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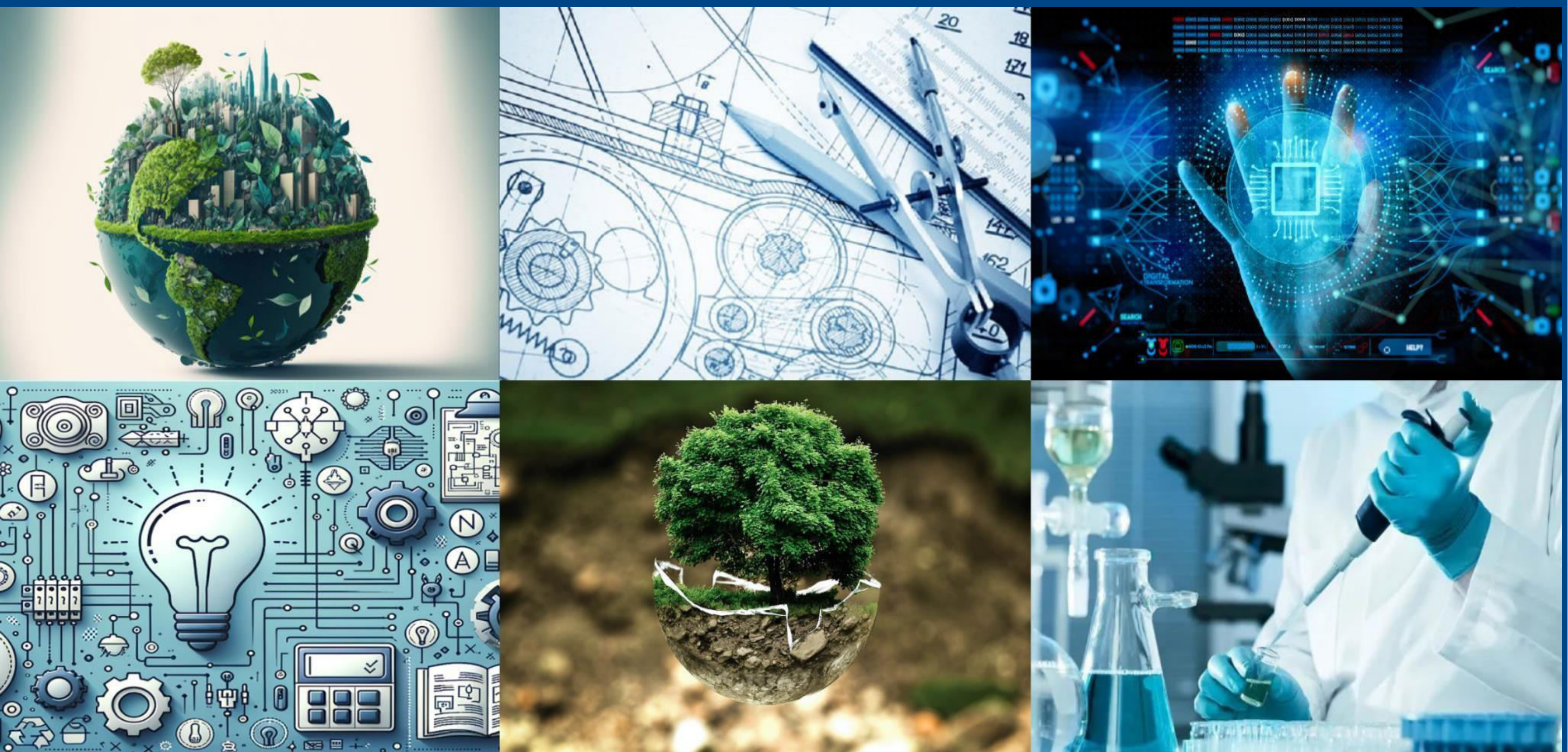

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Design & Implementation Innovative Approach for Detecting High Impedance Single-Line-to-Ground Fault in an Electrical Power Distribution System by using Current Waveforms Analysis Technique

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ABSTRACT: Successful detection of High-Impedance Fault (HIF) has primary a challenge for researchers & power system protection engineers due to the low magnitude of the fault current and fluctuating fault current that can become momentarily not stable. This paper presents a new method for detecting HIF in electrical power distribution system by using alternating current waveforms analysis technique. 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 MATLAB, Fuzzy logic toolbox & Python IDE. Results obtained show that this new technique can effectively detect high-impedance fault in electrical power distribution system at any point between 0^0 and 360^0 of the current waveforms.

