A Novel Method for Detecting High Impedance Single-Line-to-Ground Fault in an Electrical Power Distribution System Based on Analysis of Current Waveforms

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***Abstract*—Successful detection of High-Impedance Fault (HIF) has remained a challenge for researchers and power system protection engineers because of the low magnitude of the fault current and fluctuating fault current that can become momentarily unstable. This paper presents a new method for detecting HIF in electrical power distribution system based on analysis of alternating current waveforms. Since HIF current can be asymmetrical or symmetrical, the research modeled and analyzed both the positive and negative half-cycles of pre-fault and post-fault current waveforms. Fuzzy logic system is integrated with this new HIF detection system to provide a means for categorizing fluctuating average fault current values in appropriate Fuzzy subsets. The effectiveness of this new detection method was verified through numerical simulations implemented using Matrix Laboratory (MATLAB) software, Fuzzy logic toolbox and Python integrated development environment. Results obtained show that this new technique can effectively detect high-impedance fault in electrical power distribution system at any point between 0° and 360° of the current waveforms.**

***Index Terms*—electrical power distribution, fuzzy logic, half-cycle, high impedance fault**

I. INTRODUCTION

High Impedance Faults (HIFs) are generated when overhead power lines lose support and fall to a poorly conductive surface which reduces the current flowing through the live conductor below the detection level of the conventional protective system. For example, a severe weather condition can disengage overhead power line from towers (or poles) and crash it to the ground (or over tree branches). Successful detection of high impedance faults has remained a challenge for researchers and power system protection engineers because of the low magnitude of the fault current as well as fluctuating fault current that can become momentarily unstable. Fault current can be defined as the electrical current which flows in an electrical circuit during electrical fault conditions.

II. LITERATURE REVIEW

In existing literature, power system protection engineers and researchers have investigated and developed different techniques for detecting HIFs. For example, Pirmani *et al*. [1] investigated the challenge of extracting fault current characteristics, which vary significantly with operating conditions, especially fault impedance. Using the dynamic phasor method, the authors analyzed Single-Line-to-Ground (SLG) faults, deriving the fault current behavior under Resonant Grounding (RG). Their simulations revealed a persistent residual fault current even under ideal resonance, highlighting the complexity of fault analysis in RG systems and the need for robust protection. Vikram and Srikanth [2] introduced a method for fault detection and classification on mutually coupled double-circuit transmission lines, employing a single Fuzzy inference system integrated with a discrete Fourier transform. Implemented in Matrix Laboratory (MATLAB) / Simulink, the scheme demonstrated the ability to detect or classify fault types within one cycle time. An approach for HIFs detection based on the energy variation of the low harmonic orders obtained by the S-transform was investigated in [3]. Results from the tests with the IEEE 34-node test feeder using actual HIF currents recorded experimentally at a test field indicated that the method is a promising technique for HIF detection.

Bhatnagar *et al*. [4] presented a method that combined Discrete Wavelet Transforms (DWT) and Fuzzy Inference System (FIS) for HIF detection and classification. Modified IEEE 13-node test feeder system was used to validate this new scheme. In their contribution, Yu *et al*. [5] presented HIFs detection and Fault Resistance (FR) calculation method based on damping rate double-ended measurement. The simulation results show that the effective HIF detection range is up to 20 kΩ, and the FR calculation error is less than 0.1%. HIF detection method using synchronized current information was investigated in [6]. Simulation results show that this method can reliably detect HIFs with reasonable detection accuracy in noisy environments.

Biswal and Parida [7] discussed numerous fault detection methods for developing a technique to identify HIFs. This technique also differentiates the faulty events from various non-faulty ones such as switching off generators, capacitors, loads, etc. To implement and

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demonstrate this method, a 5 bus micro-grid system integrated with a wind turbine-based system generator was simulated using Power System Computer-Aided Design (PSCAD) software. Moreover, the performance of the embedded HIF modules in two commercialized HIF detection relays for an actual distribution network was investigated in [8]. The authors carried out tests to assess the relays performance for HIFs with different ground surface materials and different positions along the lines. Based on the build-up characteristics of the HIF current, a method that combines Stochastic Resonance (SR) using noise and Variational Mode Decomposition (VMD) was investigated in [9]. SR was used to detect the transient zero-sequence current in strong background noise and obtain the output current; while the VMD was adopted to decompose the output current. Results of several tests show that the method can realize accurate identification in strong background noise with an SNR = −10 dB.

Wontroba *et al*. [10] presented a method for detecting HIFs generated by cable breakage, based on the analysis of the harmonic and the symmetrical components of the current. This method was validated using real-time digital simulations and hardware implementation. Results obtained show that the methodology provided better performance under different types of HIF and models of HIF. Based on the characteristics of HIF transient zero sequence currents, a methodology for HIF detection in time domain, which includes 1-D variational prototyping-encoder and decision tree algorithm was investigated in [11]. The performance of this method was analyzed using waveform samples collected from the PSCAD / Electromagnetic Transients Direct Current (EMTDC) simulation platform and the actual distribution networks. The results show that this method provides good classification performances on both simulation and field data at high noise levels without transformation between different domains.

