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A New and Very Fast Fault Detection and Classification Method Based on a Traveling Wave in Transmission Lines

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ABSTRACT

This study introduces a single-ended method to detect the protection zone and distinguish faults occurring in the back of the relay in the transmission lines and then provides an algorithm to classify different types of faults, including a lightning strike on phases and shield wire. Accordingly, using the Wavelet Transform (WT), the first class of Traveling Wave (TW) current is separated at the beginning of all bus-connected lines. The faulty line and the protection zone are selected based on the relations governing the radiation and reflection. Then, given the features and relations extracted from these waves, the faults caused by lightning strikes on the transmission line and conventional faults are classified, considering the mutual induction between TWs on the transmission line phases. This is essential and helpful for a transmission line with single-phase tripping and auto-reclosing mechanisms. Over 1100 faults with varying conditions and locations are implemented on a 100-km line with a voltage level of 230 kV in the PSCAD software to evaluate and test the proposed method. The results of this heavy simulation confirmed the validity, speed, and accuracy of the proposed method.

Article Info

Keywords:
Auto-Reclosing, Fault Classification, High-speed Relay, Lightning, Single Pole Tripping, Transmission Line Protection, Traveling Wave, Wavelet Transform.

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I. INTRODUCTION

The operation of transmission lines entails protecting them against all kinds of faults within the shortest possible time. The protection of transmission lines includes determining the protection zone, separating the faulty line from the rest of the grid, and interrupting the power transmission process. The effect of interruptions in high voltage transmission lines, which are mainly more critical, is followed by other impacts and consequences such as the whole grid instability and sometimes blackout. Therefore, fault correction methods without losing the entire power transmission process or minimizing the interruption period are considered. Accordingly, a process called fault classification (FC) and fault phase selection (FPS) is conducted before sending the command to the protection equipment. Then, Single Pole Tripping (SPT) or Auto Reclosing operation is implemented. Regarding the importance of speed and Traveling Wave application in protecting transmission lines, it should be noted that as the fault current flows, a force proportional to the square of the fault current amplitude enters the phase conductors and equipment installed in the substations. On the other hand, the maximum fault current amplitude occurs in the first cycle after the fault; therefore, the protection system needs to detect and make the right decision before this peak [1].

The impedance measurement, artificial intelligent network (AIN), traveling wave, or combinations are used to perform protection, FC, and FPS [2]. TW has gained a special place compared to other methods due to the importance of fault

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detection and classification time in protecting the transmission lines and high-speed microprocessors' availability in recent decades. Conventional FC methods such as [3] based on the principal component and those that apply the AIN to increase accuracy lengthen the processing time because of the time-consuming collection and smartification process, making them applicable in off-line methods [4]. Reference [2] uses TW for FC; however, it should be noted that if the ignored mutual induction between the generated TWs is taken into account, the proposed decision table would not be applicable. Moreover, the lightning strike on the transmission lines is neglected in FC.

Ref [5] uses fault current at 220 kV network with a 177.4 km transmission line in the PSCAD/EMTDC. This study presents a new FC and Fault Detection (FD) algorithm using a fuzzy-neuro of less than 10ms. In [6], FD and FC are based on an analysis of the fault current and voltage at a 1.2 kHz sampling frequency with WT and ANNs. Like [6], Ref [7] uses WT and ANN to extract TW from the fault current and voltage for FD/FC (with a 200 kHz sampling rate and different mother wavelets); therefore, the proposed algorithm of this study tested for more than 3900 cases. In [8], with WT and with linear discriminant analysis extract plus the analysis of TW in the fault current within a 0.25 cycle sample for FD/FC. This study claims that improved relay reaches for FD and FC. Unlike [6] and [7], this study uses only the fault current to reach a decision. In [9], the FD and FC plan introduces for static variable compensator (SVC) compensated line, based on SSCII with a 1 kHz sampling rate. Also [10] and [11] protect compensated transmission line using game theory and traveling wave.

Using the current TW separated by WT from the main waveform, this paper examines the protection and fault classification process in the transmission line after determining the protection zone. Accordingly, unlike most studies such as [12], [13], [14], [15], which use current and voltage TW, a method is proposed that only uses the current TW to determine the fault location behind the relay. After detecting the faults in the protection zone, the FC process is implemented using the current TW extracted features at the relay site and considering the mutual induction between the phases to send the most appropriate command according to the proposed algorithm. Moreover, lightning strikes on the transmission line under two different states (lightning strike to phase or shield wire) are considered another class of faults in the proposed algorithm, the subject that none of the study such as mention in introduction discuses about. The proposed method's validity is tested on a single-circuit transmission line with a length of 100 km in a 230kv network under more than 1100 faults in five different zones, inception angle, and fault resistance.

