

Analysis of High Impedance Fault Behavioral Dynamics in Medium Voltage Distribution System

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ABSTRACT

High impedance faults (HIFs) present a significant challenge to power system protection engineers. A reliable protection scheme must meet specific objectives, including accurate fault diagnosis, consideration of all possible fault types, and the ability to account for the failure of protection equipment. HIFs, which do not make direct contact with the ground, are difficult for conventional protection equipment to detect, making them largely undetectable. This poses substantial risks to both life and equipment, particularly in systems operating below 35kV. These faults introduce nonlinear characteristics and stochastic currents that disrupt both transient and steady-state system operations, making detection difficult using conventional protection systems, which have a reported success rate of only around 20%. Given these challenges, engineers are exploring advanced identification methods such as artificial neural networks, wavelet transforms, and deep reinforcement learning. These tools offer promising potential for identifying HIFs despite the complexity and unpredictable nature of these faults. This study presents an analysis of high impedance faults in three-phase electrical systems using time series plots to characterize system behavior under various fault conditions. Simulation results reveal distinct waveform patterns during normal operation, single-phase to ground faults, and HIF scenarios. Under normal conditions, the current waveforms are balanced and sinusoidal, with negligible neutral current and minimal harmonic distortion. However, during single-phase to ground faults, a significant increase in the amplitude of the faulted phase current is observed, alongside distortions in the neutral current, indicating system instability.

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INTRODUCTION

High impedance faults (HIFs) present a significant challenge to power protection engineers [1]. A reliable protection scheme must meet specific objectives, including: accurate fault diagnosis, consideration of all possible fault types, and the ability to account for the failure of protection equipment [2]. HIFs, which do not make direct contact with the ground, are difficult for conventional protection equipment to detect, making them largely undetectable. This poses a substantial risk to both the safety of life and

equipment [3]. Systems operating at voltage levels below 35kV are particularly vulnerable to the effects of HIFs. In addition to the safety risks, HIFs can also degrade customer service, leading to financial losses for utility companies [4].

HIFs introduce nonlinear characteristics or stochastic nonlinear currents, which affect both the transient and steady-state operation of the system [5]. Detecting HIFs is extremely difficult using conventional protection systems. The Power System Relaying Committee (PSRC) working group reports that the success rate of detection

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using conventional protection schemes is only around 20% [6]. HIFs are generally classified into two categories: active and passive [7]. Active HIFs occur when underground conductor insulation degrades over time, although this is not a critical issue, as about 90% of underground cables are mechanically protected, ensuring good contact with the earth when such faults occur [8]. In contrast, passive HIFs are more common and present higher risks, particularly on overhead conductors [8].

Given the recurring nature of HIFs, power system protection engineers require a comprehensive understanding of these fault conditions to develop practical solutions [9]. A variety of protection and identification methods have been employed, including artificial neural networks, multi-resolution techniques, wavelet transforms, advanced distortion detection techniques, and deep reinforcement learning, all of which have been applied to address complex problems in various domains [10]. For the

identification of HIFs, learning algorithms may be essential and could play a key role. However, in many existing learning algorithms, some parameters must be predetermined, which is often difficult or infeasible in many applications [11]. Artificial neural networks, inspired by mathematical models of human neural biology, have emerged as a powerful tool for understanding complex brain activities and offer promising potential for fault identification in power systems [12].

MATERIAL AND METHODS

2021a MATLAB/Simulink software was used for the fault signal analysis and development of protection scheme for HIF.

METHODOLOGY

Implementation of HIF on a medium voltage distribution system and analyzing its behavioral dynamics.

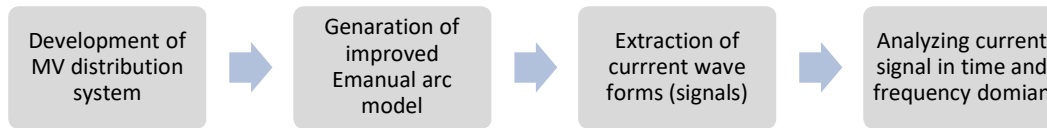


Figure 1: Process flow chart for analyzing HIF behavioral dynamics

Adopting medium voltage distribution system

Power distribution system from Nseobong I. Okpura was adopted and modified from transmission system to a distribution system that consist of three phase source star-delta

connected (three phase and neutral), three phase measurement with two section of parameters line of three phase RLC load has been used for this research.

