Traveling-wave-based Accurate Fault Location method adaptive for Evolving Faults and Switch-on Events

Hengxu Ha, Adriano Oliveira Pires, Terrence Smith, Rodrigo Donadel, Saurabh Makwana, Lucas Barcelos de Oliveira, Paulo Renato Freire de Souza

Abstract: The paper describes a novel traveling-wave-based accurate fault location scheme to overcome the impact of electromagnetic interference and transients, especially occurring during evolving and switch-on-to fault events. An independent fault detection element using Kalman's filter is employed for removing the noises and disturbances, and to make sure that the fault location is not affected. An improved algorithm is proposed to accurately locate evolving and switch on to fault events. The field and simulation results prove that the improved method can correctly recognize and locate these events with a typical accuracy of 150 meter.

1. Introduction

It is well-known that the traveling-wave-based fault location is much accurate than the impedance based fault location, the accuracy for a traveling-wave-based fault location with 5MHz sampling rate can reach to the maximum error of less than 150 meters, which means that the fault can be located at least within a span of transmission line tower, and is widely used in accurate fault location for both AC and DC lines.

There are two categories of traveling-wave-based (TW-based) fault location methods, they are single-ended methods, in which the fault distance is calculated based on the time gap between the first arrival wave and the reflected wave from fault point, and double-ended fault location methods, in which the fault distance is calculated by the arrival time difference between the two terminals. The single ended fault location depends mainly on reflection of traveling wave and is more prone to signal attenuation, also there is a difficulty to correctly identify reflected wave from the neighbour buses. However, the double ended fault location method only requires detecting the first arriving wave to both terminals and is not dependant on reflective wave. Even though the double-ended TW-based fault location method is more reliable than single-ended TW-based fault location method, there are disturbances in the measured traveling waves due to the electromagnetic interferences that might lead to inaccurate fault location, affecting its reliability. Also, it is very common that the faults occurring on the grid evolve to other faults, e.g. the fault originally on location A with single-phase-to-ground fault, and gradually evolved to be double-phase-to ground fault at another place B or same place. The transmission/distribution grid operators are keen to find out both the fault points. Furthermore, it is very critical that a traveling wave fault locator device should be able to locate faults occurring during line energization (Switch on to fault events).

The solution herein proposed uses a double-ended TW fault location scheme, where typically the accuracy can reach 150 meters, and it is not affected by the disturbances and noises. It can also accurately locate the evolving fault point and faults during closing of breaker (charging of line). To improve the accuracy, parameters such as traveling wave velocity and line length are being determined during commissioning of traveling wave fault locator. For better accuracy, it is recommended to tune these parameters from real fault incident during operation. The fault location scheme has been operating in many utilities over the globe for several years, and field and simulation data shows the high accuracy of the method, with errors of only 8 meters in some cases.

2. The basic principle of double-ended traveling-wave-based fault location method

It is well-known by the traveling wave theory that the initial transient traveling waves are induced by fault due to the sudden change of voltage at fault point and travels to both terminal from the fault point along the line, see fig.1.

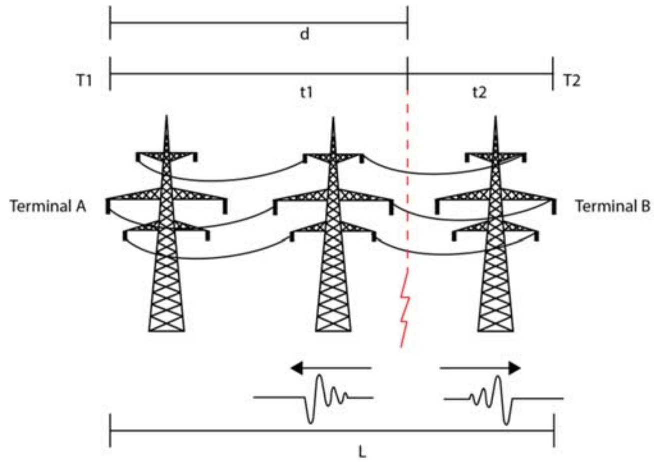

Figure 1, Traveling Waves propagation in a line.

