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Research Article

Improved Transmission Line Relay Algorithm Based on Signum Function of Incremental Currents

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Abstract: Transmission lines are a key part of the power system because they carry power from one end to the other. In case of a fault, the power transfer is perturbed, and the equipments on generation side as well as on the load side can get damaged. Transmission lines carry power from generation end to load end, so it is very important to keep the transmission lines protected. A swift protection system is necessary for the power system. For a quick protection system, rapid fault detection is crucial. A novel method for detecting as well as classifying the faults on transmission lines is reported in this paper. The direction of incremental current along the transmission line's two ends forms the base of this technique and uses a modified signum function. The effectiveness of the said technique is validated by simulating signals in a PSCAD/EMTDC environment on a 50 Hz, 230 kV, 5-bus network. The parameters considered in this study are the line loading, DC offset, fault location and the fault resistance (FR). The FR values considered for simulation purposes range from 0.01 ohm to 1000 ohms. Two types of line structures have been adopted, viz., first, a line connecting generator bus (PV bus) to a load bus (PQ bus) (L_{GL}) and second, a line connecting two generator buses (L_{GG}). Detailed results of this study show that the relay detects all internal faults with different loading levels and various FR values. The maximum operating time of the relay is ascertained as 4 ms. The technique has also been validated on IEEE 30-bus system.

***Keywords*:** transmission line, fault detection, incremental current, signum function

1. Introduction

The rapid expansion of power systems to accommodate rising electricity demand has led to increased system complexity. The electric power system consists of three main components: the generating system, which generates electricity, the transmission system, which transports electricity to regional substations via high voltage, and the distribution system, which distributes electricity to local consumers. Transmission lines (TL) [1, 2] in power system networks can experience various faults, leading to outages and instability. Immediate diagnosis and restoration of power supply is crucial. To restore power supply during a problem, it's crucial to identify the faulty phases, which requires fault categorization.

Wavelet Transform (WT) is a popular method for extracting transitory features from faulty signals. WT and artificial neural networks can accurately identify, locate, and detect faults in TL [3]. WT-based power spectral density can identify and categorize faults in various dynamic circumstances [4]. The cross correlation technique has been used in [5] to classify faults due to its minimal computing overhead. The sequence components of a faulty signal can successfully distinguish

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internal from external faults [6]. To safeguard the system, it is imperative to have a comprehensive understanding of the operation of the power system during power quality disturbances, which can be achieved through the use of Synchronous Lissajous curves [7]. The authors in [8] presented a study to classify the faults based on Lissajous figures.

T.G. Bolandi et al. reported a fault detection technique based on the integrated power related fault component [9]. For identification of faults, two threshold values were considered for short circuit resistance values below 200 ohms as well as above 200 ohms. The technique of fault detection based on line currents was discussed in [10]. Another technique based on line currents for detection and classification of faults was demonstrated in [11]. Both of these techniques fail to classify all types of faults. A technique originating from the integrated impedance magnitude for fault sensing was reported by Om Hari Gupta and Manoj Tripathy [12]. This technique works successfully for fault resistance (FR) upto 200 ohms. A setting free sensing and categorization of faults based on the average value of the reactive power produces delay in the action of the relay [13]. The programming algorithm employing ANNs provides many benefits, but it also struggles with many drawbacks, including network type selection, network architecture, huge amount of training [14].

Fuzzy logic controller was used to classify different faults in [15]. The research presented in [16, 17, 18, 19, 20, 21, 22] employed a support vector machine technique which requires current and voltage of all phases. This effectively finds faults regardless of their length or type. However, it suffers from a disadvantage of poor performance with huge input datasets. These intelligent approaches require thorough off-line training. A fault sensing and categorization technique owing to the change in direction of instantaneous power using signum function was presented in [23, 24]. The performance of this technique was evaluated for all types of faults but without considering heavy loading on the line and the results were reported to be satisfactory. However, when the performance of this algorithm was evaluated by the authors of the present paper, it was found to fail in selectivity when high fault resistance values and heavy loading were simultaneously considered [25]. The reason for the failure is explained in the second section of the present paper.

