Iranian Journal of Electrical and Electronic Engineering 02 (2023) 2594

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Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Research Paper

A Novel Fault Detection and Classification Approach in Transmission Lines Based on Statistical Patterns

Das. P. Chennamsetty*(C.A.), and Sravana K. Bali*

Abstract: Symmetrical nature of mean of electrical signals during normal operating conditions is used in the fault detection task for dependable, robust, and simple fault detector implementation is presented in this work. Every fourth cycle of the instantaneous current signal, the mean is computed and carried into the next cycle to discover nonlinearities in the signal. A fault detection task is completed using a comparison of two sub cycle means, and the same concept is extended to faulty phase classification. Under various fault and system operating situations, the suggested technique is assessed for regular faults, remote end faults, high resistive faults, and high impedance arcing faults. This paper's extensive case studies illustrate the suggested scheme's simplicity, computational flexibility, speed, and reliability. The suggested approach yields 100% consistent results in 4-8 msec detection time.

Keywords: Shifting Window, Fault Detection, Remote End Fault.

1 Introduction

THE important attributes of protection relay are reliability, computational flexibility, and Speed. Several Fault Detectors (FD) were proposed based on these properties for early separation of problematic components during faults. During failures, FDs relying on immediate time dependent signals like as current, voltage, and active power make swift judgments. Non-fault disturbances and inappropriate operation, on the other hand, have an impact on certain of these FDs. [1]. There are several FDs in the literature, including the following: The basic signal variation (current signal) utilized in the sample-to-sample and cycle-to-cycle direct FD approaches [2]-[5].

At a later time, sophisticated procedures were offered in addition to these simple ones. The moving sum technique was introduced for fault detection jobs in 2006 [3] and the idea was later expanded to fault classification [4] and high impedance fault detection in distribution systems. A summing approach, cumulative sum [5] introduced in 2008, employs a direct instantaneous current signal.

This cumulative sum is useful for discovering faults. Later, the cumulative sum technique was applied for defect detection in complicated networks with actuation signal adjustments for performance enhancement [6]. In addition, a determinant-based technique [7] was presented, this is predicated on the sinusoidal curve shape of the instantaneous current signal when sampled uniformly. This approach is straightforward, but it is susceptible to noise and system disturbances other than errors. Another useful technique for determining the nonlinear character of a curve based on its regular form is the Euclidean norm (ED). For the aim of detecting and classifying faults, an ED-based fault detection technique is supplied with an instantaneous power signal and a current phasor [8]. Along with these approaches,

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Iranian Journal of Electrical and Electronic Engineering, 2023.
Paper first received 18 Jul 2022, revised 15 Jan 2023, and accepted 29 Jan 2023.

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https://doi.org/10.22068/IJEEE.19.2.2594.

other strategies were also accessible in the literature, including the aforementioned adaptive techniques [9], techniques based on phasor estimates [10], intelligent approaches [11], and signal transformation approaches [12]-[13]. These methods require a lot of calculation time, are sophisticated, and are computationally challenging. To find problems in transmission lines, a mean-based error estimation technique [14] using three consecutive samples was recently developed. Due to the use of three successive samples, this mean varies, making it difficult to define a threshold. To identify an accurate threshold, optimization approach is also used. A gap exists to meet the necessary protection qualities with fewer calculations outside of current techniques. The statistical metrics available in earlier research studies required certain samples information to produce dependable results. These metrics are also varies with system dynamic conditions. On the other hand, superposition-based schemes are available in literature [15]-[20] with better protection attributes. In [15], superimposed current information is used to locate the faults in the shunt capacitor banks. This time-domain-based protection scheme has merits in terms of the detection time. Based on the signal similarity measure, another protection scheme is presented in [16]. There are several approaches available in the literature to identify and categories various faults that occur in transmission line networks. A superimposed components-based protection scheme is presented in [17] to support the distance protection applied to the protection of lines emanating from DFIG-based wind farms. Another choice to apply these superimposed measures is sequence quantities. In [18], negative sequence quantities are used for the protection of the lines. These schemes are useful for both normal and wind integrated systems to detect and classify the faults. Signal processing tools are also useful to detect faults [19]-[20]. Most of the aforementioned methods are still challenging in terms of the detection time and computational burden.