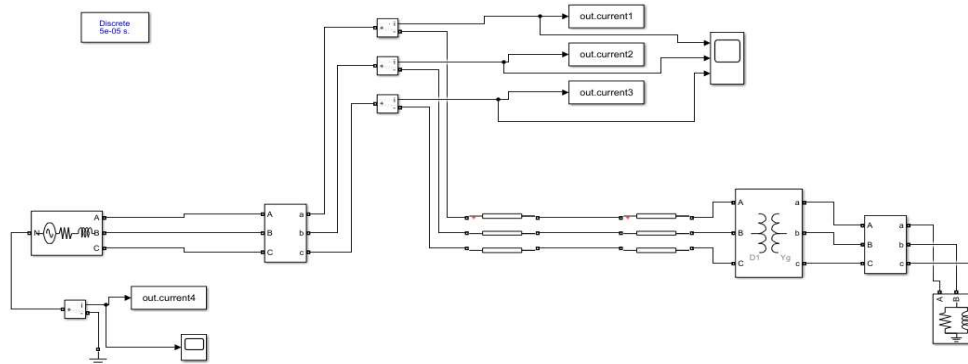


Figure 2: structural diagram of power Distribution system Simulink model

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Figure above shows a distribution system Simulink model the main components of the distribution system Simulink include three phase source star- delta connected with a neutral, measurement devices, line parameters and a load.

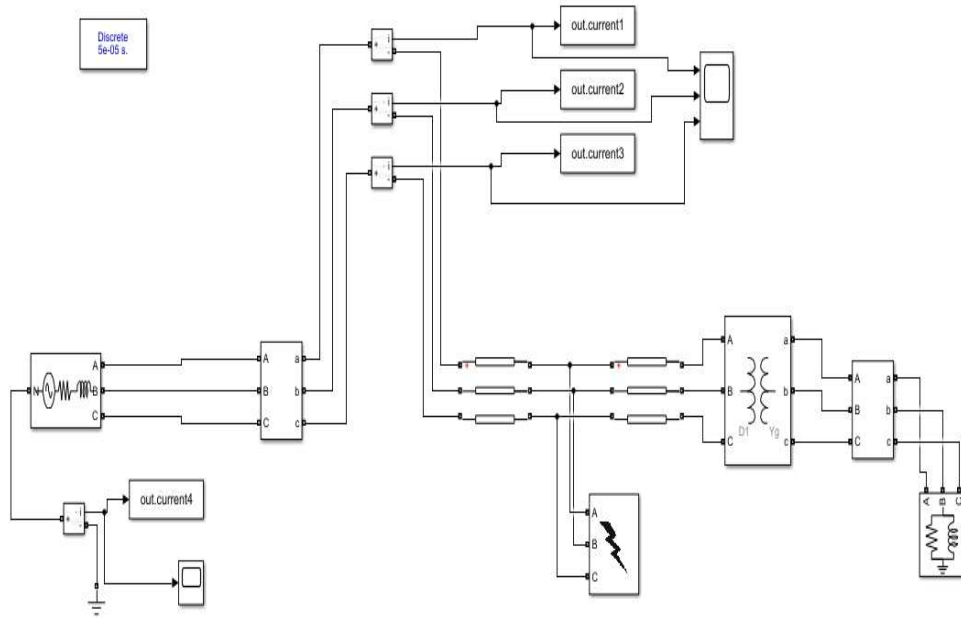


Figure 3: The figure shows modified medium voltage distribution system applied with three phase fault conditions and high impedance fault

Development of Emanuel arc model

Network with high resistive grounding can be presented as shown in figure below

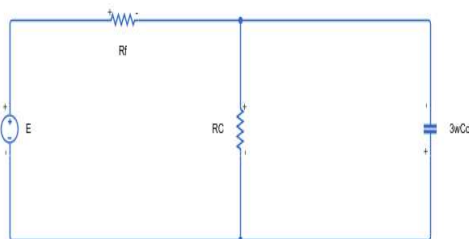


Figure 4. Network with high resistive grounding

$$I_{ef} = \frac{E}{R_e + R_f} \quad (1)$$

Above is the expression of earth fault current and the neutral voltage can be represented as

$$V_o = \frac{I_{ef}}{\sqrt{\left(\frac{1}{R_e}\right)^2 + (3\omega C_o)^2}} \quad (2)$$

Highest neutral voltage in high resistance earthed network is equal to the phase to ground voltage when the fault resistance is zero. The corresponding two phases to ground voltage of the un-faulty phase is equal to the line voltage.