To improve the relay selectivity, another approach based on incremental power was presented in [26], however, some cases of undesirable relay operations for line between the generator and load bus at low fault resistance values were reported. The purpose of this research is to show an alternative method that has been proposed in order to enhance the selectivity of the relay. Within the context of this method, incremental current serves as the fault discriminator. The signum function of incremental currents has been chosen for fault detection in transmission lines primarily because it offers several advantages like low computational demand, quick decision-making and robustness to noise that make it particularly effective in this context, despite the availability of more sophisticated learning algorithms. This method is easy to implement with minimal hardware requirement. The effectiveness of this method has been assessed using PSCAD/EMTDC on a 5-bus network operating at 230 kV and 50 Hz, as stated in the reference [27]. The two types of line structures that have been adopted are as follows: first, a line that connects a PV bus to a PQ bus (L_{GL}), and second, a line that connects two PV buses (L_{GG}). It has been determined that FR values ranging from 0.01 to 1000 ohms have been studied. In order to evaluate each fault resistance value, both zero percent and one hundred percent DC offset were also considered. Simulations of a variety of loads have also been carried out in order to investigate the impact that loading has on the proposed approach. In the second section, the rationale for the selection of incremental current as a defect discriminator is discussed. In the next two sections of the paper, system simulation and parameters of the study are discussed. The subsequent sections present results of LG fault, selection of delay and threshold time and improved relay flowchart. Simulation results for highlighting an all inclusive relay performance for LG fault sensing and categorization with different FR levels, dc offset, fault placement and line loadings are tabulated. Tabulated result for LL, LLG and LLL fault for L_{GL} and results for all faults for L_{GG} are included in the same section. The next section validates the efficacy of this technique on IEEE-30 bus system. The final section of the analysis concludes the study.

2. Incremental current selection as fault discriminator

While newer learning algorithms, such as deep learning or support vector machines, hold promise for advanced fault detection in power systems, the signum function of incremental currents remains a popular choice due to its simplicity, speed, reliability, and effectiveness in detecting faults in transmission lines. Its minimal computational requirements, noise robustness, and ability to quickly identify fault conditions make it an optimal solution for real-time fault detection and protection in electrical power systems. Instantaneous power technique derived using signum function stated in [23, 24] fails to detect contingencies at high FR coupled with high load. This is due to the fact that as the resistance to fault is higher compared to the load resistance, the instantaneous power direction is unaffected when fault hits the system. Thus, fault cannot be detected as the sensing of the same is subject to the change of the instantaneous power direction [25]. If incremental power is used as a fault discriminator, faults with high fault resistance can be detected [26], but there are several instances of undesirable operations. It requires measurement of voltage and current at each sampling instant for the calculation of power. Selecting incremental current as a fault discriminator enhances selectivity of the relay. This approach works successfully even with high fault resistance values. No unwanted operation occurs and the relay is immune to load levels. The incremental current at any instant is given by the present instantaneous current minus instantaneous current one cycle earlier. Mathematically, incremental current at 21^{st} sample (IC_{21}) is given by:

$$IC_{21} = 21^{st} sample - 1^{st} sample \tag{1}$$

Incremental current is an advanced discriminator of fault than instantaneous power since its value during normal condition is close to zero and is a significant value in the event of fault and is independent of the voltage. During normal conditions, small incremental values of current can exist. So, the signum function is transformed so that the relay no longer works in that situation. A dead band of approximately zero value is created for this purpose. This improved signum function is employed to indicate change in the sign of the incremental current before and during fault. Incremental current is measured at the end 2, $\Delta i_2(t)$, and at the end 1, $\Delta i_1(t)$ of the protected line. After that signums of the incremental currents, sgn $\Delta i_1(t)$, and sgn $\Delta i_2(t)$, are obtained. The summation of signums s(t) is eventually determined from

$$s(t) = sgn(\Delta i_1(t)) + sgn(\Delta i_2(t))$$

3. Test system under consideration

PSCAD/EMTDC software is used to study the efficacy of the proposed technique. Figures 1 and 2 represent the single line diagram (SLD) of a 230 kV, 5-bus system. Fault inception angles that have been considered are 0° and 90°. The system has been simulated both for internal faults (F1, F2, F3) and external faults (F4 and F5). Various loading levels at bus 2 in Figure 1 have been simulated (100, 50, 25, 10 and 3 MW). Furthermore, no load condition has also been adopted. In addition, each fault resistance has been simulated without any loading as well. Two types of line structures have been adopted, viz., first, a line connecting generator bus to a load bus (L_{GL}) and second, a line connecting two generator buses (L_{GG}). The SLD of the two said cases are shown in Figures 1 and 2 respectively.

4. Parameters of the study

Detailed analysis is carried out with parameters including the fault position, fault resistance, loading magnitude and the DC offset.

1. **Fault location:**
   The effectiveness of principle of incremental current flows has been evaluated by simulating faults at various locations. F3 is near generator bus (10 Km distant from bus 4), F1 is near load bus (10 Km distant from bus 2) and F2 is at the middle of line. Also, the performance of the protection scheme has been analyzed for external faults by simulating fault at F5 and F4 which are 10 kilometers distant from bus 4 and bus 2, respectively.