KEYWORDS: *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. SYSTEM DEVELOPMENT

The block diagram of the entire system is as shown in Fig. 1

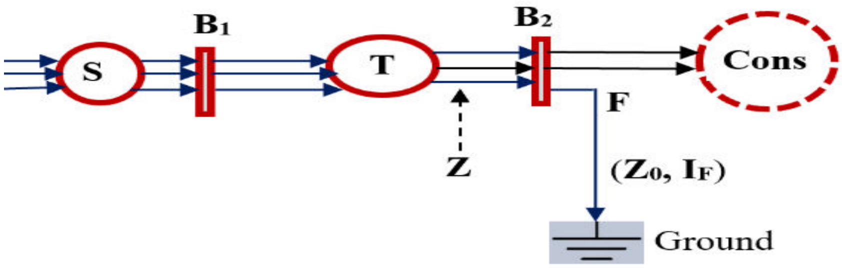

Fig (1) Block diagram of power transmission and distribution system

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Fig. 1 presents a block diagram of power transmission and distribution system, showing SLG fault at the power distribution section. In this diagram, S, B1, T, B2, 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, IF represents the HIF current while Z0 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. 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.

III. WORKING OF CIRCUIT

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 0^0 and 360^0 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

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

where $i(t)$ is the instantaneous current, (VA/Z) is the amplitude of the current waveform, ρ denotes the phase shift, VA 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 ρ=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

$$i(t) = \left(\frac{VA}{Z0}\right) e^{-(t/\tau)} \sin(\omega t+\rho) = \left(\frac{VA}{Z0e(t/\tau)}\right)\sin(\omega+\rho) \qquad (2)$$

where $i(t)$ is the instantaneous current, $VA(Z0et\tau/)$ is the amplitude of the fault current waveform (with increasing impedance in relation to the time-constant), ρ denotes the phase shift, VA denotes the peak amplitude of the phase voltage & $Z0$ 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.

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IV. 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 400A. This current research is based on a phase voltage value of 15 kV and feeder current value of 400A, which yield a line impedance of 37.5Ω (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 (Iavg_steady) in time interval Δt, i.e. $(t\beta - t\alpha)$ is computed by Eq. (3) as follows

$$I_{avg\_steady} = \left(\frac{1}{t\beta - t\alpha}\right) \left(\frac{VA}{z}\right) \left(\frac{T}{2\pi}\right) \times \left\{-\cos\left(\frac{2\pi t\beta}{T} + \rho\right) + \cos\left(\frac{2\pi t\alpha}{T} + \rho\right)\right\}. \quad (3)$$

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 (Iavg_HIF) in time interval Δt i.e. $(t\beta - t\alpha)$ is computed by Eq. (4) as follows:

$$I_{avg\_steady} = \left(\frac{1}{t\beta - t\alpha}\right) \left(\frac{VA}{Z0}\right) \left(\frac{4\pi 2\tau 2}{T2 + +4\pi 2\tau 2}\right) (-A+B) \quad (4)$$

Here

$$A = \left(\frac{T2}{4\pi 2\tau}\right) e{-}^{t\beta/\tau} \sin\left(\frac{2\pi t\beta}{T} + \rho\right) - \left(\frac{T}{2\pi}\right) e{-}^{t\beta/\tau} \cos\left(\frac{2\pi t\beta}{T} + \rho\right)$$

$$B = \left(\frac{T2}{4\pi 2\tau}\right) e{-}t\alpha/\tau \sin\left(\frac{2\pi t\alpha}{T} + \rho\right) - \left(\frac{T}{2\pi}\right) e{-}t\alpha/\tau \cos\left(\frac{2\pi t\alpha}{T} + \rho\right)$$

where $t\alpha$ and $t\beta$ 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 0^0 and 360^0 of the sinusoidal current waveforms. The novel detection methodology presented in this current research can detect fault that occurs at any point between 0^0 and 360^0 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]