Biswal and Parida [12] presented a methodology based on using discrete wavelet transform and support vector machines for HIF detection. This paper discussed the nature of the HIF current arc and presented a scheme for separating the faulty events. The accuracy of this technique was tested on a 5 bus micro-grid system integrated with a wind generator which is simulated using Power System Computer-Aided Design (PSCAD) software. A faulty feeder detection technique based on transient energy and cosine similarity was investigated in [13]. The effectiveness of this detection methodology was verified in the radial distribution network and the modified IEEE 34-bus distribution network. Furthermore, an improved arc based on single-ground arcing fault conducted on a 10 kV experimental platform under different fault conditions was investigated in [14]. Test results show characteristic parameters under different fault conditions. PSCAD/EMTDC software supported the verification of the improved arc model.

Liu *et al*. [15] presented a method for distinguishing Single-Line-to-Ground Faults with Line Breaks (SLGFs-LBs) and Single-Line-to-Ground Faults (SLGFs). The source-side and the load-side voltage characteristics of SLGFs and SLGFs-LBs were analyzed, and the phase difference between the voltage of the fault phase and non-fault phase at the load side was selected as the identification criterion. Field testing and simulation experiments were conducted to verify the effectiveness and robustness of this method. A transfer function method for evaluating the effect of impedance and location of faults by analyzing the voltage and current signals in the frequency domain was investigated in [16]. To improve the performance of the transfer function method, the authors utilized combined conventional neural network and hybrid model of deep reinforcement learning to identify and locate single-phase to ground short circuit faults in transmission lines. A monitoring system embedded with machine learning analytics that ensures a fast and accurate detection of HIFs in power system was investigated in [17].

Torres-Garcia *et al.* [18] presented a resistive HIF model that was implemented using the Alternative Transient Program of the Electromagnetic Transient Program (ATP/EMTP) software to represent the main characteristic of HIFs. The model was compared with well-proven models by using two multiresolution approaches. This analysis demonstrated that the HIFs detection may be identified under specific frequency bands. An intelligent HIF detection technique for distribution lines incorporating the distributed generators was investigated in [19]. Input patterns were extracted using variation mode decomposition. The technique was verified on a modified IEEE 13-bus feeder for various events considering the changes in distributed generator parameters and noise levels.

Additionally, Mohammadnian *et al*. [20] developed a data mining-driven scheme based on Discrete Wavelet Transform (DWT) for high impedance fault detection in active distribution networks. The performance of this technique was investigated for two active distribution networks including 13-Bus and IEEE 34-Bus systems. Silva *et al*. [21] investigated application of an incremental learning algorithm based on data streams to detect high impedance faults in power distribution systems. Discrete wavelet transform was used as a feature extraction method combined with evolving neural network for recognizing spatial-temporal patterns of electrical current data. Results show that the detection system is efficient and robust to changes.

In an interesting contribution, a detection methodology for high-impedance SLG fault in overhead power distribution system using wavelet and fuzzy logic was presented in [22]. Fuzzy logic module was integrated with the detection system design to provide capability for effective tripping of the protective system. The effectiveness of this detection system was tested via numerical simulations implemented in MATLAB and Fuzzy logic toolbox. Results show that the detection scheme could effectively detect high impedance SLG fault and separate affected segments from the rest of the power distribution system. Ghaffarzadeh and Vahidi [23] presented a methodology to effectively discriminate between the HIF and the normal system operation events in power distribution network by combining a preprocessing module based on wavelet packet transform with an Artificial Neural Network (ANN). Wavelet packet was applied to extract distinctive features of current signals, and this information was then introduced to training the ANN for identifying HIF from the normal system operation events. The simulated results show that this technique can accurately identify the HIF in an overhead distribution feeder.

The key contributions of this research are:

1) This new method can detect high-impedance SLG fault for both asymmetrical and symmetrical fault currents as it analyzes the positive and negative half-cycles of the current waveform for all cycles of interest.
2) This new method can effectively differentiate HIF from other power distribution system conditions such as noisy loads, capacitors and generator switching. This is achieved by analyzing several cycles to determine significant difference between the pre-fault (reference) and post-fault average value of the HIF current waveform.
3) This new method can detect HIF that occurs at any point between 0° and 360° of each cycle of the current waveform; for example, detecting HIF that occurs in the first half-cycle of first cycle of the current waveform.
4) The integrated fuzzy logic system provides effective means for handling HIF current fluctuation and instability. By using proper terms for the Fuzzy subsets of the universe of discourse, fluctuating average current values can be categorized (or classified) in the appropriate Fuzzy subsets.

The rest of the paper is organized as follows. Motivation and problem formulation are presented in Section III. Modeling of HIF current in power distribution system is presented in Section IV. Problem solution is presented in Section V. Results and discussion of results as well as comparison of the numerical simulation results with existing literature are presented in Section VI. Section VII concludes the paper.

III. Motivation and Problem Formulation

A. Motivation

Abrupt occurrence of SLG fault in alternating current power distribution (or transmission) system, results in asymmetrical fault current in the sub-transient and transient regions because of the direct current offset, before reaching a steady state. Asymmetric fault current means that amplitude of the current waveform stays on the time axis but there may be disproportionate representation of the positive and negative amplitudes. Since HIF current waveform is characterized by decreasing amplitude of the current waveform over several cycles, this research analyses both the positive and negative half-cycles of current waveforms.

This novel method detects HIFs by analyzing the attenuation of fault current waveform amplitude across sub-transient and transient regions, spanning multiple half-cycles. This research contributes a novel method for high impedance SLG fault detection in overhead power distribution systems, improving both detection speed and robustness against HIF current fluctuations.