2. **Fault Resistance (FR):**
   Different values of FR have been adopted to test the impact of FR on accuracy of sensing the fault. The FR values were determined by considering the range of possible resistances in a 230 kV network [28]. The highest resistance

in a 230 kV system for line faults and ground faults is 200 ohms. Therefore, line faults have been simulated with fault resistance of 200 ohms. Additional FR values of 0.01 and 10 ohms have been employed in this simulation. A model is also given in [28] in order to evaluate the impedance of towers. FR of 10, 0.01, 1000, and 100 ohms have been simulated in case of LG fault. For symmetrical fault only two values of FR have been simulated which include 0.01 and 10 ohms because it is mostly a solid fault.

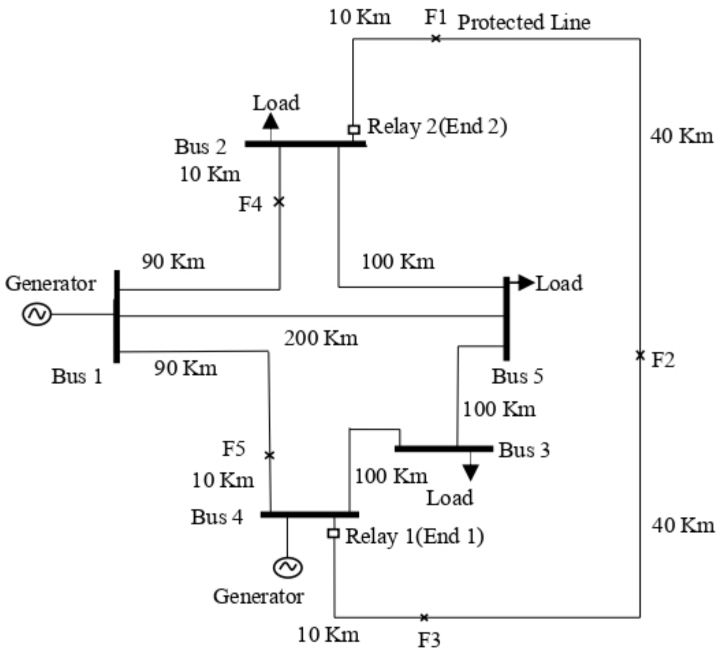

Figure 1. SLD of test system depicting protected line connecting PV bus with PQ bus

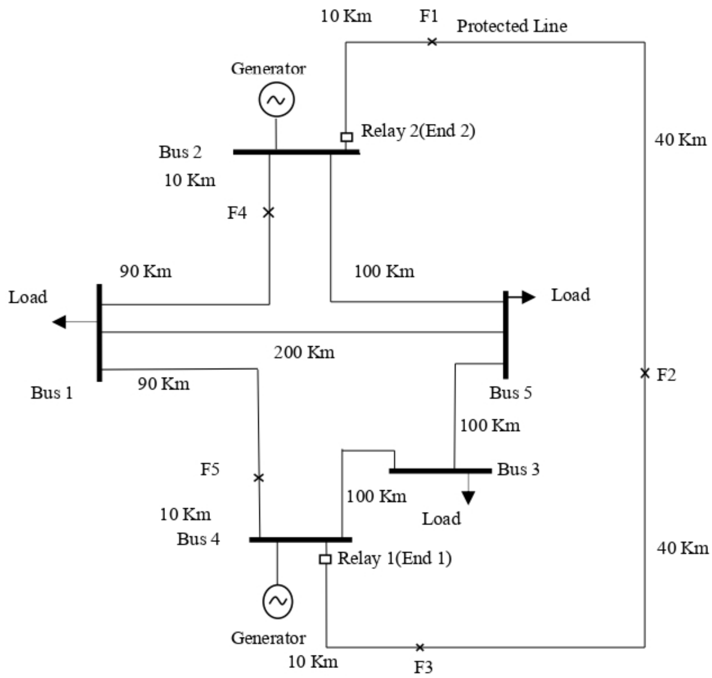

Figure 2. SLD of test system depicting protected line connecting two PV buses

3. **DC offset:**
   In order to test the efficacy of incremental current flows concept, two DC offset values, i.e., 0 percent and 100 percent have been simulated.

4. **Load:**
   To test the effect of the load on the proposed fault detection scheme, different loads of 100, 50, 25, 10 and 3 MW have been simulated. In addition, no loading condition is simulated. Of course, the load is not a variable parameter for the line connecting two PV buses.