Based on the symmetrical fluctuation of instantaneous current under normal operating circumstances, this work describes a fault detection and defective phase recognition method based on sub cycle means. Shifting window is introduced to the mean calculation method to enhance detection and reduces the computational effort. The method can quickly produce results for both detection and classification of a wide variety of problems that are covered in more detail in subsequent sections of the article. Due to variation of the mean value with the fault inception, the method produces trip commend within 1-2 quarter cycles. The symmetrical nature during normal conditions is valid for any system and therefore the suggested approach may be used with any system component type. These advantages are validated with wide range of case studies. Rest of the paper organizes as follows: Proposed method description is provided in section 2, test system details in section 3 and simulation studies in section 4. Conclusions are reported in section 5.

2 Proposed Method

The majority of FDs are built based on instantaneous currents since the abnormal changes in these signals during fault circumstances make it simple to identify abnormalities in them. The recommended strategy to creating a fault detection unit (FDU) uses three phase instantaneous current signals, and the same method can categories the defective phase, the instantaneous current signal is provided by

$$i_p(t) = I_P\, sin(2\pi f_o t + \varphi) \tag{1}$$

Where p is the phase, $f_o$is the fundamental frequency of the system in Hertz and φ is the phase angle shift with respect to reference frame in rad/second. With a sample frequency of sampling frequency of f_s , this continuous time signal is discretized, and the discrete form of Eq. (1) is given by:

$$i_p(n) = I_P \sin\left(2\pi f_o \left(\frac{n}{f_s}\right) + \varphi\right), n = 0,1,2, \ldots \tag{2}$$

Equation (2) rewritten as:

$$i_p(n) = I_P \sin\left(2\pi\left(\frac{n}{f_s/f_o}\right) + \varphi\right) \tag{3}$$

The number of samples taken from the instantaneous current signal C_k for the k^{th} cycle during one complete cycle is given as f_s/f_o in Eq. (3). The current samples in each subcycle are determined by dividing the full cycle into four equally sized sub cycles using the formula $C_k/4$. The mean of such samples stays unchanged during normal operating settings and exceeds its value under fault conditions due to the symmetrical character of the sub-cycle model. For example, consider that the peak instantaneous current I of a specific phase on a 50.0 hertz system with a 1.0 kilo Hertz sampling frequency is given by:

$$i(t) = I\sin(100\pi t) \tag{4}$$

According to Eq. (3), each cycle of Eq. (4) has 20 samples, hence the successive samples array while Eq. (4) is working normally is provided by

$$i = I * \left[\sin 0 \sin {}^{\pi}/_{10} \sin {}^{2\pi}/_{10} \cdots \sin {}^{k\pi}/_{10} \cdots . \sin {}^{N\pi}/_{10}\right] \tag{5}$$

The mean is provided by using a shifting window with a length of one quarter cycle.

$$i_{S1\_mean} = k_1 and i_{S2\_mean} = k_2 \tag{6}$$

Because this means either $\pm k_1$ or $\pm k_2$ for the fault detection index (γ) is implemented for each subcycle using the absolute mean difference, the value of which is given by:

$$| i_{S1_{mean}} - i_{S2_{mean}} | = u \tag{7}$$

The difference between consecutive means is zero throughout the signal under ideal conditions, denoted by γ, since this absolute value is the same for all sub cycles during normal operation. This number varies when there are interruptions and can be utilized to log errors. As a consequence, defects may be recorded as follows using the following equation:

$$\gamma(k) > u \tag{8}$$

where u is the specified threshold under ideal system conditions. This set threshold, however, is system specific and was established through extensive simulations on the test system. However, FD is impacted by non-fault disturbances, thus zero ideal value is inaccurate. In contrast, the instantaneous sample-based defect detection index may not produce a consistent trip signal. As a consequence, rather than utilizing the difference of consecutive means as the defect detection index, the cumulative sum of the successive means difference is utilized, as the final fault detection index β, and its equation is provided by

$$\beta(k) = \beta(k-1) + \max(\gamma(k) - u, 0) \tag{9}$$

In discrete mode, $'k'$is the time instant. Finally, fault detection and faulty phase identification are performed using β calculated values for each individual phase provided by:

$$\beta_a(k) > v, \quad \beta_b(k) > v, \quad \beta_c(k) > v \tag{10}$$

In Eq. (10), $\beta_a, \beta_b$and $\beta_c$are the a phase, b phase, and c phase fault detection indices, respectively. The typical threshold for combined fault classification and detection tasks is v, as determined by extensive simulation case reports on the test system where the FD must be implemented. Because of the shifting window idea, these indices are applicable for each quarter cycle, and the identical indices are utilized for the cycle's rest of the samples until the following window shifting is updated. The shifting window-based mean computation process under both normal operating conditions and fault conditions is shown in Fig. 1. The absolute mean value for each window, displayed in green dots, is constant because, under typical circumstances, each window has the same samples in terms of magnitude. When there is a failure, this mean value fluctuates from window to window, changing the difference between successive means since each window has different data. These means are comparatively having greater values than normal operating state means because the instantaneous current magnitude is big in case of problems, making fault detection duty readily done. This changing window's calculation flexibility is another benefit. One important feature of FD is its decreased computational overhead, which is achieved for each quarter cycle by computing one index and carrying it for all samples in that cycle. In general, the advantages of the suggested technique give precise, secure judgments quickly detailed in the result sections.

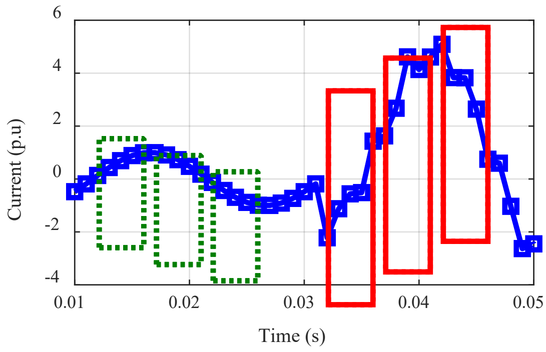

Fig. 1 Calculation of shifting window mean in current signal under normal and fault situations.

3 Test Results for Simulation Studies

A similar power system model from several research publications is used, and its single line diagram is shown in Fig 2. On this model, the proposed combined fault detection and classification approach is assessed for computational flexibility, speed, and dependability. The specifications of this test system are 400 kV, 50 Hz, and the transmission line's positive and zero-sequence impedances (per km base) are (0.03 + j 0.34) Ω and (0.28 + j 1.04) Ω, respectively. Positive-sequence impedance (Z1) = 2.21 +j 25.04 Ω/km, Zero-sequence impedance (Z0) = 4.90 + j 31.51 Ω/km is evaluated on the source-1 side. The instantaneous current is sampled at 1 kHz frequency, while the system operating frequency is 50 Hz. As a result, each cycle has 20 samples available, and each sub cycle has 5 samples using the shifting window. The fifth sample is shared by the first and second shifting windows in this approach, and analogous shared samples are present at each window's edge for symmetry. After reviewing the usual operating circumstances of the test system as well as a number of other occurrences, a standard threshold of 5.0 is created as the post threshold for analyzing any other concerns detailed in the findings section.

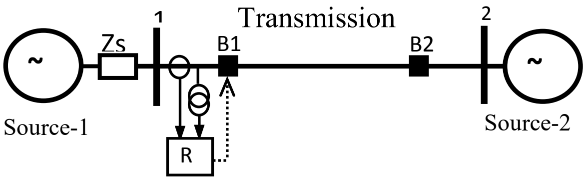

Fig. 2 Representation of a Single line test system is v.