B. Problem Formulation

Fig. 1 presents a block diagram of power transmission and distribution system, showing SLG fault at the power distribution section. In this diagram, S, B_1, T, B_2, and Cons, denotes sub-station, Bus 1, distribution transformers (step-down transformers), Bus 2, and consumers, respectively. In addition, Z represents pre-fault power line impedance, F denotes point of occurrence of the SLG fault, I_F represents the HIF current while Z_0 represents the high impedance associated with this fault current. Even though this research investigates high impedance SLG fault on a single-phase of a power distribution system (say, on Phase 1), the same processing applies to the other two phases (i.e., Phases 2 and 3) of a 3-Phase power distribution system.

Steady current flow in single-phase power line can be described by symmetrical sinusoidal waveform characterized by stable amplitude, frequency and phase offset.

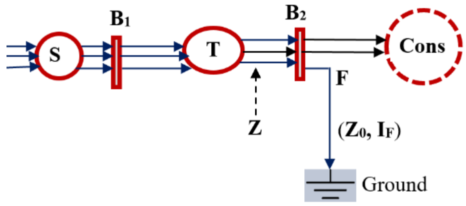


Fig. 1. Block diagram of power transmission and distribution system.

The HIF detection problem is formulated as follows:

1) Modeling steady alternating current flow in power line. This provides a stable pre-fault reference.
2) Modeling HIF current flow in power line (i.e. damped current flow in power line due to high impedance fault).
3) Integrating Fuzzy logic system with this new detection system for effective handling of fluctuation and instability of HIF current flowing in power line.

IV. Modeling High Impedance Fault (HIF) Current on Single-Line-to-Ground (SLG)

HIF can occur at any time along the sinusoidal current waveform in each cycle (i.e., in either positive or negative half-cycle). This research focuses on HIF occurring at any point between 0° and 360° of the current waveforms. The asymmetrical fault current is at its maximum during the first half-cycle after the HIF occurs and gradually becomes symmetrical in later cycles. Two scenarios are considered as follows: 1) steady current flow in overhead power line, and 2) fault current flow in downed power distribution line due to occurrence of high impedance SLG fault.

Scenario 1: Steady alternating current (AC) flows in overhead power distribution line.

The instantaneous steady alternating current flowing in single-phase of the power distribution line is modeled by

$$i(t) = \left(\frac{V_A}{Z}\right)\sin(\omega t + \rho) \qquad (1)$$

where $i(t)$ is the instantaneous current, (V_A/Z) is the amplitude of the current waveform, ρ denotes the phase shift, V_A represents the peak amplitude of the phase voltage, ω represents angular frequency, and Z is the power line impedance. Moreover, t denotes time which is measured in seconds. For this research, it is important to note that $\rho = 0$, since there is no phase offset.

Scenario 2: Fault current flows in power line (due to occurrence of high-impedance SLG fault).

HIF current flowing in distribution (or transmission) power line is characterized by a decaying sinusoid (caused by the increasing impedance) and is modeled by

$$i(t) = \left(\frac{V_A}{Z_0}\right) e^{-(t/\tau)} \sin(\omega t + \rho) = \left(\frac{V_A}{Z_0 e^{(t/\tau)}}\right) \sin(\omega + \rho) \quad (2)$$

where $i(t)$ is the instantaneous current, $V_A/\left(Z_0 e^{t/\tau}\right)$ is the amplitude of the fault current waveform (with increasing impedance in relation to the time-constant), ρ denotes the phase shift, V_A denotes the peak amplitude of the phase voltage, and Z_0 is the line impedance value from the starting point of the HIF current. Moreover, τ is time constant and t denotes time, both measured in seconds.

The time constant is a measure of how quickly the detection system respond to a change in current as a result of the high impedance single-line-to-ground fault. In the context of HIFs, the time constant is influenced by the system's inductance and capacitance, as well as the fault resistance. A higher fault resistance leads to a longer time constant. The capacitance of the distribution system, including cable capacitance and insulator capacitance, plays a significant role. Moreover, the inductance of the power lines and transformers also affects the time constant, with a higher inductance leading to a longer time constant. High impedance faults are characterized by high resistance values which directly affects the time constant calculation (that is, τ=inductance (L)/resistance (R)). Due to arcing (which introduces nonlinearities and high-frequency components into the waveforms) and intermittency, HIFs do not have a fixed time constant. The current research simulations utilize time constant of 50 ms and 100 ms to observe these transient phenomena.

V. Problem Solution

The voltage level of an electrical power distribution system can range between 5 kV and 35 kV; however, most common power distribution voltages are in the 15 kV class. Moreover, feeder load current can be as high as 600 A, but mostly below 400 A. This current research is based on a phase voltage value of 15 kV and feeder current value of 400 A, which yield a line impedance of 37.5 Ω (i.e., the line impedance (Z) up to the starting point of the high-impedance fault current). A 60 Hz power distribution line yields a period of 16.67 ms (i.e., one cycle time is 0.016667 s), while a 50 Hz power distribution yields a period of 20 ms (i.e., one cycle time is 0.02 s).

A. Steady Current Flows in Power Line

For steady current flow in power distribution line, the average current ($I_{\text{avg\_steady}}$) in time interval Δt, i.e. $(t_\beta - t_\alpha)$ is computed by Eq. (3) as follows:

$$I_{\text{avg\_steady}} = \left(\frac{1}{t_\beta - t_\alpha}\right)\left(\frac{V_A}{Z}\right)\left(\frac{T}{2\pi}\right) \times \left\{-\cos\left(\frac{2\pi t_\beta}{T} + \rho\right) + \cos\left(\frac{2\pi t_\alpha}{T} + \rho\right)\right\}. \quad (3)$$

B. High Impedance SLG Fault Current Flows in Power Line

From the point of occurrence of SLG fault, impedance increases in relation to the time constant. This increasing impedance implies that the fault current decreases but never reaches zero.