5. Results and discussion for LG fault

Incremental current theory has been utilized for different types of faults (LG, LL, LLG and LLL) at different locations (F1, F2, F3, F4 and F5) under different load conditions (100, 50, 25, 10, 3 MW and no load) with different FR values at 0 percent and 100 percent dc offset. The waveforms of instantaneous current of all phases at the two ends has been shown in Figure 3 for a LG fault at fault location F2 with a load of 100 MW having fault resistance 0.01 ohm and 0% dc offset. Figure 3a shows the instantaneous current at end l of the protected line shown in Figure 1. Figure 3b shows the instantaneous current at end 2 of the protected line shown in Figure 1. As fault considered is single line to ground fault on phase A, the instantaneous current of phase A increases abruptly on fault simulation. It is noteworthy to mention here that the instantaneous current magnitude is higher at end 1 because it is near to generator.

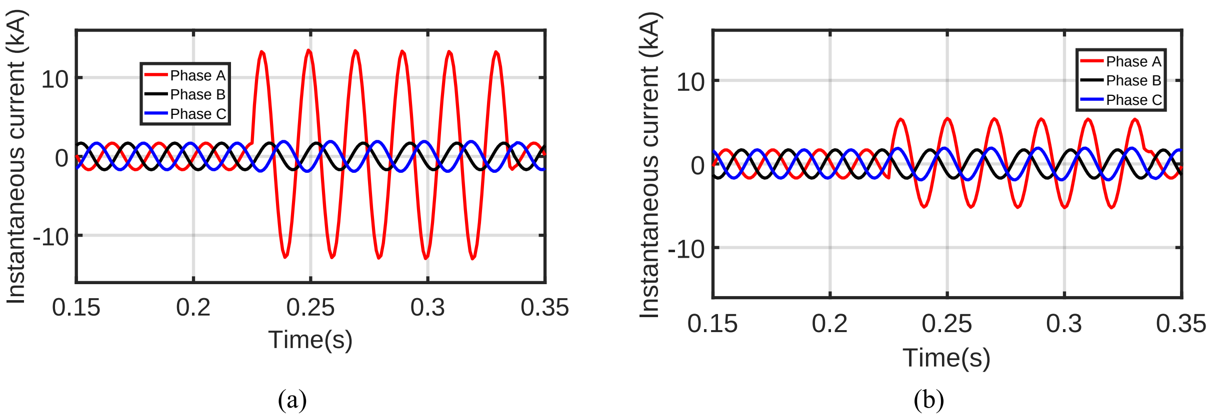

Figure 3. Instantaneous current waveform for phase A, phase B and phase C (**a**) end 1 (**b**) end 2

The incremental current of all phases have been shown in Figure 4 for a LG fault at fault location F2 with a load of 100 MW having fault resistance 0.01 ohm and 0% dc offset. Figure 4a depicts the incremental current of phase A. It is clear that incremental current gains a significant value on fault occurrence and is equal to zero in normal condition which forms the base of the proposed technique. Figure 4b,c depict incremental current of phase B and phase C respectively. It is clear that incremental current is very small in these two phases as the fault is simulated on phase A only.

The results presented in Figures 3 and 4 highlight the importance of incremental current in fault detection. By monitoring the current changes at both ends of the transmission line and analyzing the incremental current of each phase, protection systems can quickly identify the presence of a fault. The sharp rise in incremental current on phase A (as shown in Figure 4a) is the key indicator of the fault, providing a reliable basis for fault detection. The small incremental currents in phases B and C demonstrate that the fault is localized to phase A, which helps in fault isolation. By using this incremental current approach, the protection system can differentiate between normal operating conditions and fault conditions, ensuring a fast and accurate response to the fault, which is critical for maintaining system stability and protecting equipment.

