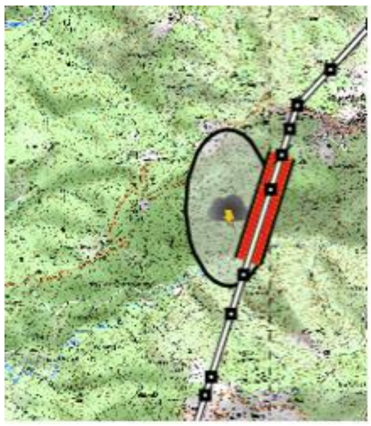

Fig. 14. “FACES” Software fault location

This interface allows TSOs and DSOs to easily visualize the fault position, the exact zone of intervention, and reduces maintenance time.

VIII. Conclusion

The feedback from monitoring several high voltage lines on different grid configurations (transport and distribution) has demonstrated the technical insight of the hardware (“GDS”) and software (“FACES”) solutions developed by SDEL CONTRÔLE COMMANDE.

On an electrical power grid, TWs are not only generated by faults. Changes in grid configurations, switching of circuit breakers... are also TWs generators. TWs spread throughout the network, regardless of its topology (mesh or tree). A section, a part or a line of the network can therefore carry TWs without being the cause of their appearance.

A fault position calculation based only on TWs could determine false locations due to many reflections at each ends of the network.

For each event, an impedance-based analysis determines its nature (fault or parasite), its position in relation to the protected line (inside, backward, forward), its type... When the fault is detected, location based on TWs is performed and gives much more precise results compared to impedance-based algorithms. But these two methods remain complementary to each other.

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