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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

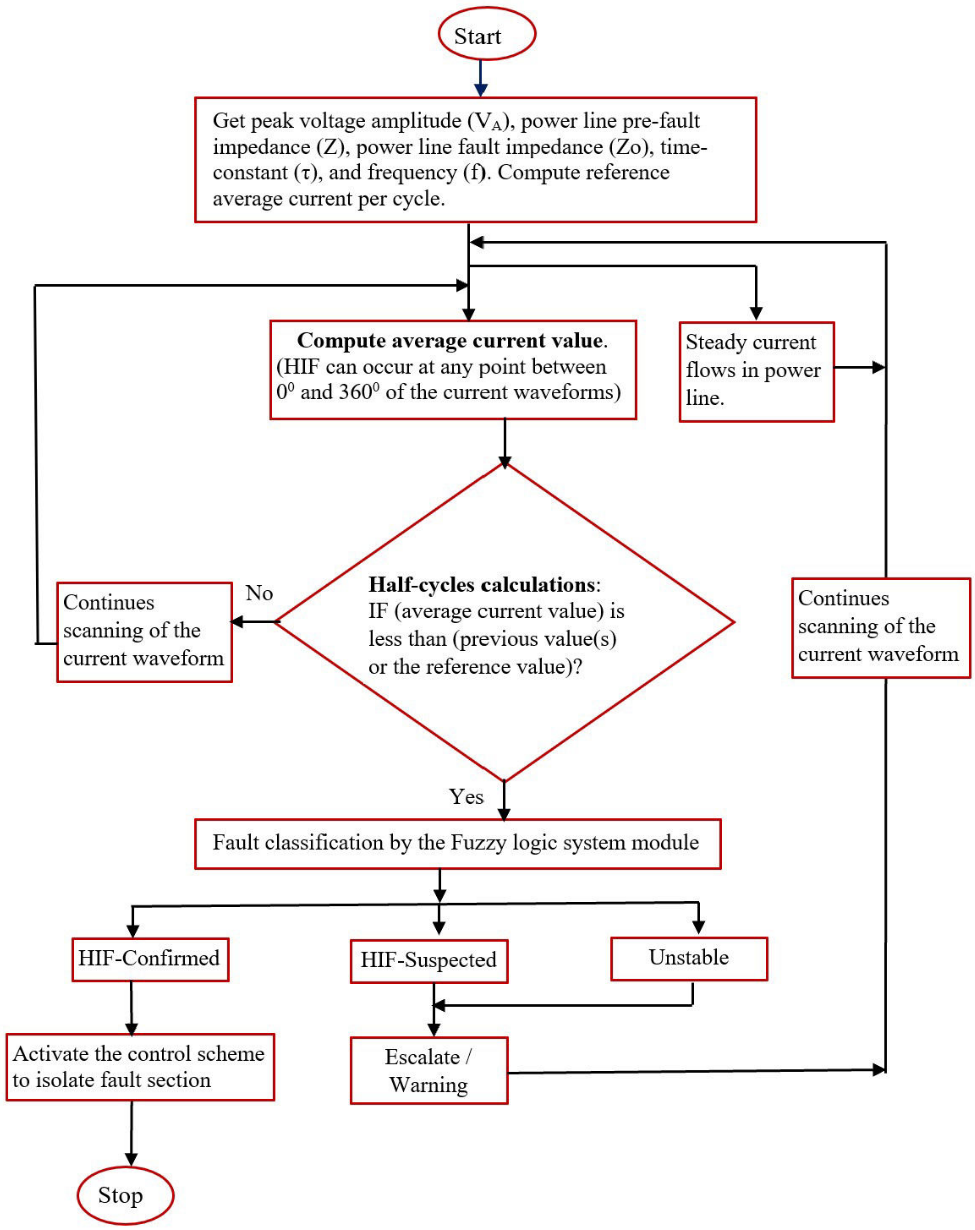

Fig. 2.The new HIF detection system flowchart.