II. BASIC PRINCIPLE

If a fault happens in the transmission line, a TW is generated with various features depending on the fault type and flows to both ends. Accordingly, the fault types are investigated, and the relations associated with TW radiation and reflection are reviewed. Numerous methods are also applied to extract high-frequency TWs, one of the most powerful of which is the wavelet transform that its mathematical relations and the performance are discussed in section (II-C).

A. TW Fault Classification

a) Single-Line to Ground Fault (SLG): This fault happens when one of the transmission line phases is connected to the ground (by resistance) directly or indirectly. Accordingly, the phase faults current increases while the current does not change in the other two phases. However, in terms of TW, when a single-phase to ground fault occurs, TW takes place in the fault zone and the faulty phase. However, no TW is generated in the other two phases [2]. Given the mutual induction between the line phases at the beginning of the line, where the relays are located, TW is present on all three phases. The TWs received at the beginning of the line enjoys two essential features; first, the induced TW amplitude in the other two phases is equal (given that the transmission line phases have regular permutations), and second, their polarity is the opposite of the faulty phase, Fig. 1(A).

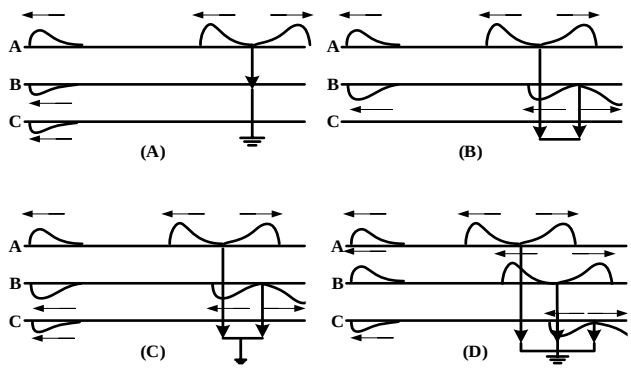


Fig. 1. Fault type base on Traveling Wave

b) Phase-to-Phase Fault: If the two phases of the transmission line are connected, the current of these two phases will be identical with opposite signs, and the current will be intact in the third phase [16]. However, the generated TW has an equal amplitude and inverse polarity in the faulty phases and fault zone. The same waves are received at the beginning of the line (with attenuation caused by losses in the transmission line). More importantly, the TW in the third phase is not received at the beginning of the transmission line. TWs are generated in the third phase because of inducing the other two phases, but they have a zero output because of equal amplitude and inverse polarity, Fig. 1(B).

c) Phase to Phase to Ground (or LLG Fault): since the fault

current flowing in the two phases in the two faulty phases is not equal, the generated amplitude of TW is not the same [2], [16]. Therefore because of mutual induction, TW is generated in the healthy line and thus, TW will exist at the beginning of the line on all three phases (Fig. 1(C)).

d) Three-Phase Fault (and ground): According to Fig. 1(D), when a three-phase fault occurs, TW is generated in each of the three phases based on the voltage range of each phase at the fault moment, and there is TW with different amplitudes at the beginning of the line in each of the three phases.

e) Lightning: Another class of faults that occur in transmission lines is the lightning strike on these lines, which statistically plays the most significant role [17]. In this study, the equation of lightning current is considered as Equ. (1), [18], [19].

$$I = A \times ((B.e^{-Ct}) - (D.e^{-Ct})) \quad (1)$$

The lightning strike on the transmission line is studied under two conditions. First, lightning strikes one of the phases directly and leads to a severe current flow in that phase(Shielding failure). Receiving TW at the beginning of this line makes this mode similar to the single-phase to ground short circuit as you can see in Table I. In the second case, lightning strikes the shield wire, induces a current in the phases. Based on the performed simulations, TW is received on three phases at the beginning of the line with similar polarity and amplitude. But in some cases, if the ground resistance of the tower is high, it will lead to flashover [20].

According to the above discussion and the obtained data from TW analysis, the features and specifications of all fault types are classified in Table I.