Let's assume that the fault is happening on time T_F, and the time of first wave arriving terminal A is T_A, and the time arriving to terminal B is T_B, the total line length is L, the fault distance to terminal M is d, then one can get the equation presented below.

$$c(T_A - T_F) + c(T_B - T_F) = L \qquad (1)$$

Where c is traveling wave speed.

Therefore, one can get the T_F from equation 1,

$$T_F = \frac{(T_A + T_B)}{2} - \frac{2L}{c} \qquad (2)$$

Subsequently, the fault distance to terminal M is presented below:

$$d = c(T_A - T_F) = \frac{L + c(T_A - T_B)}{2} \qquad (3)$$

The traveling wave speed depends on the line parameters (both for overhead transmission lines and underground cables).

As we can see that the traveling-wave-based fault location method relies only upon the arriving time of traveling waves, and is not impacted by load variation, non-uniform line impedance, weak infeed condition, impedance values etc. The accuracy of double-ended traveling-wave-based fault location (see equation 3) is only impacted by line/cable length and traveling wave speed.

3. TWFL Architecture, and some of the difficulties faced in actual Substations

3.1 TWFL Architecture

The architecture presented in **Error! Reference source not found.** can locate conventional/normal faults, evolving faults and Switch-on to fault using double ended traveling wave method. It is composed of: (a) Remote acquisition unit, monitoring Traveling Waves using high sampling rate up to 5MHz; (b) Multifunctional Digital Fault Recorders (DFR), to capture and record disturbance, and fault events from the remote acquisition unit; (c) GNSS clocks providing synchronization to the DFRs through IRIG-B Protocol, and (d) An external record concentrator software, to download all records associated to an event in a line and perform fault location.

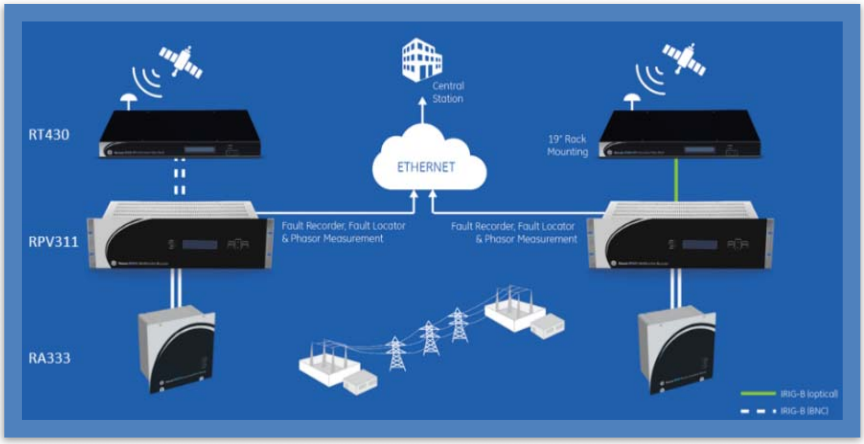

Figure 2, Architecture for traveling-wave-based fault location solution

3.2 Disturbances and electromagnetic interference

Other than the factors of line length and traveling wave speed, the accuracy of double-ended traveling-wave-based fault location is dependent on the accuracy of arrival time detection, which relies on the bandwidth of the transient traveling wave, sampling rate of the acquisition devices, and accuracy of time synchronization. A simulated traveling wave is presented in figure 3 and compared with the real recorded voltage traveling wave from the site, shown in figure 4, one can see that the real signature of traveling wave is not as clean as the simulated, there is a disturbance of around 2.5 milliseconds before the actual fault.