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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 currentwaveforms 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 (VA, 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

V. 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	t0[k] (s)	t1[k] (s)	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	cycle 1
2	0.033	0.050	124.5	8.60	—	cycle 2
3	0.050	0.067	124.3	—	6.31	cycle 2
4	0.067	0.083	124.3	5.58	—	cycle 3
5	0.083	0.100	124.3	—	2.90	cycle 3
6	0.100	0.117	124.3	2.06	—	cycle 4
7	0.117	0.133	124.3	—	1.53	cycle 4
8	0.133	0.150	124.3	0.81	—	cycle 5
9	0.150	0.167	124.3	—	0.50	cycle 5

(Time constant $\tau = 50$ 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	t0[k] (s)	t1[k] (s)	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	cycle 1
2	0.033	0.050	124.5	6.45	—	cycle 2
3	0.050	0.067	124.3	—	5.96	cycle 2
4	0.067	0.083	124.3	5.41	—	cycle 3
5	0.083	0.100	124.3	—	3.83	cycle 3
6	0.100	0.117	124.3	3.53	—	cycle 4
7	0.117	0.133	124.3	—	3.46	cycle 4
8	0.133	0.150	124.3	2.24	—	cycle 5
9	0.150	0.167	124.3	—	2.06	cycle 5

(Time constant $\tau = 100$ 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.

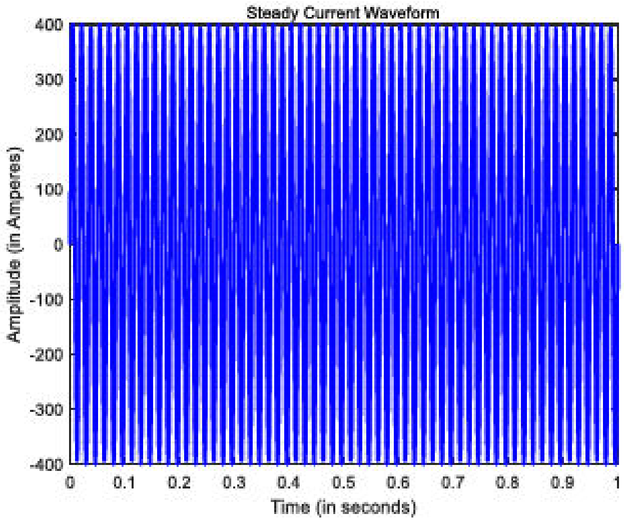

Fig. 3. Current waveform of 60 Hz power line showing steady current flow (i.e., pre-fault current).

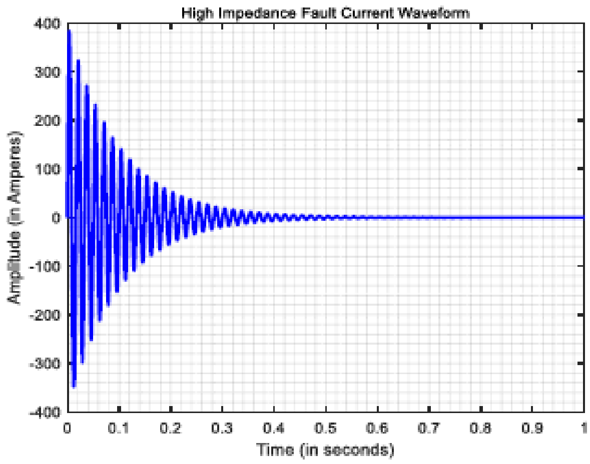

Fig. 4. Current waveform of 60 Hz power line showing high-impedance fault has occurred.

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.

VI. EXPECTED 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

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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 0^0 and 360^0 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.

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