TABLE I
TW SPECIFICATION OF DIFFERENT FAULT'S

Fault type			i_A	i_B	i_C
Single Phase to Ground		AG	i_A^T	$-Mi_A^T$	$-Mi_A^T$
		BG	$-Mi_B^T$	i_B^T	$-Mi_B^T$
		CG	$-Mi_C^T$	$-Mi_C^T$	i_C^T
Phase to Phase		AB	i_A^T	$-i_A^T$	0
		AC	i_A^T	0	$-i_A^T$
		BC	0	i_B^T	$-i_B^T$
ABC and Phase to Phase to Ground			i_A^T	i_B^T	i_C^T
Lightning	To Phase	A	i_A^T	$-Mi_A^T$	$-Mi_A^T$
		B	$-Mi_B^T$	i_B^T	$-Mi_B^T$
		C	$-Mi_C^T$	$-Mi_C^T$	i_C^T
	To Shield Wire		i_M^T	i_M^T	i_M^T

As is seen in Table I, in single phase to ground faults, because of the mutual induction (in that M is mutual induction coefficient and T is an abbreviation for TW, so i_A^T means: current TW of phase A), two phases have equal amplitude and opposite polarity to the faulty phase just the same as when lightning strikes one of the phases, so we discuss this item in section III. Also in phase to phase faults, according to circuit equations, the same amplitude with opposite polarity TW generate in faulty phases but in the third one not received any TW.

B. TW and their equations

As a fault occurs in the transmission line, the TW voltage and current are generated in that zone and flow to the ends of the line, at a speed close to the speed of light. The amplitude of the generated TW is proportional to that of the voltage at the fault zone one moment before the fault occurs (V_F). The magnitude of TW, voltage, and current are as follows [14], [13]:

$$V_1 = \frac{-Z_C}{Z_C + 2R_F} V_F \quad (2)$$

$$i_1 = -\frac{V_1}{Z_C} = \frac{1}{Z_C + 2R_F} V_F \quad (3)$$

where R_F is the fault resistance and Z_C is the characteristic impedance of the faulty line. According to Fig. 2, a part of the generated TW is reflected in the fault zone by reaching the two line ends, and the other part is transferred towards the network (lines) connected to bus A. The radiation and reflection coefficients of TW current are obtained as follows:

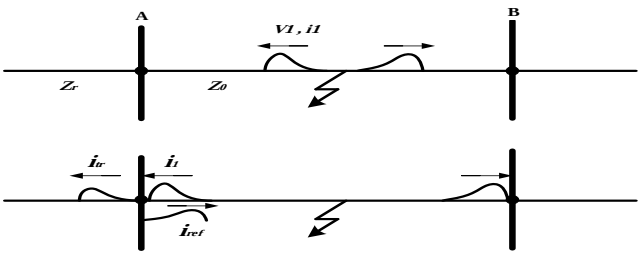


Fig. 2. Initial Traveling Wave on Transmission line

$$K_{ref}^i = \frac{Z_0 - Z_r}{Z_0 + Z_r} \rightarrow i_{ref} = K_{ref}^i \times i_1 \quad (4)$$

$$K_{tr}^i = \frac{2Z_0}{Z_0 + Z_r} \rightarrow i_{tr} = K_{tr}^i \times i_1 \quad (5)$$

If more than one line is connected to bus A (Fig. 3), the above relations will be re-written as follows:

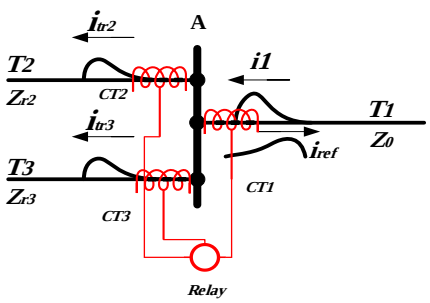


Fig. 3. Traveling Wave on bus A

$$i_{tr2} = \frac{2Z_{eq}}{Z_0 + Z_{eq}} \cdot \frac{Z_0}{Z_{r2}} \cdot i_1 \quad (6)$$

$$i_{tr3} = \frac{2Z_{eq}}{Z_0 + Z_{eq}} \cdot \frac{Z_0}{Z_{r3}} \cdot i_1 \quad (7)$$

where Z_{eq} is the equivalent impedance of T2 and T3.

C. Wavelet Transform (WT)

The Fourier series is applied to analyze the constituent harmonics of a signal; however, it cannot distinguish between the inception and disappearance of different harmonics. WT is one of the mathematical transformations capable of providing a time-frequency signal analysis. WT is formed by combining the low and high-pass filters in terms of frequency content, which could divide the frequency band of the input signal into two parts at each stage [21], [22].

The high-pass filter's output is the details or high-frequency harmonics, and that of the low pass filter is considered an approximation of the input signal. If the intended signal $f(n)$ has discrete data, the performance of the discrete WT (DWT) is expressed as follows:

$$A_{2^j}^d.f(n) = \sum_k h_k.A_{2^{j-1}}^d.f(n-2^{j-1}k) \quad (8)$$

$$W_{2^j}^d.f(n) = \sum_k g_k.A_{2^{j-1}}^d.f(n-2^{j-1}k) \quad (9)$$

where $A_{2^j}^d.f(n)$ is the signal approximation coefficients and $W_{2^j}^d.f(n)$ is the detail coefficients (high frequency) at the level of2^j, and h_k and g_k re the applied high and low-pass filters' coefficients in WT.