4 Results of Simulation for Algorithm Assessment

A wide range of fault parameters, including fault type, fault location (FL), fault inception angle, and fault resistance (FR), are simulated since the suggested technique is used for integrated fault detection and classification. This is done to assess the effectiveness of the proposed strategy. In addition to these usual normal failures, the approach must evaluate remote end faults, high resistive and impedance faults, faults at zero crossings, and remote end high resistive faults. This section additionally looks at source impedance variations, loading angle changes, and changes in line parameters in addition to these errors. The outcomes are all given below.

4.1 Assessment of the Algorithm for Line-to-Ground Faults

Transmission lines frequently experience line to ground faults. Even though these flaws are not severe in nature, it might be challenging to find them under typical circumstances due to low indices. On a three-phase system, there are three line-to-ground faults known as AG, BG, and CG. By altering their characteristics, these three defects are simulated on the test system. In the first scenario, the FL, inception, and FR are 120 km, 0.3 seconds, and 35Ω, respectively, for the AG fault. Fig. 3.a displays the case's outcome. The suggested approach detects this problem after 5 ms, and the algorithm also knows the fault phase at that point. Since there is little time between the onset of a defect and its discovery, even the magnitude of the fault detection index is quite small. This demonstrates the benefit of the suggested approach for constructing mean functions along with shifting window. In the second scenario, the FL, inception, and FR are 80 km, 0.24 s, and 70Ω, respectively, for the BG fault. Fig. 3.b presents the case's outcome. The suggested approach detects this defect after 5 ms, and the algorithm also knows the fault phase at that point. In the third scenario, the FL, inception, and FR are 200 km, 0.2s, and 20Ω respectively. Fig. 4.a shows the outcome in this situation. The suggested approach finds this issue after 8 seconds, and the algorithm also knows the fault phase at that point. Similar to the AG fault example, the suggested approach also quickly detects BG and CG problems. Without the need of any complicated phasor estimate signals, fault categorization is also quick. Along with line-to-ground faults, a few more faults are simulated using settings for fault initiation angle, FR, and fault length, with the results shown in Table 1.

4.2 Assessment of the Algorithm during Line-to-Line Faults

These faults, like line to ground faults, are not severe in nature, but they are simple to identify in normal conditions due to large fault indices. Since they exist between two phases, these faults are often referred to as multi-phase faults without ground involvement. On a three-phase system, there are three types of line-to-line faults: AB, BC, and AC. Because there is no direct contact to ground, these faults provide reduced FR. On the test system, three failures are also simulated by changing the parameters. An AB fault with FL, start, and FR of 50 kilometers, 0.32 seconds, and 10 Ohms is employed in the first scenario. Fig. 4.b depicts the outcome of this instance. The suggested system detects this issue after 3 seconds. The outcomes of a BC and an AC fault with FLs of 90 km, fault inceptions of 0.27s, and FR s of 2Ω are shown in Figures 5.a and 5.b. Since the magnitudes rise as a result of multi-phase involvement, the suggested approach discovers these three faults, together with inaccurate phase classification, more quickly than line to ground faults. Table 1 displays the results of simulating a few different failures in addition to line-to-line faults using random FL, fault inception angle, and FR parameters.