For the case in which the high impedance fault occurs, the average current ($I_{\text{avg\_HIF}}$) in time interval Δt i.e. $(t_\beta - t_\alpha)$ is computed by Eq. (4) as follows:

$$I_{\text{avg\_HIF}} = \left(\frac{1}{t_\beta - t_\alpha}\right)\left(\frac{V_A}{Z_0}\right)\left(\frac{4\pi^2\tau^2}{T^2 + 4\pi^2\tau^2}\right)(-A + B) \quad (4)$$

here

$$A = \left(\frac{T^2}{4\pi^2\tau}\right) e^{-t_\beta/\tau} \sin\left(\frac{2\pi t_\beta}{T} + \rho\right) - \left(\frac{T}{2\pi}\right) e^{-t_\beta/\tau} \cos\left(\frac{2\pi t_\beta}{T} + \rho\right)$$

$$B = \left(\frac{T^2}{4\pi^2\tau}\right) e^{-t_\alpha/\tau} \sin\left(\frac{2\pi t_\alpha}{T} + \rho\right) + \left(\frac{T}{2\pi}\right) e^{-t_\alpha/\tau} \cos\left(\frac{2\pi t_\alpha}{T} + \rho\right)$$

where t_α and t_β in Eq. (3) and Eq. (4) represent half-cycle time boundary values (in seconds); In a physical power system, a fault can occur at any point between 0° and 360° of the sinusoidal current waveforms. The novel detection methodology presented in this current research can detect fault that occurs at any point between 0° and 360° of the current waveforms. This means that the technique can detect HIF occurring in the first half-cycle following occurrence of the HIF.

C. Fuzzy Logic System Design

High impedance SLG fault exhibits not only low-magnitude fault current, but fluctuating fault current levels (i.e., due to arcing and fault resistance changing rapidly over time) which can become momentarily unstable. This research uses fuzzy logic system to handle the HIF current fluctuation and instability. Fuzzy logic is a many-valued logic rather than binary logic. Using the membership function of fuzzy subsets, fuzzy logic provides a means for representing truth value between false (0) and true (1). For this research, the linguistic variable is "Detection-Result" and the linguistic values (terms) are "HIF-Confirmed", "HIF-Suspected", and "Unstable", where each term is a label of a fuzzy subset of the universe of discourse.

TABLE I: Fuzzy Input (Name, Type and Parameters)

Name	Type	Parameters
Avg.input1	Triangular	[0 10 20]
Avg.input2	Triangular	[18 50 80]
Avg.input3	Triangular	[75 100 130]

TABLE II: Rules, Weight and Name

Rules	Weight	Name
If Avg.val (in Amperes) is Avg.input1 then Detection-Result is "HIF-Confirmed".	1	Rule1
If Avg.val (in Amperes) is Avg.input2 then Detection-Result is "HIF-Suspected".	1	Rule2
If Avg.val (in Amperes) is Avg.input3 then Detection-Result is "Unstable".	1	Rule3