III. Proposed Algorithm

The proposed method in this article has two main parts. In the first part, the faulty line is detected among all the bus-connected lines, and in the second part, the type of fault and faulty phases are determined. Then, the fault zone is easily calculated using the existing relations and TW velocity.

A. Determining the faulty transmission line

For example, consider bus A in Fig. 3, which is connected to three lines. If a fault occurs on line T1, TW is generated and flows to bus (A) based on the TW behavior. As the TWs reach this bus, a part of them is reflected to the fault point, and the other part is transferred to the other two lines.

It is worth noting that the received TW through CT1 is equal to the sum of the radiated waves in the fault zone and reflected from the bus, that is:

$$i_{CT1}^{TW} = i_1 + i_{ref} \quad (10)$$

According to section II-B, the received TW amplitude by CT2 and CT3 is equal to:

$$i_{CT2}^{T.W} = \frac{2Z_{eq}}{Z_0 + Z_{eq}} \times \frac{Z_0}{Z_{r2}} \times i_1 \quad (11)$$

$$i_{CT3}^{T.W} = \frac{2Z_{eq}}{Z_0 + Z_{eq}} \times \frac{Z_0}{Z_{r3}} \times i_1 \quad (12)$$

where ($Z_r^{eq} = Z_2 \parallel Z_3$), and according to the circuit laws:

$$i_{CT1}^{T.W} = i_{CT2}^{T.W} + i_{CT3}^{T.W} \quad (13)$$

In other words, if TW is measured on the three lines connected to bus A and the sum of the two values is equal to the third, the faulty line will be detected by examining the conditions of the Equ. (13). This work has two main advantages. First, using a relay device allows protecting any number of bus-connected lines, which leads to significant savings and makes it possible to use a relay as the backup for the rest of the line's relays. The second major advantage of this method is to detect the protection zone and separate the out-of-zone and the fault location behind the relay. It should be noted that studies such as [12]- [15] use the TW voltage to determine these faults, which is a difficult task due to the limited frequency band of the voltage transformers [16], [14].

B. Fault classification

After identifying the faulted line (based on Equ. (13)), in order to distinguish phase to phase and three phase faults, the algebraic sum of current TWs is calculated on all three phase. If the algebraic sum of current TWs wasn't zero and the received TW polarity is precisely equal on each of the three phases, the fault is caused by a lightning strike on the protective lines (shield wire) above the transmission line. Furthermore, in some cases, it may cause a back flashover. If the amplitude of current TW is precisely the same, flashover has not occurred. Nevertheless, in some cases, a short time after the lightning strikes the shield wire, back flashover occurs, so depending on the type of flashover, the studied algorithm detects SLG (as shown in Fig.5) or another type of fault, and if the received TW polarity isn't equal fault is SLG or shield failed.

Suppose the ratio of received TW amplitude of the 1st level in the two phases is equal to $i_{ph1}/i_{ph2} = 1$, but the TW amplitude of the third phase has more amplitude, and polarity is inverse. In this case, the fault is a single-phase type or shield failed, and the faulty phase is the one with a higher amplitude. To distinguish between these two types of faults, the ratio between the details of the first and second WT levels must be calculated. If this ratio is less than TH, then shield failure occurs elsewhere, and SLG fault accrues. In this study, TH is set at 0.3.

If received current TW on phases have different amplitude ((iA/iB) or (iA/iC) or (iB/iC) ≠1) phase-to-phase to ground (LLG) fault occurs. However, identifying the phases under fault in LLG faults is not easy because, in less than 30% of cases, the fault may occur between two phases whose current polarity is similar. In this case, due to the mutual induction, high-amplitude current TW occurs in the healthy phase, and so it will be challenging to detect faulty phases.

For more details, consider the following three phases voltage waveform (Fig.4); if LLG fault occurs between two phases in the dotted zones, the polarity of the current TW generate become similar, and therefore the polarity of the induced current TW in the healthy phase is similar and add together. In such cases, the detection of faulty phases is very

complicated.