Emmanuel arc model is based on theoretical components and laboratory measurements in which the arc in high impedance fault is modeled using two DC sources connected as anti-parallel by two diodes.

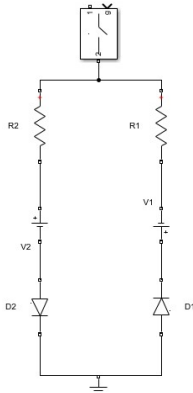


Figure 5: Emanuel arc model

This HIF arc model includes two batteries sources, V1 and V2 respectively which represent the arcing voltage of air, trees and soil and earth resistance. When the line voltage is greater than the positive voltage V1 the fault current starts flowing towards the ground then the current starts flowing backward, when the line voltage bees less than negative voltage V2 in this state the line voltage is in between V1 and V2 which makes the voltage to be counter balanced so that no fault current flows

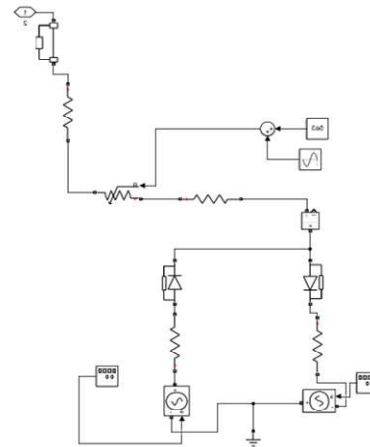


Figure 6: improved Emanuel arc model arc model

The Veerasamy model was improved Eamnuel arc model adopted for this research because of it features that gives a non-linear characteristic and the diodes. This developed model has improvement in dynamics of arc current features which replicates the non-linearity of ground resistance. Fault signal under different conditions has been extracted from the developed distribution power system model generated.

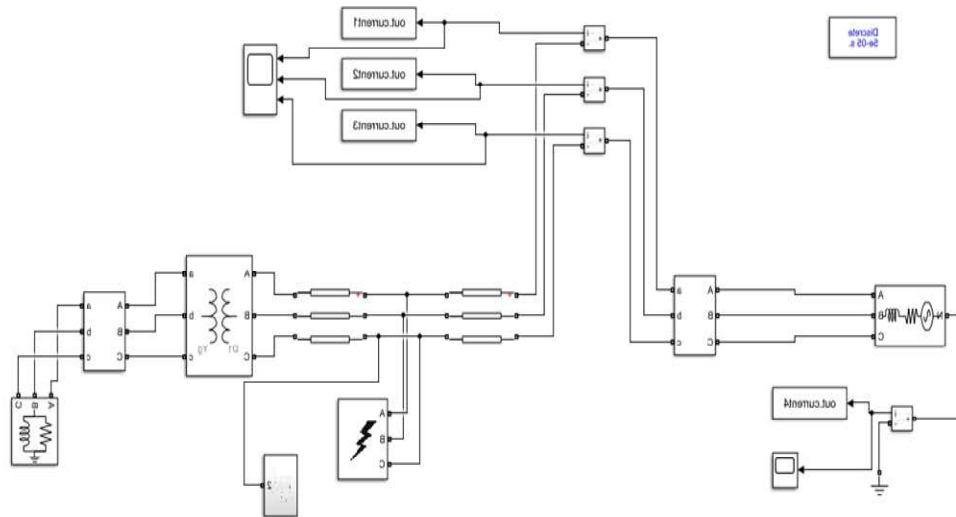


Figure 6: Medium voltage distribution system with three phase fault condition and high impedance fault model as a subsystem.

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Extraction and analysis of high impedance fault signal

After implementing both the distribution system and high impedance fault on matlab Simulink the current signal for normal working condition and all fault condition has been extracted it has been sent to work space for the spectral analysis under time and frequency domain. After extraction of the current signal, plots have been developed using time series plot by defining sampling frequency (fs) and time, this time series plot was also used to plot the spectrogram.