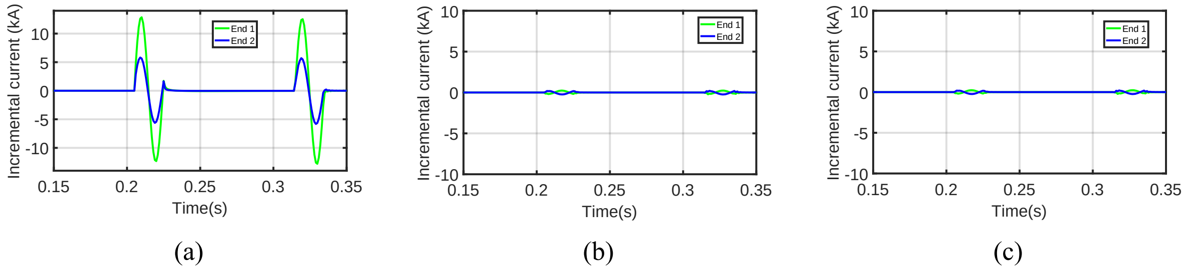

Figure 4. Incremental current of (**a**) phase A (**b**) phase B (**c**) phase C

The sum of signums of all phases is shown in Figure 5. Figure 5a shows the sum of signums of phase A. It is clear that sum of signums becomes equal to 2 quickly on fault occurrence on phase A and is equal to zero during normal condition. Figure 5b,c depict the sum of signums of phase B and phase C respectively. In the case of phase B and phase C, which are not directly involved in the fault (since the fault is on phase A), the sum of signums does not reach +2 or −2 continuously over the next 3 milliseconds. This suggests that there is no significant change in the current of phases B and C because the fault is isolated to phase A.

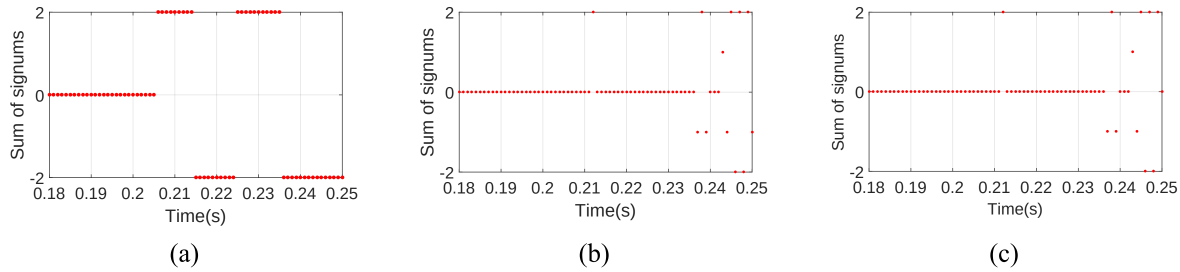

Figure 5. Sum of signums of (**a**) phase A (**b**) phase B (**c**) phase C

The sum of signums in phases B and C remains near zero, meaning that there is no fault in the currents of these phases. In other words, the sum of signums does not show a large positive or negative peak in response to the fault, confirming that the fault does not affect these two phases. The mention of the 3 ms period is important because it sets a threshold to detect the fault's effect. If the fault affected phases B or C, the sum of signums would likely become +2 or −2 during this period, but since it does not, it confirms that only phase A is impacted by the fault.

6. Selection of threshold value (ΔI_{TH}) and delay time (T_{TH})

The modified signum function used in this paper is as:

$$sgn(\Delta i) = \begin{cases} 1, & \Delta i > 0.0001 \\ 0, & \Delta i = \pm 0.0001 \\ -1, & \Delta i < 0.0001 \end{cases} \tag{2}$$

For L_{GL} dead band of ± 0.0001 is selected to eliminate unwanted relay operations on no fault condition. If the delay time T_{TH} is chosen as 1 ms, it may lead to improper tripping as we obtain s(t) = −2 or 2 for 1 ms in case of normal condition and s(t) = −2 or 2 for 2 ms continuously for external fault condition. To be more cautious, we take T_{TH} = 3 ms for both sensing as well as categorization. For L_{GG}, we take T_{TH} = 1 ms for fault detection. However, T_{TH} is taken as 3 ms for fault classification because a shorter delay is found to yield wrong fault classification in some cases.

7. Improved relay algorithm

Figure 6 depicts the flowchart for improved relay algorithm of a line connected between buses 2 and 4 (Figure 1). There are two current transformers (CTs), one at either end of the protected line indicated in Figure 1 to measure current at each instant. Then, incremental currents are calculated as discussed before using Equation (1), for all phases. After that, signum of incremental currents are calculated along each end of the line and transferred from one end to the other. At both ends, we next calculate the signums of each phase, as $s(t) = sgn(\Delta i_1(t)) + sgn(\Delta i_2(t))$