Therefore, to detect the phases involved in the LLG faults, define a pilot function (PF) with the following specifications for each phase, when the absolute voltage of each phase is less than half of the nominal value and the value of the pilot function of that phase remains equal to on for T/6 s. for example, phase (a) pilot function is defined as follows:

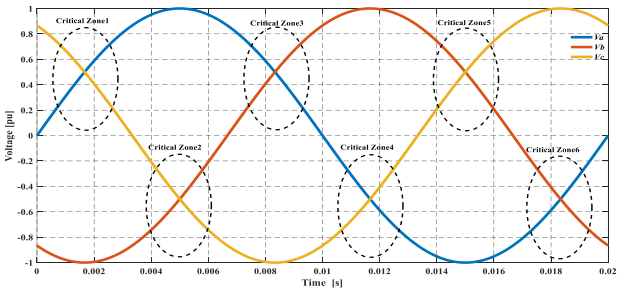


Fig. 4. Critical Zone on three phase's voltage waveform.

$$P.F = \begin{cases} 1 & if\ [|V_a| - 0.5 \times V_n^{max}] < 0 \\ 0 & if\ [|V_a| - 0.5 \times V_n^{max}] > 0 \end{cases} \quad (14)$$

According to the above explanations, LLG fault detection is divided into two categories. IF the average absolute magnitude of (detail level 1) current TW is greater than the third one AND pilot function (PF) of the phase with the least amount of current TW is zero, THEN the fault occurred between those two phases, and if this condition does not apply, fault accrues in the critical zone. For identifying these LLG faults, the polarity of voltage (at 60Hz) should be checked, and faults accrued between phases with similar polarity.

If the algebraic sum of TW is zero and the TW amplitude of a phase is zero and the ratio of received TW amplitude on the other two phases is $i_{ph1}/i_{ph2} = -1$, the fault is phase to phase type, and the faulty phases have TW. In reality, a TW is induced in the faultless phase with minimal amplitude due to the phase conductors' complete dissimilarity. The maximum amplitude of these TWs is related to the fault at the end of the line, and it is possible to obtain a threshold for it. If none of the above conditions is met and the received TW is present on each of the three phases, the fault is of the three-phase type.

According to the above explanations, Fig. 5 indicates the proposed algorithm for classifying the fault types and specifying the faulty phases. Note that, in Fig. 5 all of the i_A, i_B and i_C are details of the first level of WT.

It should be noted that the proposed method uses the TW amplitude of the current obtained from the relay without using any time-consuming calculations. This increases the proposed algorithm's effectiveness and reduces the decision time in single-phase cut-off operations, which is vital in this regard.

IV. Simulation Studies

This research is conducted on a single-circuit three-phase line with a length of 100 km in a network with a voltage of 230 kV, and 60 Hz frequency in PSCAD software (Fig. 6). Since the proposed algorithm is based on high-frequency TW analysis, the Frequency-Dependent (Phase) model is selected for transmission line analysis, which is highly similar to a real line and has a wide range of frequency bands of different parameters.

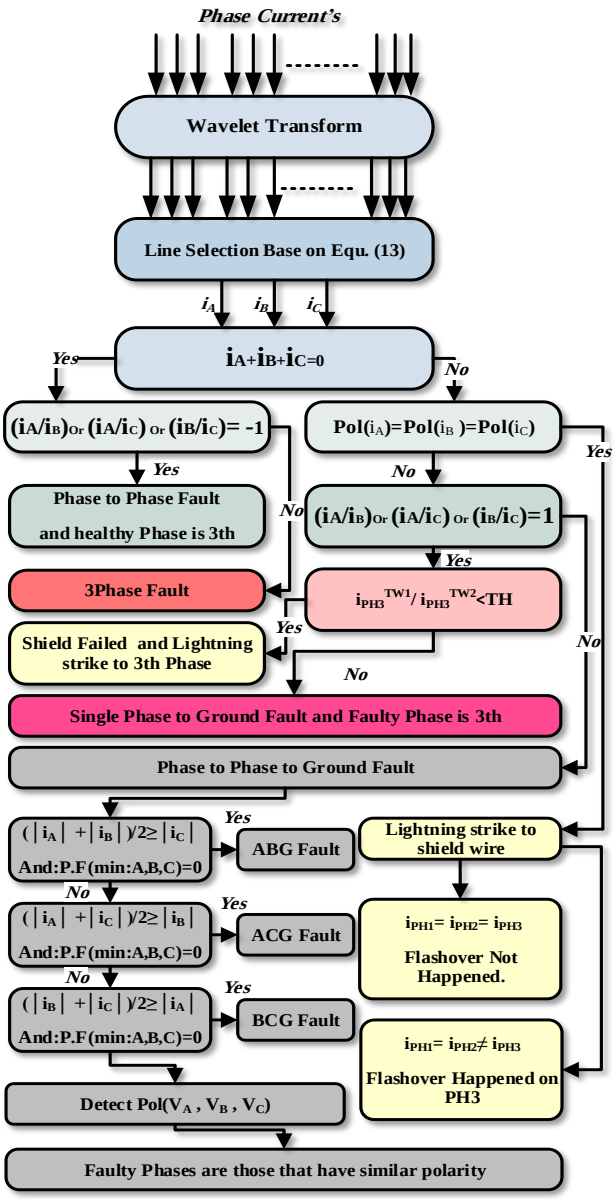


Fig. 5. Propose Flowchart for FC

The CTs with a conversion ratio of 5/1600 based on the Lucas model is used to extract TW from the line current [23]. Moreover, the sampling frequency is 500 kHz, and the details of the first level of WT (by selecting the mother wavelet db4) are used.