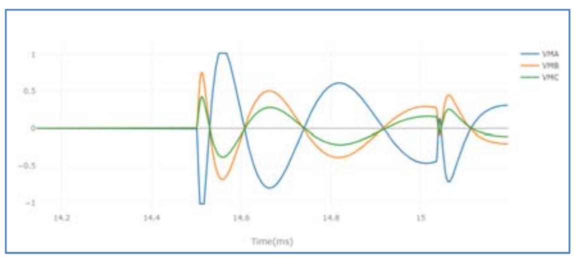

Figure 3, Simulated traveling wave at both terminal

The solution is to combine the DFR waveform and supervise the detection of arrival time of traveling waves. The details of the algorithm are presented in figure 5. In this architecture (see figure 2) both ends are monitored using the DFRs and thresholds must be configured for triggering both TW and fault recorder. These thresholds can be set for over currents, under voltage and digital input information used for protection function and circuit breaker status.

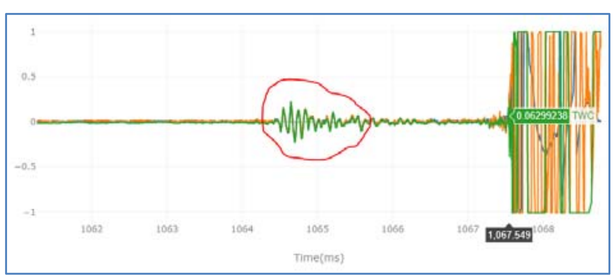

Figure 4, Real measured traveling waves at both terminal

Once an event occurs and the records are made the concentrator software downloads the files and starts the TW fault location as per the flowchart presented in **Error! Reference source not found.**. If there is any abnormality and the fault record is not downloaded, then the basic fault location mode is performed.

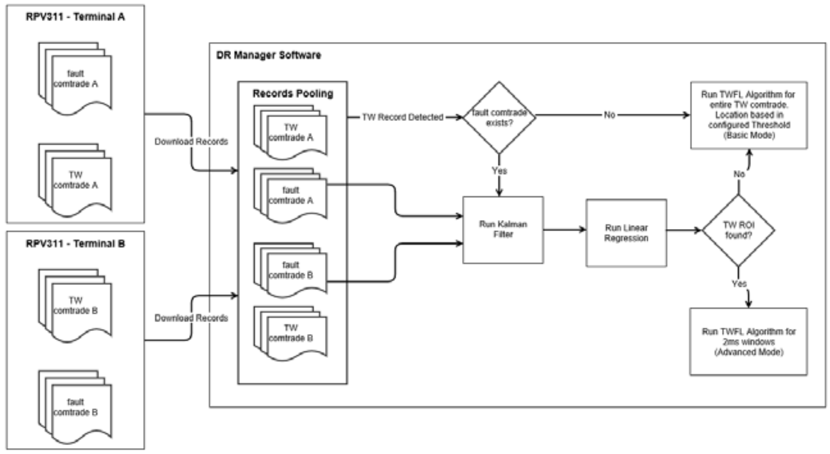

Figure 5, Concentrator Software flowchart for TW-based fault location

If both records are available, then the software uses Kalman Filter and a linear regression on the current circuit stored in the fault record to find a rough estimation of when the fault happened. If the configured current circuit has no abrupt changes, the algorithm doesn't recognize it, as a fault and the Basic Fault Location method is used as backup option.
In case a fault is recognized by the algorithm, then the Advanced Fault Location method is executed, where a base timestamp is estimated using the results of the Kalman Filter and then is used as base to search for the wave front in the TW record. All TW data in this timeframe is filtered by signal processing techniques that allows to find more accurately the point when the wave front arrived in each terminal. To elucidate the importance of Advanced Fault Location method, figure 3 and figure 4 shows the behaviour of simulated and real traveling waves respectively. The simulated signal is clear and does not include any noise, for this type of waveform, may be the use of small threshold and Basic Fault Location method would be enough to accurately determine the wave front arrival. The figure 4 shows noise in waveform and requires more sophisticated technique (Advanced Fault Location method) to determine the arrival time, it relies on the fault record for an automatic pre-fault analysis and becomes less dependent on user configured threshold and noise not related to faults.

3.3 Evolving faults

It is very likely that evolving faults are not at the same location, for example, the original fault could be an external fault (out of the line), which could be evolved to an internal fault, or, vice versa. The traveling wave signature at both ends of a typical evolving fault (external fault evolved to an internal fault) is presented in figure 6. The initial external fault occurs on phase A to ground at 0.0265s, the evolving time is 10ms, at 0.0365s, to an internal phase A and phase C to ground fault.