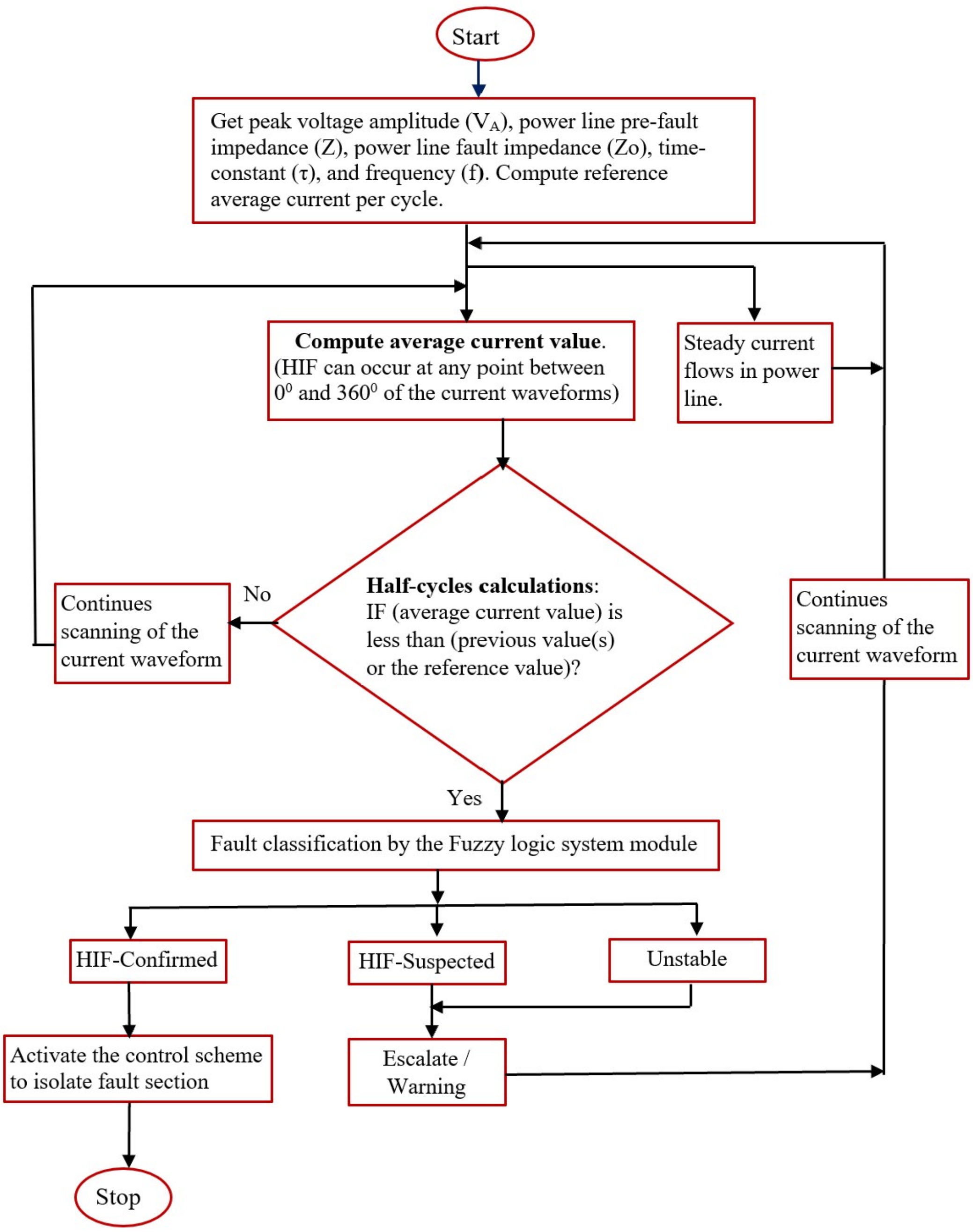


Fig. 2. The new HIF detection system flowchart.

Fuzzy input details (name, type, and parameters) and fuzzy rules are presented in Tables I and II, respectively.

a) Fuzzy input

Name: Avg.val (in Amperes)

Range: [0, 130]

Number of membership functions: 3

b) Fuzzy rules

The numerical simulations analyze blocks of current waveforms consisting of five consecutive cycles (i.e., ten half-cycles: five positive and five negative half-cycles). The computed half-cycle average values of current are stored in variables avg1, avg2, avg3, avg4, …, avg10 (refer to Table III). These consecutive average values are then compared to determine the applicable decision of the integrated fuzzy logic system.

TABLE III: DESCRIPTION OF ABBREVIATIONS USED FOR NUMERICAL SIMULATIONS

Abbreviation	Description
phc	Positive half-cycle of current waveform
nhc	Negative half-cycle of current waveform
t_0[k]	Start time of half-cycle of current waveform
t_1[k]	End time of half-cycle of current waveform
k	Indexing variable (range: 0, 1, …, 9)
Avg.val	Average value (for universe of discourse)
Avg.input1	Input (membership function of Fuzzy sets)
Avg.input2	Input (membership function of Fuzzy sets)
Avg.input3	Input (membership function of Fuzzy sets)
Avg1	Average value for half-cycle 1
Avg2	Average value for half-cycle 2
Avg3	Average value for half-cycle 3

Avg4	Average value for half-cycle 4
Avg5	Average value for half-cycle 5
Avg6	Average value for half-cycle 6
Avg7	Average value for half-cycle 7
Avg8	Average value for half-cycle 8
Avg9	Average value for half-cycle 9
Avg10	Average value for half-cycle 10

D. New HIF Detection System Flowchart

The new HIF detection system flowchart is presented in Fig. 2. The system acquires electrical parameters (V_A, Z, Zo, τ, f), computes reference and half-cycle average currents, and compares the latter to previous or reference values. If the half-cycle average current is lower, a fuzzy logic module classifies the condition as Unstable, HIF-Suspected, or HIF-Confirmed. A confirmed HIF triggers fault isolation, while other classifications trigger a warning.

VI. Results, Discussion of Results and Contributions of the Research

The results of the numerical simulations are presented in Table IV and Table V. The results in Table IV are based on a time constant of 50 ms. The pre-HIF average value of the current is 124.33 A. At the occurrence of HIF, the steady average current value decreases sharply from 124.33 A to 17.87 A within the first half-cycle. The average value of current then decreases from 17.87 A in the positive half-cycle to 13.67 A in the negative half-cycle of the first cycle after the occurrence of HIF. In the second cycle, the average value of current decreases further from 8.60 A in the positive half-cycle to 6.31 A in the negative half-cycle. In following cycles, the average current value decreases to 0.81 A in the positive half-cycle to 0.50 A in the negative half-cycle of the fifth cycle.

TABLE IV: RESULTS OF NUMERICAL SIMULATIONS

k	**$t_0[k]$ (seconds)**	**$t_1[k]$ (seconds)**	**Pre-HIF (Amps)**	**Average Value: HIF (in Amps)**		**Cycles**
				phc	nhc	
0	0.000	0.017	124.3	17.87		cycle 1
1	0.017	0.033	124.3		13.67	
2	0.033	0.050	124.5	8.60		cycle 2
3	0.050	0.067	124.3		6.31	
4	0.067	0.083	124.3	5.58		cycle 3
5	0.083	0.100	124.3		2.90	
6	0.100	0.117	124.3	2.06		cycle 4
7	0.117	0.133	124.3		1.53	
8	0.133	0.150	124.3	0.81		cycle 5
9	0.150	0.167	124.3		0.50	

(Time constant τ = 50 ms. Period = 1/frequency = 1/60 = 16.6667 ms)

The results presented in Table V are based on a time constant of 100 ms. The pre-HIF average value of the current is 124.33 A. The occurrence of the HIF causes the current to drop sharply from 124.33 A to 9.96 A in the half-cycle immediately following the HIF occurrence. The average value of current decreases from 9.96 A in the positive half-cycle to 8.64 A in the negative half-cycle of the first cycle after the occurrence of HIF. In the second cycle, the average value of current decreases further from 6.45 A in the positive half-cycle to 5.96 A in the negative half-cycle. In following cycles, the average current value decreases from 2.24 A in the positive half-cycle to 2.06 A in the negative half-cycle of fifth cycle.