A wide variety of faults are analyzed in 3 different location with various fault resistance and inception angle to check the validity of the algorithm presented in this research, a small part

of which is presented below:

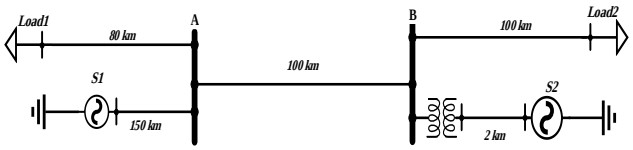


Fig. 6. Simulated network

A. *Single-phase to ground fault (SLG)*

These faults are the most probable ones statistically [17]. According to Table I and Fig. 5, when a single-phase to ground fault happens, the faulty phase's received TW amplitude is higher than two other phases and it has an inverse polarity, also the TW amplitude ratio of the other two phases equals one. Fig. 7 shows the single-phase to ground fault in phase A at a distance of 60 km from bus A (in Fig. 6) under two fault resistances of 1 and 50Ω.

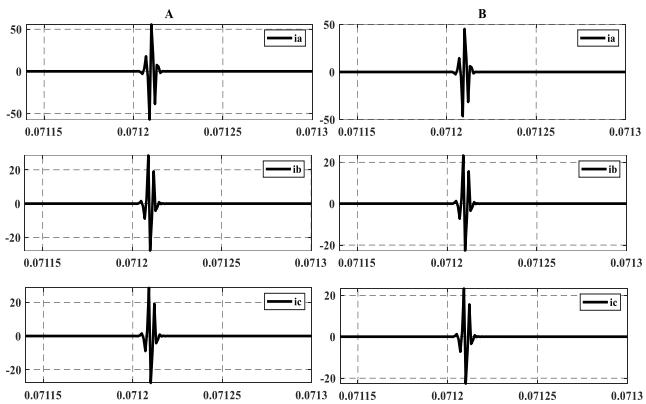


Fig. 7. Current TW Fault in 60km (A): R_f=1Ω, (B): R_f=50Ω

As the proposed algorithm is sorted based on the first received TW class and decisions, the equipment saturation problem in faults close to the bus will not arise. Table II includes information about some single-phase to ground faults at different distances, fault inception angles, and fault resistances.

TABLE II
RESULT OF SLG FAULT IN DIFFERENT CONDITION

$\lvert i_a^{TW}\rvert$	$\lvert i_b^{TW}\rvert$	$\lvert i_c^{TW}\rvert$	Time-ms	Fault Type	Fault location	Fault-Res	$\frac{\lvert i_a^{TW}\rvert}{\lvert i_b^{TW}\rvert}$	$\frac{\lvert i_a^{TW}\rvert}{\lvert i_c^{TW}\rvert}$	$\frac{\lvert i_b^{TW}\rvert}{\lvert i_c^{TW}\rvert}$
74	36	36	55	AG	30km	1	2/07	2/07	1
61	30	30	63	AG	30km	50	2/07	2/07	1
15	30	15	55	BG	30km	1	0/48	1	2
15	31	15	63	BG	30km	50	0/48	1	2/07
21	21	44	55	CG	30km	1	1	0/48	0/48
14	14	30	63	CG	30km	50	1	0/48	0/48
58	31	31	55	AG	60km	1	1/89	1/89	1
48	25	25	63	AG	60km	50	1/89	1/89	1
18	18	33	55	CG	60km	1	1	0/53	0/53
12	12	22	63	CG	60km	50	1	0/53	0/53

B. *Phase to phase fault*

According to section III-B, if the single-phase TW magnitude is zero (or very small) and the received TW amplitude on the other two phases is -1, the phase-to-phase fault takes place (Table III).