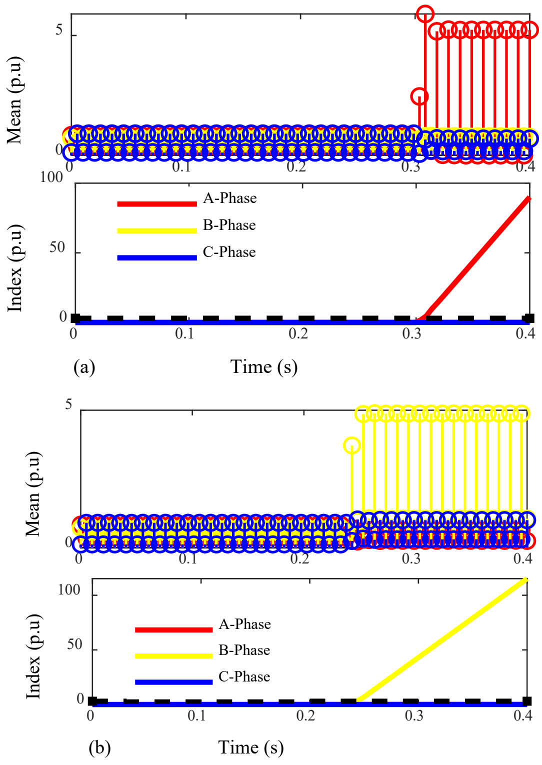

Fig. 3 Revelation plot: (a). AG fault (b). BG fault.

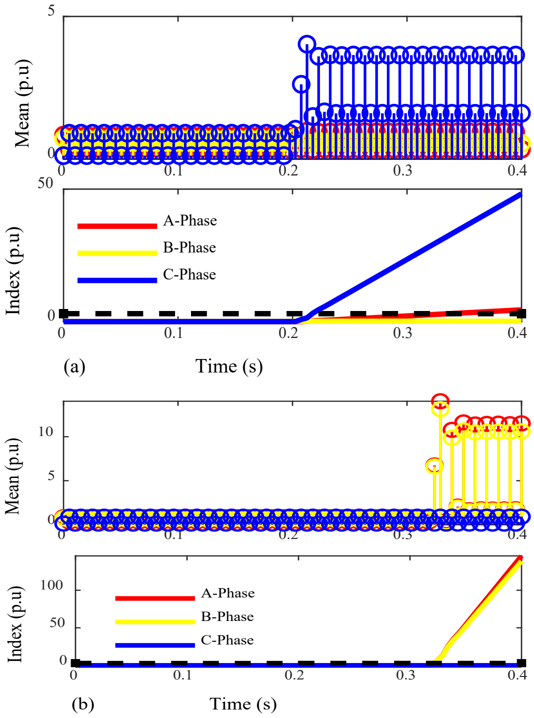

Fig. 4 Revelation plot: (a). CG fault, (b). AB fault.

Table 1 Response of suggested approach for random fault instances.

Fault type	FL (km)	FI (s)	FR (Ω)	FDI (p.u)	FDT (s)	Fault Phase
AC	285	0.3	5.0	3.827	8	A, C
AB	150.0	0.260	10.0	3.522	3	A, B
AG	145.0	0.20	50.0	3.092	7	A
BG	75.0	0.220	20.0	4.299	3	B
CG	225.0	0.240	10.0	4.509	14	C
ABCG	185.0	0.370	15.0	3.717	4	A, B, C
BCG	40	0.330	25.0	6.181	4	B, C

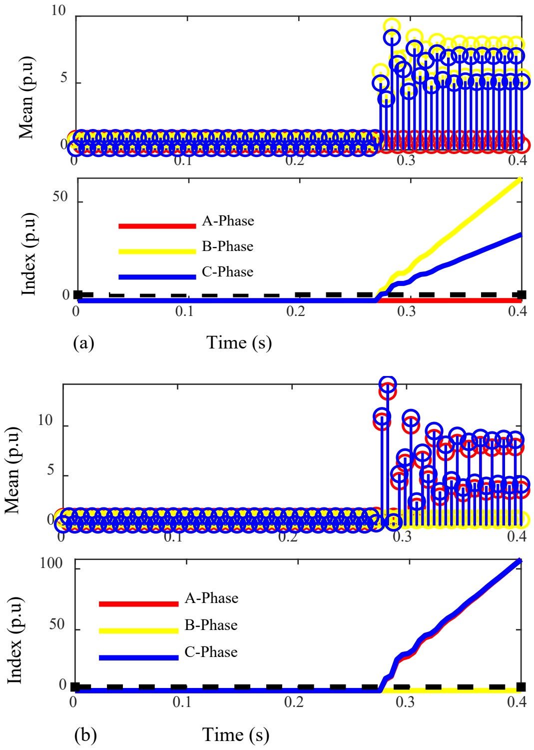

Fig. 5 Revelation plot: (a). BC fault, (b). AC fault.