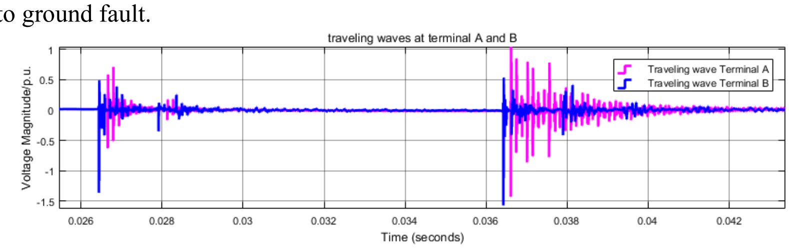

Figure 6, the signature of traveling wave for external phase A to ground fault evolving to internal phase AC to ground fault

One can see that the transient traveling wave of evolving fault event can be regarded as two separate independent fault events as the evolving time is much longer than the duration of transient traveling waves, and on the other hand the lower frequency components which are involved deeply with evolving faults are removed by the high pass filters.

The details of the solution for the evolving faults are described as below. In terms of fault location using traveling waves, the challenge for evolving faults is to have a system prepared to analyze more than a single event in a short timeframe. The solution is using a TW record triggering system that allows the DFR to record up to four consecutive faults, allowing to save traveling waves from unusual events. **Error! Reference source not found.** demonstrates simulation of various faults in loop mode, where four consecutive faults happen in less than 500 milliseconds, and all traveling waves were captured.

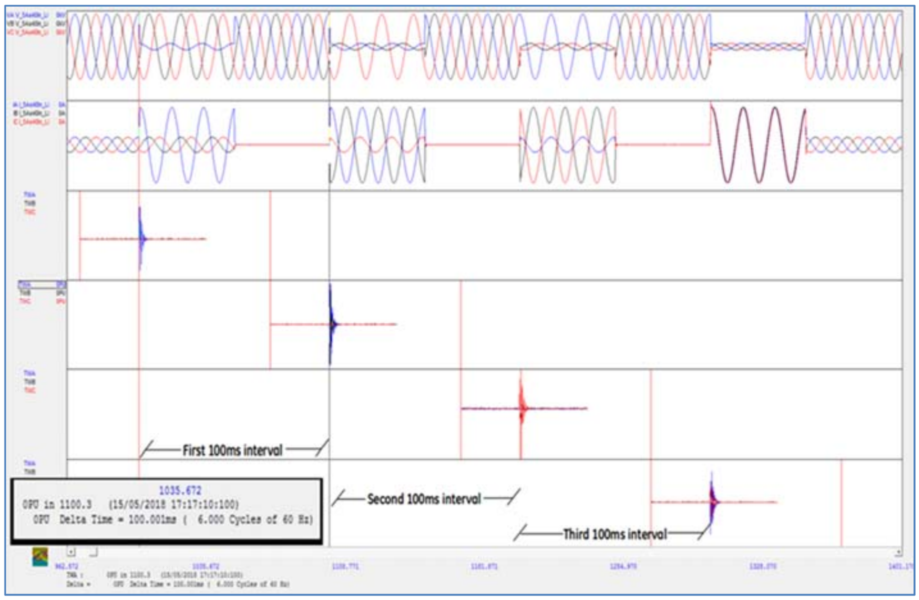

Figure 7, Hardware in the Loop simulated signals showing TWFL solution for consecutive faults

After the records are created, the flowchart to find the location for evolving faults is described in Figure, where the concentrator software tries to find an event in the fault record, if it does, then the advanced fault location method described in previous sections determine a timestamp, and the software restart its process for the time after this timestamp.