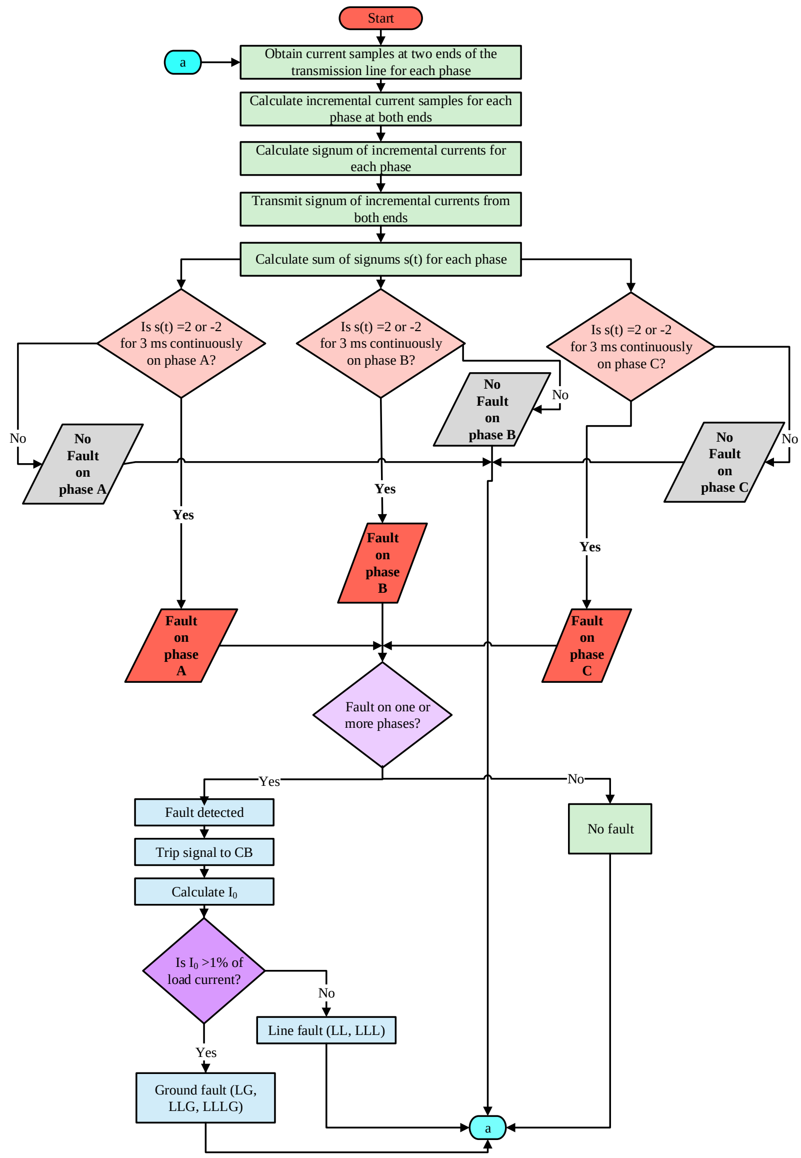

Figure 6. Flowchart for fault detection and classification for line between generator bus and load bus

Fault on phase A if s(t) = 2 or −2 for 3 ms continuously else no fault on phase A. Similar decisions on Phase B and Phase C is taken for fault. In the event that there is a fault in any phase, a signal is sent to the circuit breaker (CB) to cause it to trip, and the problematic component of the circuit is disconnected from it. Zero sequence current is computed in three phases from line currents. Under normal circumstances, there may be a slight mismatch between the currents of the three lines. In case the mismatch is greater than 1%, it means ground fault, else it is a phase fault. As for the line connecting two PV buses, the flowchart will be same with minor modification as the delay time will be 1 ms for for detection and 3 ms for phase identification (i.e., fault classification).

8. Concise results

8.1 *Case 1: Line connecting PV bus and a PQ bus*

The proposed scheme is tested for different locations shown in the Figure 1 and the results for LG fault are given in Table 1. It is clear from Table 1 that fault detection is possible at all locations with different fault resistance values for LG fault. The highest time for detecting a fault and its classification is 4 ms. Also, it is imperative to mention that no case of maloperation of relay is experienced.

For other faults the concise results are shown in Table 2.

It is evident from the above table that all internal faults are detected within 3 ms irrespective of the line load. There is also no case of unnecessary operation of relay. The fault classification time (not shown in the table) varies from 3 ms to 6 ms.

Table 1. Detailed result for LG fault

Fault location	FR (Ω)	DC offset (%)	FST[a]/FCT[b] (ms)					
			(100 MW)	(50 MW)	(25 MW)	(10 MW)	(3 MW)	(No load)
F1	0.01–1000	0	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		100	(4/4)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		0	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		100	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
F2	0.01–1000	0	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		100	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		0	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		100	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
F3	0.01–1000	0	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		100	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		0	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
		100	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)	(3/3)
F4	0.01–1000	0	NFS[c]	NFS	NFS	NFS	NFS	NFS
		100	NFS	NFS	NFS	NFS	NFS	NFS
		0	NFS	NFS	NFS	NFS	NFS	NFS
		100	NFS	NFS	NFS	NFS	NFS	NFS
F5	0.01–1000	0	NFS	NFS	NFS	NFS	NFS	NFS
		100	NFS	NFS	NFS	NFS	NFS	NFS
		0	NFS	NFS	NFS	NFS	NFS	NFS
		100	NFS	NFS	NFS	NFS	NFS	NFS