4.3 Assessment of the Algorithm during Line to Line to Ground Faults

These faults have the potential to offer high FR since they are multi-phase with ground involvement. For the purpose of evaluating the proposed design, an ABG fault is triggered at 0.28s, situated 230km from bus 1, and has a FR of 20Ω. The suggested approach detects all of these flaws, and the results are presented in Fig. 6. In addition to ABG fault, BCG and ACG faults are examined, the results are displayed in Table 1. The cases 4.1 through 4.3 all contain asymmetry flaws. In addition to these faults, transmission lines can experience severe 3-phase symmetrical faults with a low likelihood of occurrence and high severity. Case 4.4 investigates and reports on these cases.

Where FL, FIT, FDI, FDT, and FR stand for Fault Location, Fault Inception Time, Fault

Detection Index, Fault Detection Time and FR, respectively.

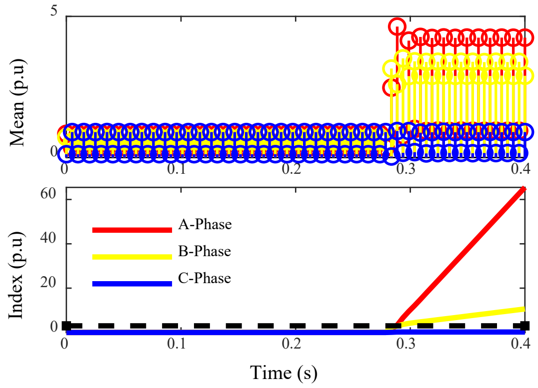

Fig. 6 Revelation plots ABG fault.

4.4 Assessment of the Algorithm during 3-Phase Faults

Transmission lines typically experience the ABC and ABCG faults, two 3-phase faults that can cause significant damage if not identified and isolated from the functioning power system. Without a doubt, the suggested technique detects these faults readily since the relative fault indices magnitudes are quite huge in comparison to all other system occurrences. Assume an ABC fault arises on a transmission line with a FL of 220 km and an inception time of 0.3s. Since this fault is not connected to the ground, the FR is set to 5.0 Ohms. Fig. 7. (a) displays the comparable ABC fault discoveries using the recommended technique.. ABCG faults occur on transmission lines with fault locations of 130 km and inception times of 0.18s, respectively. Because the fault involves a ground, 15Ω is used as FR. Fig. 7.b depicts the suggested scheme's findings for the ABCG fault. The suggested approach can generate trip commands in both circumstances in 3-4 msec. Table 1 displays a few additional symmetrical fault results.

4.5 Assessment of the Algorithm during Zero İnception Angle Faults

When the magnitudes of the fault detection index/indices are small, the task of detecting faults gets increasingly challenging. Line-to-ground faults involving zero inception angles fall into this group. A BG fault having zero inception angle is analyzed to assess the feasibility of the proposed technique both for detection and classification. Fig. 8 demonstrates a possible scheme reaction to such a flaw. This response clearly demonstrates the benefit of the suggested technique for detecting such low index errors. (AG, 100 kilometers, 0.1583, 40 Ohms).