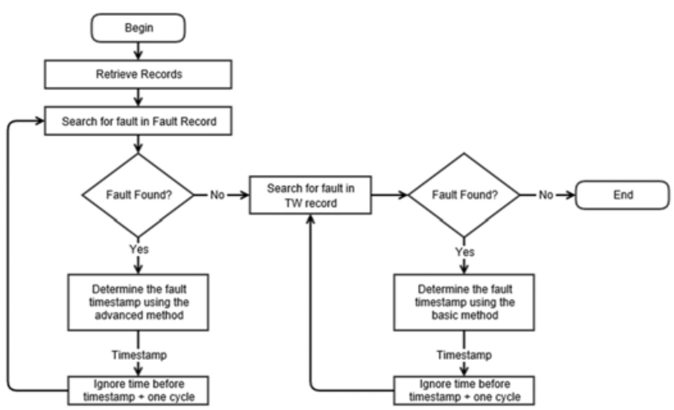

Figure 8, Flowchart for evolving faults location

3.4. The traveling waves during Switch-on-to-fault event

Based on the traveling wave propagation theory, the initial traveling waves are induced at fault point by sudden change of voltage, however for switch onto fault event, the initial traveling waves are induced at the source due to the switching of breakers. The traveling wave propagation can be seen in figure 9.

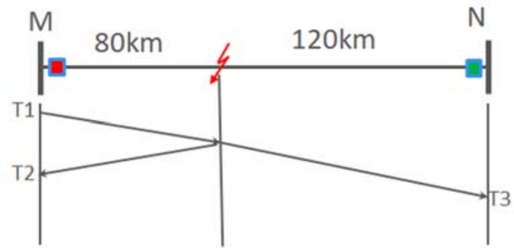

Figure 9, The traveling wave propagation

From figure 9, one can see that the initial traveling wave is originated from the source traveling to terminal M and then propagation along the line until it meets the fault point where the surge impedance is discontinuous, and separate into two waves, one is reflective wave propagating back to terminal M and another is refractive wave continuously propagating to terminal N. Therefore, at terminal M, the initial traveling wave and the reflective wave can be received, however at terminal N, only the refractive wave is received, see figure 10.

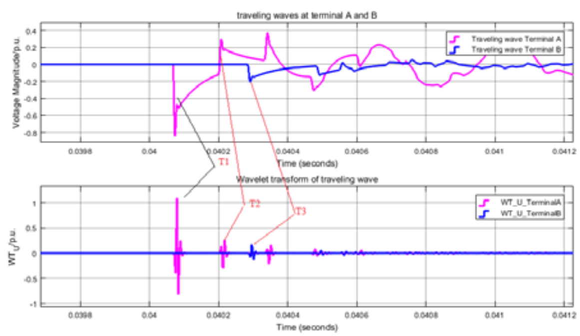

Figure 10, the propagation of traveling wave in signature

In some scenarios, the first wave (T1) might not be seen, for example, if it is phase A to B fault and the point-on-wave of the breaker switching on for phase A is zero, then the wave of T1 in figure 9 can not be seen due to the breaker switching on point, however the point-on-wave of fault is not zero. The signature of traveling wave can be seen in figure 11.

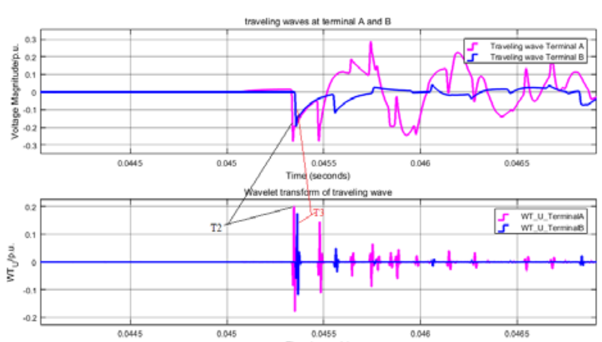

Figure 11, traveling wave signature

3.4.2 Switch-on-to-fault location

After having identified the event as Switch-on to fault type, the software uses a portion of the TW record from one millisecond before the fault inception to the end of the record, then it is filtered using signal processing techniques for making it easier to find transmitted and reflected wave fronts. After finding transmitted and reflected wave, it uses loop searching within the defined timeframe to find a local maximum of the filtered TW signal. This whole process runs for both terminals to calculate fault location using equation 3.