TABLE V: RESULTS OF NUMERICAL SIMULATIONS

k	**$t_0[k]$ (seconds)**	**$t_1[k]$ (seconds)**	**Pre-HIF (Amps)**	**Average Value: HIF (in Amps)**		**Cycles**
				Phc	Nhc	
0	0.000	0.017	124.3	9.96		cycle 1
1	0.017	0.033	124.3		8.64	
2	0.033	0.050	124.3	6.45		cycle 2
3	0.050	0.067	124.3		5.96	
4	0.067	0.083	124.3	5.41		cycle 3
5	0.083	0.100	124.3		3.83	
6	0.100	0.117	124.3	3.53		cycle 4
7	0.117	0.133	124.3		3.46	
8	0.133	0.150	124.3	2.24		cycle 5
9	0.150	0.167	124.3		2.06	

(Time constant τ = 100 ms. Period = 1/frequency = 1/60 = 16.6667 ms)

Fig. 3 demonstrates the behavior of the steady current flow in power distribution lines prior to the occurrence of HIF.

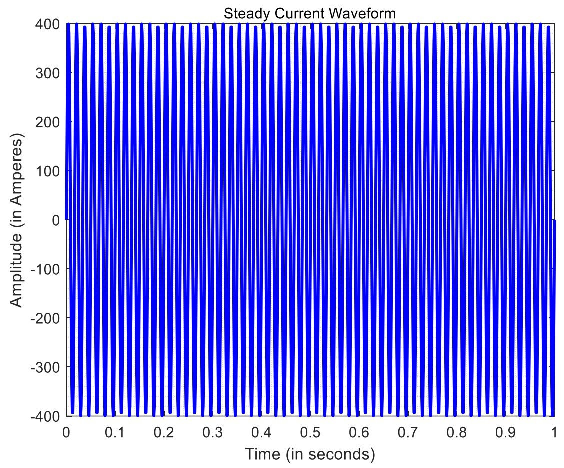


Fig. 3. Current waveform of 60 Hz power line showing steady current flow (i.e., pre-fault current).

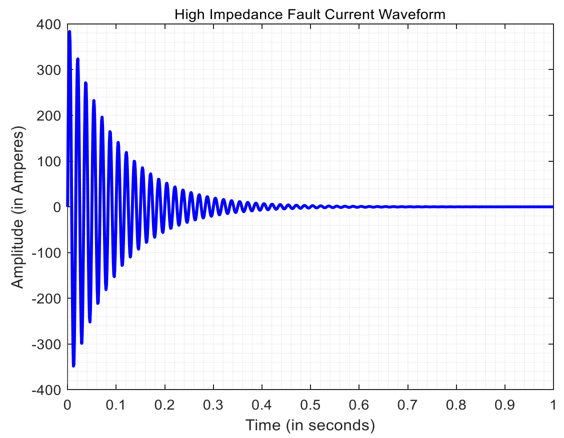


Fig. 4. Current waveform of 60 Hz power line showing high-impedance fault has occurred.

Using a time-constant of 100 ms (i.e., 0.1 s) and for a 60 cycles per second power line, the results presented graphically in Fig. 4, shows occurrence of high-impedance single line-to-ground fault. This result demonstrates the behavior of the current waveform due to the occurrence of the HIF. The HIF is characterized by the decreasing amplitude of the fault current due to increasing line impedance.

A. Fuzzy Inference Rules Simulation Results

The membership function has the linguistic variable “Detection-Result”. The Fuzzy terms of this linguistic variable are: “HIF-Confirmed”, “HIF-Suspected”, and “Unstable”. For each element (i.e., average current value), the degree of membership of a fuzzy subset ranges from 0 to 1.

The Fuzzy Inference Rules simulation results are presented in Fig. 5. The simulation result in Fig. 5 (a) shows that the input value of 17.2 A yields an output value of 10 A. This means the input value of 17.2 A yields an output corresponding to the Fuzzy subset “HIF-Confirmed”.

The result presented in Fig. 5 (b), shows that the average current value of 3.29 A yields an output value of 10 A, which also corresponds to the output Fuzzy subset “HIF-Confirmed”. It is important to note that fluctuation of average current values (for example, due to arcing) within the range 0 A to 20 A will be classified appropriately in the Fuzzy subsets “HIF-Confirmed”.

Moreover, Fig. 5 (c) shows that the average current value of 50.12 A yields an output value of 48.3 A, corresponding to the Fuzzy subset of “HIF-Suspected”. It follows that fluctuation of average current values within the range 15 A to 80 A will be classified appropriately in the Fuzzy subsets “HIF-Suspected”.

In Fig. 5 (d), the average current value of 117.4 A yields an output values of 102 A which corresponds to the Fuzzy subset of “Unstable”. It is noted that fluctuation of average current values within the range 75 A to 130 A will be classified appropriately in the Fuzzy subsets “Unstable”.