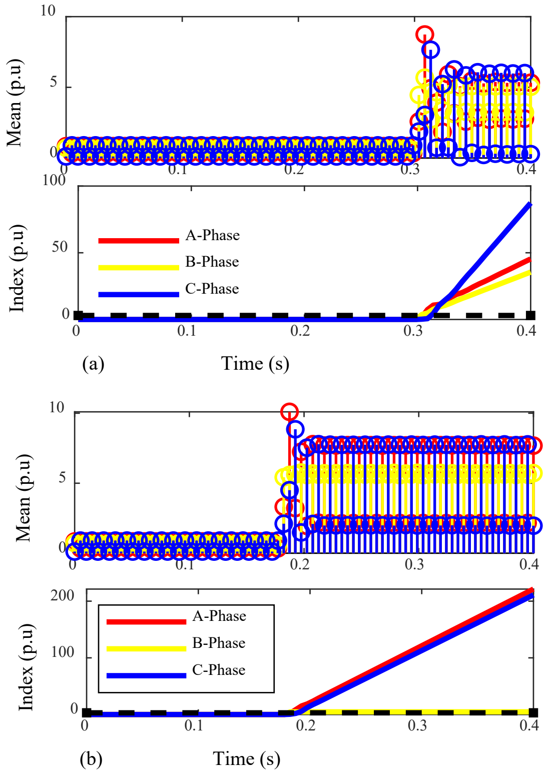

Fig. 7 Revelation plot: (a). ABC fault, (b). ABCG fault.

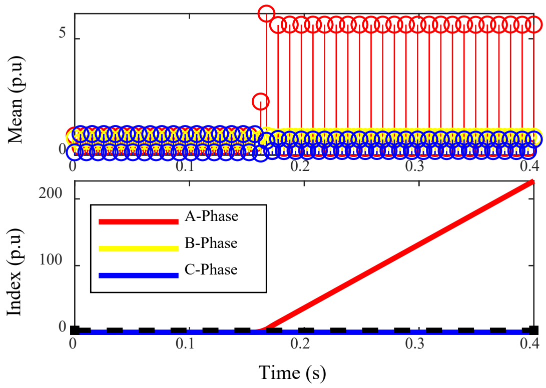

Fig. 8 The suggested technique response to zero inception defect.

4.6 Assessment of the Algorithm during Remote End Faults

Fault detection is challenging in the context of distant end faults (faults which happen long away first from relay point) because the line impedance is large and thus fault detection indices have small value. In this article, Table 1 shows the results of evaluating a few remote end LG faults to validate the effectiveness of the suggested system. In addition to these findings, Fig. 9 displays the suggested approach detection outputs for a CG fault located 270.0 kilometers distant. This fault location accounts for 90% of the line's entire length, comes under the distant fault case. Overall, the findings demonstrate the algorithm's reliability in the face of remote end problems.

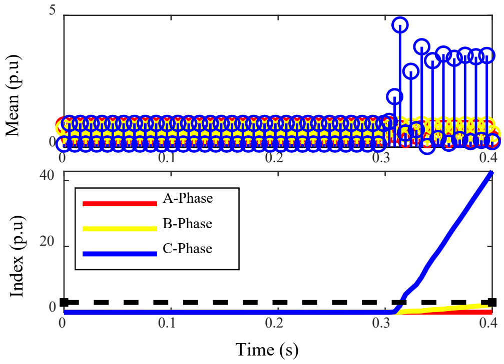

Fig. 9 The suggested technique response to a remote end fault.

4.7 Assessment of the Algorithm during High Resistance Faults

Sometimes, Due to the contact between the line and the ground, faults may present significant FR. Due to the high impedance that the relay sees, these errors cannot even be detected by distant relays. These problems are quickly identified by the proposed approach thanks to its well-constructed process. A BG fault is started at 0.3 seconds with a FR of 120Ω at a distance of 90kilometers to support this claim. The suggested scheme's related findings are shown in Fig. 10. The findings suggest that the proposed approach is effective at detecting these common errors.

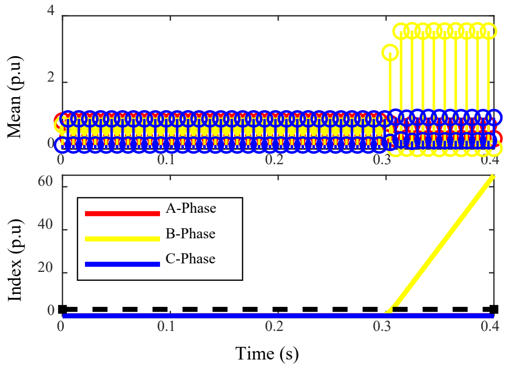

Fig. 10 The suggested technique response to a high resistive fault.