4. Simulation results and field trial cases

The system associated with the validations is shown in figure 14. The traveling wave acquisition devices are deployed in the two substations, Altamira and Tucurui.

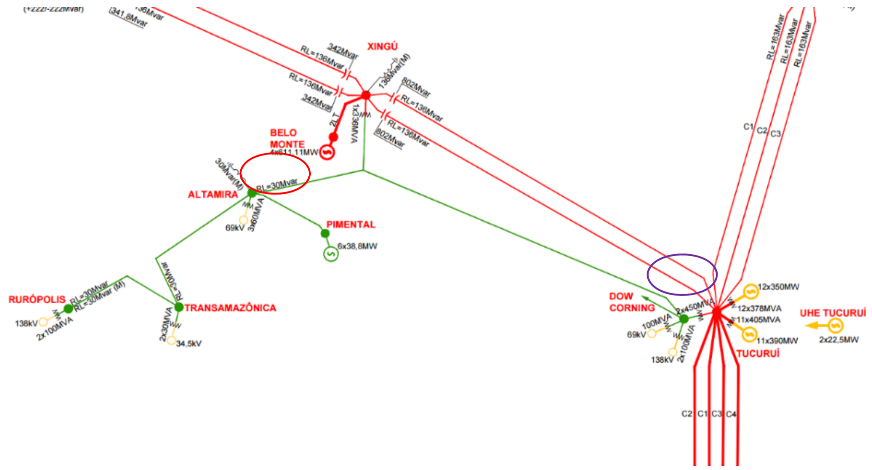

Figure 14, the associated system for validations

The overall line length from substation Altamira to Tucurui is 325.73km.

4.1 Actual field events, for accuracy

In 2009 and 2010, there are 5 cases of faults occurring on the line between the two substations. The located fault distance compared to the real distance is presented in the following table, in which the fault distance indicates the distance from fault point to substation Tucurui. One can see from table 1 that the maximum error is 108 meters and the minimum error is only 4.6 meters. This table shows the accuracy of the proposed fault location method.

Tab. 1 The accuracy of the traveling-wave-based fault location method, sampling rate, 5MHz

Case No	Fault happen time	substation A	Substation B	Calculated distance to A (km)	Real distance to A (km)	error (meters)
1	20/09/2009-07:12:28.145369	TUCURUI	ALTAMIRA	1.22583275373154E+02	122.513	-70.27537315
2	24/01/2010-01:24:22.990746	TUCURUI	ALTAMIRA	6.46286039047013E+01	64.624	-4.603904701
3	27/09/2009-07:01:14.857737	TUCURUI	ALTAMIRA	3.25808888852854E+02	325.721	-87.88885285
4	10/10/2009-16:11:07.072651	TUCURUI	ALTAMIRA	99.39798341	99.506	108.0165936
5	11/11/2009-09:51:55.932415	TUCURUI	ALTAMIRA	1.57120235934913E+02	157.099	-21.23593491

4.2 Validation for evolving faults

Based on system shown in figure 14, the traveling wave data for validating the evolving faults are modelled by using PSCAD. The different scenarios are modelled, such as, external to internal, internal to external at different location with different evolving fault type and different fault point-on-wave. Part of the simulation results are shown in table 2.

Tab. 2, the simulation validations for evolving faults (evolving time 10ms)

Case no.	Fault type	Fault resistance (Ohm)	point-on-wave (degree)	Real fault location 1 (km)	Fault location by TWFL (km)	error (meters)	Real fault location 2 (km)	Fault location by TWFL (km)	error (meters)
1	ext AG-int ABG	10	90	325.73	325.684	46	32.573	32.5942	21.2
2	ext BG -int BCG	10	45	325.73	325.684	46	130.292	130.2413	50.7
3	ext CG - in ACG	10	90	325.73	325.684	46	162.865	162.865	0
4	ext AB - in ABG	10	45	325.73	325.684	46	195.438	195.414	24
5	int BG - int ABG	10	90	77.719	77.7142	4.8	97.719	97.6924	26.6
6	int CG - int ACG	10	45	87.719	87.7407	21.7	137.719	137.7328	13.8
7	int AG - int ACG	10	90	67.719	67.6876	31.4	177.719	177.68035	38.65
8	in AG - ext ABG	10	45	97.719	97.6924	26.6	325.73	325.6842	45.8
9	int BC - ext ABC	10	90	177.719	177.68035	38.65	325.73	325.6842	45.8
10	int AC - ext ABCG	10	45	197.719	197.73345	14.45	325.73	325.6842	45.8