[a]Fault sensing time, [b]Fault categorization time, [c]No fault sensed

Table 2. Concise result for LL, LLG and LLL fault

Fault type	Fault resistance	Fault location	Various loads FST
LL	0.01–200 ohms	F1, F2, F3 (internal faults)	3 ms
		F4, F5 (external faults)	NFS
LLG	0.01–1000 ohms	F1, F2, F3 (internal faults)	3 ms
		F4, F5 (external faults)	NFS
LLL	0.01–10 ohms	F1, F2, F3 (internal faults)	3 ms
		F4, F5 (external faults)	NFS

8.2 *Case 2: Line connecting two PV buses*

Concise results for all faults for line located between two generator buses are shown in Table 3. It is clear from Table 3 that all faults are detected in just 1 ms and classified in 3 ms. Also, no case of unwanted operation is observed.

Table 3. Concise result for all faults

Fault type	Fault resistance	Fault location	Various loads FST/FCT
LL	0.01–200 ohms	F1, F2, F3 (internal faults)	1/3 ms
		F4, F5 (external faults)	NFS[c]
LG, LLG	0.01–1000 ohms	F1, F2, F3 (internal faults)	1/3 ms
		F4, F5 (external faults)	NFS
LLL	0.01–10 ohms	F1, F2, F3 (internal faults)	1/3 ms
		F4, F5 (external faults)	NFS

9. Validation for the IEEE-30 bus system

The proposed technique has also been validated on IEEE-30 bus system. The IEEE-30 bus system consists of loads, capacitor banks, transmission lines, and generators. Figure 7 depicts a part of the PSCAD model of the IEEE 30-bus system. Line T1_2 between bus 1 and 2 represents L_{GG} and line T1_3 between bus 1 and 3 represents L_{GL}. The faults have been simulated on transmission lines (T1_2 and T1_3) at different locations with different FR values. The concise results for IEEE-30 bus system are shown in Table 4. The technique performs well by detecting all internal faults and can efficiently discrimate between internal and external faults, which is the necessary condition for any fault algorithm.

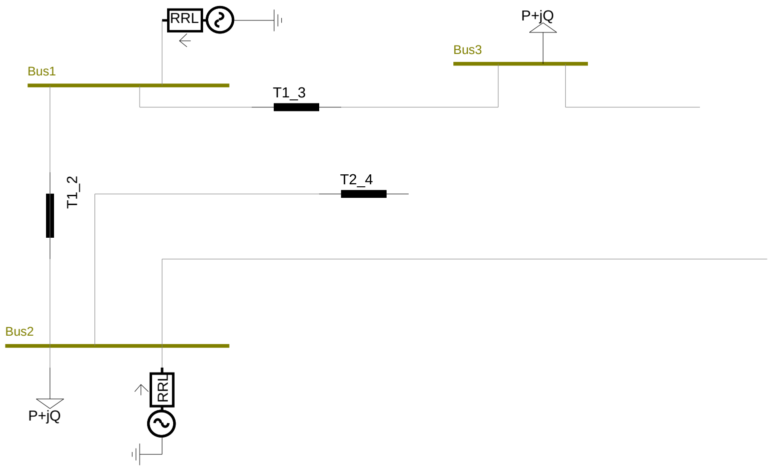

Figure 7. Part of IEEE-30 bus system in PSCAD

Table 4. Concise results for IEEE-30 bus system

Fault type	Fault location	Relay decision
LG, LL, LLG, LLL	Internal	Fault detected
LG, LL, LLG, LLL	External	No fault detected

10. Improvement of incremental current approach over other approaches

More than four hundred cases have been simulated for each fault type with different FR values, locations and DC offsets. The proposed technique has been compared with approach 1 employing instantaneous power [23, 24, 25]. Figure 8 shows the number of times the relay fails to detect the fault for the line connecting generator bus with PQ bus. The technique works well with symmetrical fault only while for other faults considerable number of relay failures are reported as the load increases. Figure 9 shows the number of times the relay fails to detect the fault for the line connecting two PV buses. The technique works well with symmetrical fault only while for other faults considerable number of relay failures are reported as the FR increases. However, no case of unwanted operation of relay is reported using instantaneous power concept. The proposed technique has also been compared with approach 2 employing incremental power [26]. Figure 10 shows the unwanted operations of relay for the line connecting generator bus with PQ bus. The technique works well with symmetrical fault only while for other faults considerable number of unwanted operations of relay are reported as the load increases. However, no case of failure of relay to detect fault is reported using incremental power concept. The comparative analysis of approach 1 employing instantaneous power [23, 24, 25] as fault discriminator, approach 2 employing incremental power [26] as a powerful fault discriminator and approach 3 employing incremental current as fault discriminator which is proposed in this paper is performed and the following outcomes are drawn:

1. The technique employing instantaneous power [23, 24, 25] as conventional fault discriminator is not able to identify fault with high load and high FR values.