An important case to note is when an average current value (i.e., input value) is within the intersection of adjoining two Fuzzy subsets; for example, an average current value within the intersection of “HIF-Confirmed” and “HIF-Suspected”, or within the intersection of “HIF Suspected” and “Unstable”. This is an additional important aspect of Fuzzy logic integration with the HIF detection system. It provides smooth transition between two adjoining Fuzzy subsets. According to [24] and [25], a technique for handling such intersection is to choose one of the two intersected Fuzzy subsets which has the minimum degree of membership at each point in the universe of discourse. This essentially means that fluctuation or momentary instability of the high impedance fault current value within the intersection of two adjoining Fuzzy subsets can be properly classified by this new HIF detection system.

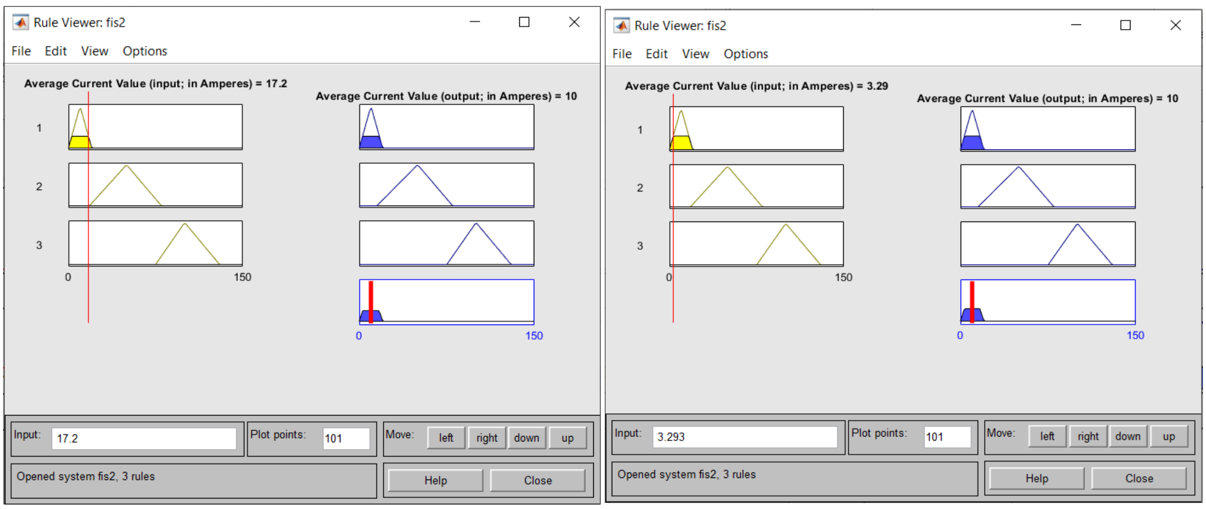
B. Numerical Simulation Results in Comparison with Existing Literature

Numerical simulation results demonstrate that the current method detects high impedance faults (HIFs) in the first half-cycle of the first cycle following the occurrence of HIF by identifying a sharp decrease in the average current between the last pre-HIF half-cycle and the first half-cycle of the first cycle following the occurrence of HIF. This rapid detection is achieved through a novel comparative analysis of the steady-state reference current and the first half-cycle of first cycle of the fault current waveform, representing a significant advancement in HIF detection for electrical power distribution systems.

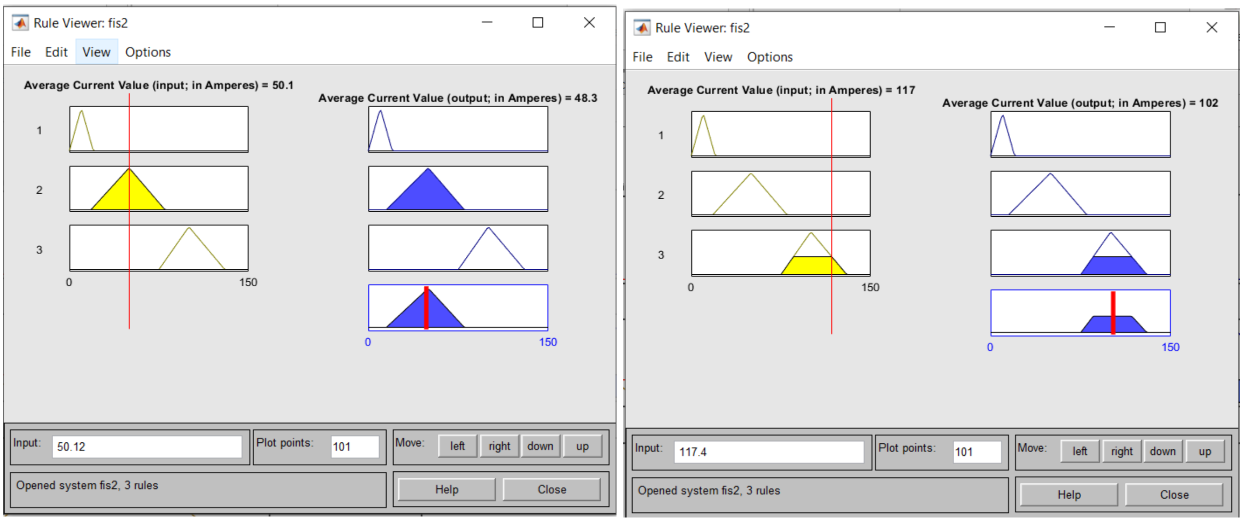
While existing methods, such as the Fuzzy Inference System coupled with Discrete Fourier Transform implemented in MATLAB/Simulink (presented in [2]), reported ability to achieve fault detection within one cycle time, this current research demonstrates a significant speed improvement, enabling high impedance fault detection within the immediate half-cycle following high impedance fault initiation.