4.8 Assessment of the Algorithm during High Impedance Arcing Faults

The chances on high voltage overhead transmission lines, there is reduced likelihood of arcing faults with high impedance occurring; a case study is looked at to demonstrate the effectiveness of the suggested solution. On the test system, an AG failure is simulated for this purpose. The fault is 120.0 kilometers distant, the inception time is 0.25 s, and the FR is 100.0 Ohms. Fig. 11 depicts the reaction of the proposed scheme for this arcing fault. The approach can also detect high impedance defects, according to the results.

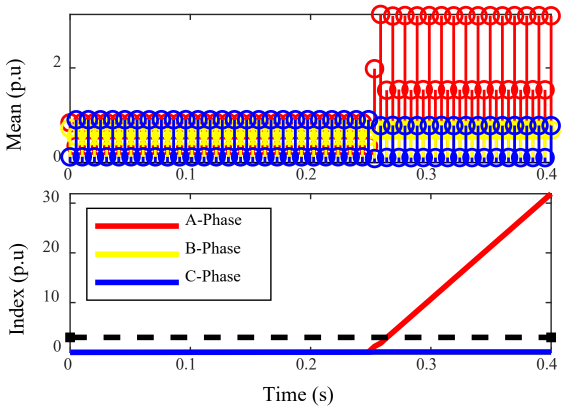

Fig. 11 HIF response to the suggested approach.

4.9 The Influence of Source Impedance on Relay Decision

Whenever faults occur, source impedance may change, influencing relay selection. In order to investigate the consequences of source impedance fluctuation, an AG fault at 140.0 kilometers was simulated and triggered at 0.280 seconds with a FR of 20 ohms. Fig. 12 displays the response of the suggested system for the case study with and without source impedance. According to the findings, the method's response is accurate in both situations, making simultaneous detection and categorization achievable.

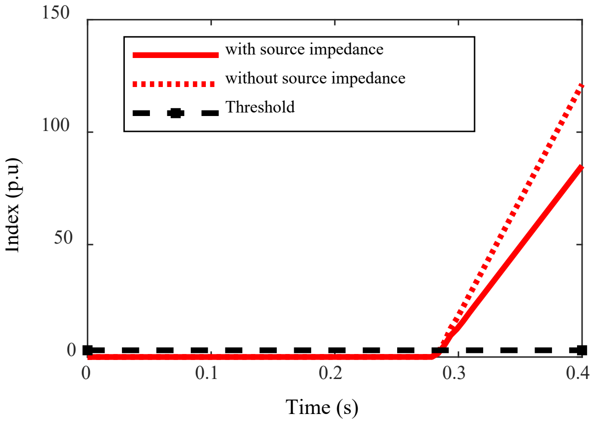

Fig. 12 The suggested technique's response in the presence of source impedance fluctuations.

5 Conclusions

The simultaneous fault detection and classification method based on the quarter cycle mean developed in this work is based on the symmetrical structure of power system signals under fault and normal operating conditions. This approach gave dependable and accurate results in a short period of time for both detection and faulty phase identification, regardless of fault operating factors such as fault location, origin, type, and FR. During common fault instances, the approach also delivered right judgments. Another benefit of the technique is that since the mean is calculated four times for each cycle and no phasor computation is necessary because it is based on instantaneous currents, the computing cost is negligible. Overall, the suggested approach meets the majority of the protective relay properties.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing to publication, with respect to intellectual property.

Funding

No funding was received for this work.

Credit Authorship Contribution Statement

Das. P. Chennamsetty: Idea & Conceptualization, Research & Investigation, Analysis, Project Administration, Methodology, Software and Simulation, Original Draft Preparation. **Sravana K. Bali:** Idea & Conceptualization, Research & Investigation, Data Curation, Project Administration, Supervision, Verification, Revise & Editing.

Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.

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