2. Even though the technique employing incremental power [26] as fault discriminator detects all internal faults yet, relay demonstrates unnecessary operations with low fault/short circuit resistance values and high loading rates in the event of external faults.

3. The technique employing incremental current as fault discriminator detects all internal faults and does not show any unwanted operation in case of external faults irrespective of fault resistance values and loading levels. Also, the fault detection time is very less in approach 3 as compared to approaches 1 and 2. In other words, approach 3 is an improvement over approach 1 and approach 2.

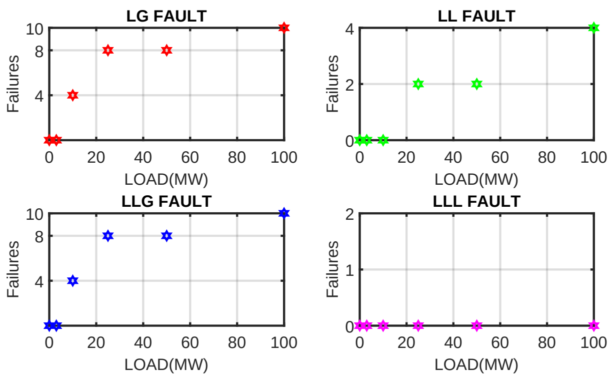

Figure 8. Number of failures reported for L_{GL} using instantaneous power concept [23, 24, 25]

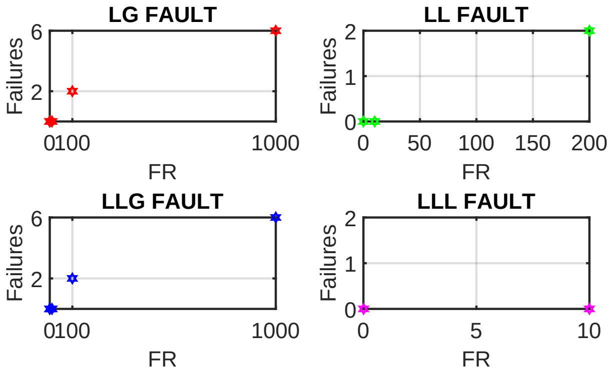

Figure 9. Number of failures reported for L_{GG} using instantaneous power concept [23, 24, 25]

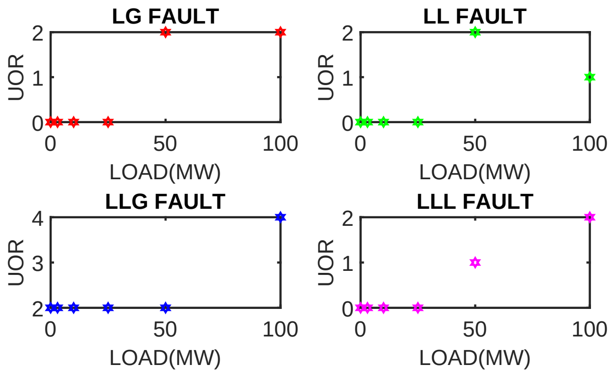

Figure 10. Number of unwanted operations of relay for L_{GL} using incremental power concept [26]

11. Conclusions

This paper presents a novel technique for detection and classification of faults on an uncompenated transmission line. The technique employs incremental current as fault discriminator. The incremental current technique is extensively enquired for its efficiency and effectiveness for two line structures, viz., a line connecting PV bus to a PQ bus (L_{GL}) and second, a line connecting two PV buses (L_{GG}), under different types of faults and fault resistance values, dc offset and loading. The proposed technique works successfully for both lines. The following inferences are made:

- It is not affected by different loads.
- The technique works without failure or unwanted operation for 100% as well as 0% offset.
- It is not affected by fault resistance.
- It is not affected by location of the fault.
- It requires measurement of currents only.

The technique proposed here does not account for the time lag inherent in transmitting data between two ends of a transmission line; this is something that will be addressed in future work.

Conflict of interest

The authors declare no conflict of interest

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