TABLE III
PHASE TO PHASE FAULT WITH 10Ω FAULT RESISTANCE

$\lvert i_a^{TW}\rvert$	$\lvert i_b^{TW}\rvert$	$\lvert i_c^{TW}\rvert$	Time-ms	Fault Type	Fault_loc
78/52001	78/52001	4/74E-07	63	AB	60km
70/91948	70/91948	4/74E-07	71	AB	60km
74/96908	4/73E-07	74/96908	63	AC	60km
58/43128	4/73E-07	58/43128	71	AC	60km
2/12E-09	3/550927	3/550927	63	BC	60km
2/12E-09	12/4882	12/4882	71	BC	60km
58/66404	58/66404	4/74E-07	55	AB	90km
63/07616	63/07616	4/74E-07	63	AB	90km
62/98396	4/73E-07	62/98396	55	AC	90km
2/12E-09	9/682649	9/682649	71	BC	90km

C. *Three-phase and phase-to-phase to ground faults*

The algebraic sum of the received TW at the beginning of the line is calculated to detect these faults. According to the algorithm, if the sum of the current TW is zero, a three-phase (and ground) fault happens(or two-phase fault as previously described), otherwise, it is the phase-to-phase to ground fault. If LLG fault occurs, current TWs are received at the beginning of the line on all three phases, and in most conditions, the faulty phases have a larger amplitude, but as mentioned above, when the voltage of the faulty phases is in the critical zone, the amplitude of the TW on a healthy phase is sometimes more significant than the faulty phases. Fig.7 shows the waveform of voltage, current, and current TW of these two types. Table IV contains BCG fault data at a distance of 60km; the red line in Table IV indicates the LLG faults in the critical zone. In the proposed algorithm shown in Fig.5, voltage polarity at the main frequency is used to detect faults occurring in the critical zone.

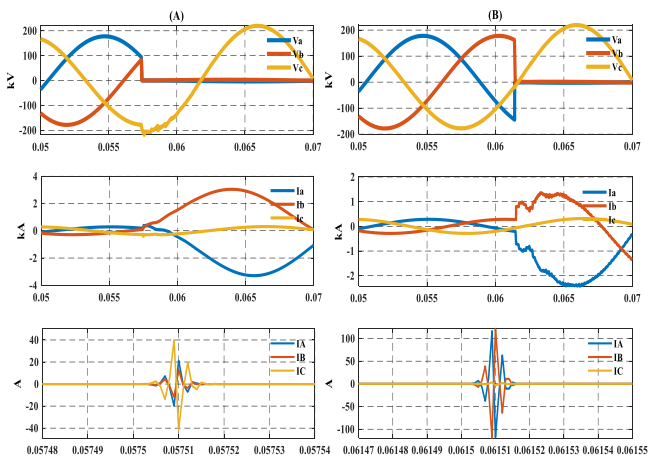


Fig. 7. 24 (A): ABG fault at 0.0574 [s] in critical zone, (B): ABG fault at 0.614 [s]

TABLE IV
BCG FAULT AT 60KM WITH 1Ω FAULT RESISTANCE

i_a^{TW}	i_b^{TW}	i_c^{TW}	Fault Time
-27/75	+4.13	-19.86	5/50E-02
-32.84	+28.77	-59.05	5/58E-02
+28/00	+62/22	-87/82	5/66E-02
+19/83	+88/23	-107/36	5/74E-02
+9/49	+102/99	-111/65	5/82E-02
-0/79	+111/96	-111/24	5/90E-02

D. Lightning

Two cases may arise in terms of the lightning strike on the transmission lines, discussed in section (II-A). If the lightning strikes one of the line phases, Fig. 8 and Fig. 9-A, the situation at the beginning of the line is like a single-phase to ground fault. However, the received TW amplitude can be much more than a single-phase to ground fault based on the lightning strength. Fig. 8 presents the received currents and TW amplitude at the beginning of the line after a lightning strike on one of the phases within a distance of 60 km.