One can see from table 2 that the accuracy is not impacted by the evolving faults, it is as accurate as the normal non-evolving fault location, secondly the proposed algorithm can locate accurately for the internal fault evolves to another internal fault.

4.3 Validation for Switch-on Events

Switch on to fault events are simulated using PSCAD for system shown in figure 14. The SOTF simulations are issued with various scenarios, such as, fault location, which are at 10%, 20%, … 90% of the line length, different fault type, and different point-on-wave. The fault location results by the new proposed algorithm are shown in table 3.

From Table 3, one can see that the point-on-wave and the fault location has impact on the accuracy of the fault location, this is because the SOTF fault location relies on the reflective wave from fault point, and the point-on-wave and fault location can severely affect the high frequency component of the traveling wave, in the extreme scenarios (the fault is too far), the reflective wave even does not exist due to the attenuation and the device can't locate the fault, eg case no 9 from table 3.

Tab. 3, the validation for SOTF algorithm by simulations

Line lenth (km)			325.73			
Case no.	Fault type	Fault resistance (Ohm)	point-on-wave (degree)	Real fault location (km)	Fault location by TWFL (km)	error (meters)
1	AG	10	90	32.573	32.5757	2.7
2	BG	5	45	65.146	65.092	54
3	CG	0.5	10	97.719	97.683	36
4	AB	0.5	90	130.292	130.199	93
5	BC	0.5	45	162.865	162.656	209
6	CA	5	10	195.438	195.247	191
7	ABG	5	90	228.011	227.822	189
8	BCG	5	45	260.584	260.338	246
9	ACG	5	10	293.157	failed	failed
10	AG	5	90	293.157	292.93	227
11	BG	5	45	260.584	260.339	245
12	CG	5	10	228.011	227.822	189
13	CG	10	90	195.438	195.307	131
14	BG	20	45	162.865	162.7155	149.5
15	AG	30	10	130.292	130.199	93
16	BG	20	45	97.719	97.683	36
17	CG	10	90	65.146	65.092	54
18	ABC	0.5	45	32.573	32.516	57

5. Conclusions

This paper describes a solution for traveling-wave-based accurate fault location for evolving and switch on to fault events. The Kalman's filter is employed to supervise the detection of the first arriving wave, and to make sure that the arriving time detection is not impacted by the disturbances, noises and electro-magnetic interferences. The method used for fault location for evolving fault is proposed, the simulation results shows that the proposed method can locate the fault with a typical accuracy of 150 meter. In terms of switch-onto-fault, the fault distance is embodied in the first and second wave at sending end or embodied in the time difference of the first arriving time between the two terminals, therefore, the second reflective wave as well as the first wave of the remote terminal can be used for determining the fault distance for these cases. The solution has been implemented delivered to the real commercial use. Both the simulation and site data tests show that the new proposed solution not only is very accurate but also working perfectly in evolving faults and switch-on events. To achieve better accuracy and differentiate reflective wave arriving from upstream station bus, special measures should be taken to identifying such events. The PSCAD results shows accuracy for evolving and switch onto fault events.

6. References

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Biography

Hengxu HA, was born in Penglai, China, on 3rd, Nov. 1972. He obtained his bachelor, master and PHD in electrical engineering in Gezhouba institute of hydro-electrical engineering, Shandong University and Xian Jiaotong University in 1993, 1999 and 2002 respectively. He is now Technical Lead (emerging technologies manager) in Innovation and technology team, R&D function department, GE Grid solutions. His research interest is innovative conception, algorithms and methods in protection, control and automation for electric power system particularly in traveling-wave-based protection and fault location.

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