A comprehensive review of the literature indicates that this study demonstrates the fastest reported detection of high impedance faults to date.

Furthermore, the integrated fuzzy logic system effectively mitigates the inherent fluctuations and instability of HIF current waveforms, showcasing its robust performance and practical applicability.



(a) (b)



(c) (d)

Fig. 5. Fuzzy inference rules simulation results: (a) rule inference simulation for detection-result ("HIF-confirmed"), (b) rule inference simulation for detection-result ("HIF-confirmed"), (c) rule inference simulation for detection-result ("HIF suspected"), and (d) rule inference simulation for detection-result ("Unstable")

C. Additional Discussion

In this paper, specific features (or parameters) most indicative of HIFs extracted from the half-cycles are low magnitude, highly unstable, random fluctuating fault current levels. While noisy loads can cause current fluctuations, the wide and erratic fluctuation associated with HIFs are often more pronounced and less directly tied to the load cycle. Moreover, the resulting waveforms from capacitor switching are relatively predictable and decay quickly. Like capacitor switching, generator switching can introduce transients, but these are generally well-behaved and decay over a short period. Current waveforms for normal operations are generally sinusoidal at fundamental frequency, and there are no arcing-related harmonics, random or unstable current fluctuations. The hallmark of HIF is its low, wildly fluctuating, and unpredictable current pattern, which stands in stark contrast to the more stable or transient nature of normal operations and other system events.

Half-cycle analysis significantly improves HIF detection for both symmetrical and asymmetrical faults by focusing on the short-duration changes and unique characteristics of HIFs that might be missed by methods relying on full-cycle measurements or steady-state analysis. By breaking down the analysis into smaller, more focused windows, it can magnify and reveal the high-frequency, non-linear, and asymmetric signatures that are the key indicators of HIFs, leading to more reliable and faster detection compared to methods that average out or overlook these critical characteristics.

Half-cycle current comparison (e.g., analyzing each positive and negative half-cycle independently or comparing feature(s) between them) offers significant improvements. By analyzing data over a shorter half-cycle window, the method becomes highly sensitive to the immediate effects of arc re-ignition or extinction. The rapid generation of high-frequency components or sudden shifts in current characteristics are not averaged out. The "on-off" nature of intermittent arcing is more apparent when examining half-cycles. A sudden absence of arcing characteristics in one half-cycle, followed by their appearance, becomes a clear signature.

Fuzzy logic typically does not directly process raw waveforms; instead, it relies on feature extraction technique (i.e., half-cycle analysis) to provide relevant inputs. The fuzzy logic then acts as an "intelligent decision-maker" that weighs these quantified features. In the Fuzzy logic module for HIF detection, the differentiation between "HIF-suspected" and "HIF-confirmed" largely depends on the degree of membership of input feature(s) to predefined fuzzy set, and how these memberships are combined through the fuzzy rule base.

The Fuzzy Logic System (FLS) mitigate false alarms by embracing imprecision and uncertainty in data. This prevents alarms from being triggered by minor fluctuations or noisy data that would otherwise trip a rigid threshold. FLS is properly designed to reliably distinguish from transient disturbances like capacitor switching or noisy loads.

Fuzzy intersection and the min-max operator ([24, 25]) was adopted in this paper to ensure reliable classification of HIFs across overlapping current ranges. For example, the intersection of Fuzzy subsets "HIF-Suspected" and "HIF-Confirmed" represents the Fuzzy "AND" operation. For any element k in the universe of discourse, its degree of membership in the intersection of "HIF-Suspected" and "HIF-Confirmed" is determined by the minimum of its membership degrees in these Fuzzy subsets individually.

VII. Conclusion

This paper presented a novel method for detecting high-impedance SLG fault in electrical power distribution system based on analysis of the current waveforms. Alternating current flowing in power line during steady power distribution system conditions was modeled and analyzed to provide a pre-fault reference. Thereafter, current flowing in power line post-occurrence of the high-impedance SLG fault was modeled to analyze the transient behavior of the damped current waveform in the sub-transient and transient regions. Fuzzy logic system was integrated with this new HIF detection technique to provide a means for effective handling of the fluctuation and instability that may be associated with the HIF current. Electrical power distribution voltage level of 15 kV and feeder current level of 400 A were used to compute the line impedance of 37.5 Ω, which was then used for the numerical simulations.

The effectiveness of this novel HIF detection system was tested through numerical simulation which was implemented in Python interpreter and integrated development environment, MATLAB software, and Fuzzy logic toolbox. Results obtained show that this new method can detect high-impedance SLG fault within the first half-cycle of the first cycle immediately following the occurrence of HIF in electrical power distribution system.

Moreover, this research contributes to knowledge in the following ways: 1) detection of high-impedance SLG fault for asymmetrical (or symmetrical) fault current as it analyzes both the positive and negative half-cycles of current waveforms; 2) effectively differentiates HIF from other power distribution system conditions such as noisy loads, capacitors and generator switching; 3) detection of high-impedance SLG faults in electrical power distribution system at any point between 0° and 360° of the current waveforms; and 4) the Fuzzy logic system integrated with this new detection technique provides effective means for handling the HIF current fluctuation that can become momentarily unstable.

Future work will focus on validating the methodology through real-world implementation.

Conflict of Interest

The author declares no conflict of interest.

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