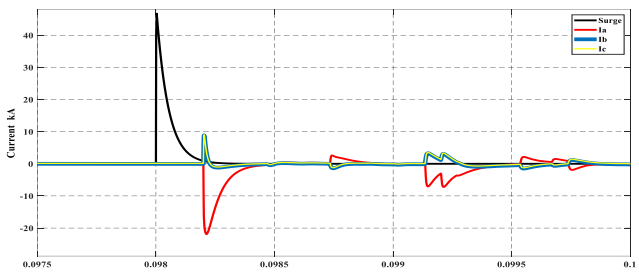


Fig. 8.Lightning strikes to phase A and Phase Current receive at beginning TL

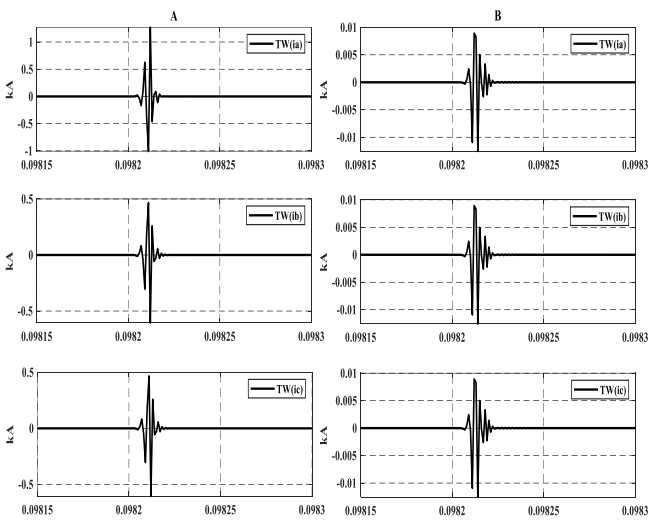


Fig. 9.Lightning strikes A: to phase (a), B: to Shield Wire

If lightning strikes the shield wire above the line, the induced currents in the three lines are quite similar to each other (given that the line is totally transposed) Fig. 9-B. In this case, if the ground resistance of one of the towers close to the place of the lightning strike is high a flashover may occure between one of the phases and the tower. In this case, depending on the location of the flashover, the amplitude of the induced TWs is slightly disturbed or it is seen as an SLG fault by the proposed algorithm.

E. Close in Faults

One of the modes that challenge the FC algorithms is remarkably close faults. However, our proposed method uses the first set of TWs; hence there will be no problem with the saturation of measuring equipment. As shown in Table V, the proposed method has an excellent ability to detect close-in faults.

TABLE V
SIMULATION RESULTS FOR CLOSE-IN FAULTS WITH 10Ω FAULT RESISTANCE

i_a^{TW}	i_b^{TW}	i_c^{TW}	Fault Type	Fault Loc	Fault Time
+207	-0.05	-0.05	AG	0.02km	0.0614 s
+75	-0.74	-0.74	AG	0.5km	0.062 s
-141.19	+141.19	-1.13 E-09	AB	0.02km	0.059 s
+12.48	-4.12 E-07	-12.48	AC	0.03km	0.052 s
-160.42	+255.59	-0.04	ABG	0.03km	0.052 s
+281	-201	-80	ABCG	0.03km	0.054 s

F. The effect of noise on the proposed algorithm

The effect of noise in traveling wave protection can be divided into two categories:

a) Interfere with algorithm activation

b) Failure to correctly identify the type of faults

To activate the process of protection (that involves fault detection, classification and location), the amplitude of TW should be selected according to the maximum expected noise level in the transmission line.

To investigate the effect of noise on the proposed fault classification algorithm, some random Gaussian white noise with SNR 20dB is added to phase current, for example, the results for an SLG fault are shown in Fig. 10.

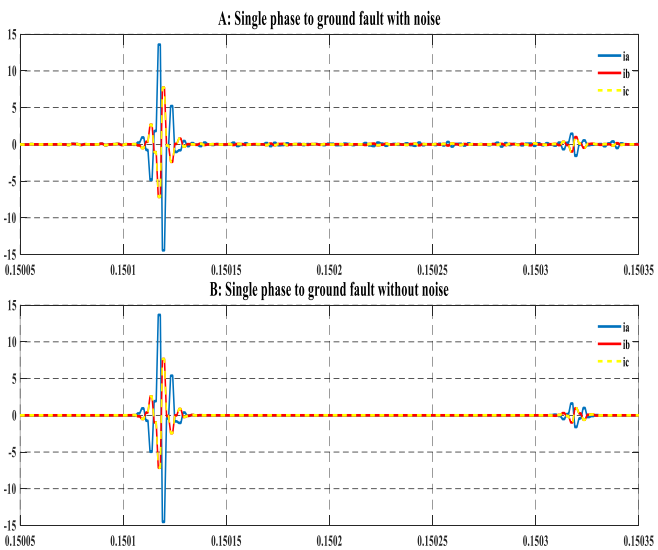


Fig. 10.Single phase to ground fault in 30km with and without noise

According to the results, the proposed algorithm has correct performance in the presents of white Gaussian noise.

III. CONCLUSIONS

Ignoring the fault-induced TW mutual induction challenges the performance and ultra-high-speed protection algorithms of transmission lines. Moreover, the lightning strike on the line and neglecting such situations as another class of faults cause the relays to send wrong commands. Therefore, given the above cases and separating fault behind the relay faults, this study proposed a fast, reliable, and simple method without heavy mathematical calculations by applying the first TW current class. The results of performed simulations that only a small part of them are presented in this study show that the proposed method is not sensitive to fault resistance and inception angle and has good performance for transmission lines with recloser and single-phase cut-off mechanism. Moreover, given the frequency band limitation of PTs, only the TW current is used for the algorithm's decision-making.

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