RESULTS AND DISCUSSION

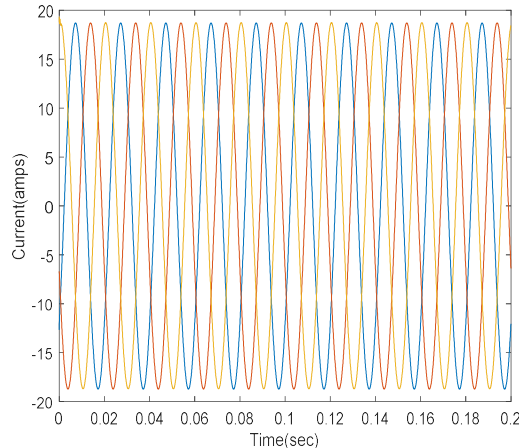


Figure 7: Current waveform against time for normal condition.

Figure 7 shows the result obtained after simulating normal working condition, the sinusoidal and symmetrical nature of the waveform indicates that the three-phase system is balanced. the sum of the currents in the three phases at any instant is zero, leading to minimal current in the neutral wire as seen in figure 8 below. The small magnitude of the neutral current (in the order of 10^{-11} A) further supports this balance and the waveform does not show significant distortion, implying that there are minimal harmonic components in the neutral current. Harmonic distortions would typically result in a more complex waveform shape.

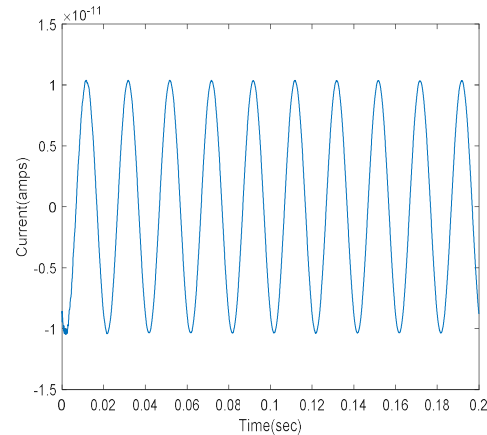


Figure 8: Neutral current wave form under normal condition.

Figure 9 below illustrate the current waveforms of a three-phase system under a single-phase to ground fault condition. The plot shows three sinusoidal waveforms, representing the currents in each phase (Phase A, Phase B, and Phase C) of a three-phase system. The x-axis represents time in seconds (Time(sec)). The y-axis represents the current in amperes (Current(amps)). When a single-phase to ground fault occurs, the current in the affected phase will experience a significant disturbance. This is typically seen as a sudden increase in current amplitude.

The orange waveform shows a significant increase in amplitude around the 0.01 to 0.06-second mark, indicating the phase where the fault has occurred. The other two waveforms (blue and red lines) show smaller disturbances, which are the result of the fault affecting the overall system but not to the same extent as the faulted phase. After the fault (post 0.1 seconds), the waveforms seem to return to a more regular sinusoidal pattern but still show some residual disturbances, which is characteristic of the system stabilizing post-fault. The fault occurs at approximately 0.01 seconds and lasts until about 0.06 seconds, during which the affected phase current amplitude significantly increases. Likewise, in figure 10 the neutral current wave form shows significant increase in current and high level of distortion

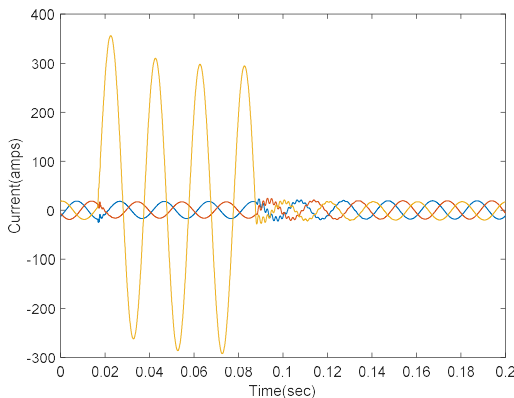


Figure 9: Single wave form of Line to ground (LG) fault condition.

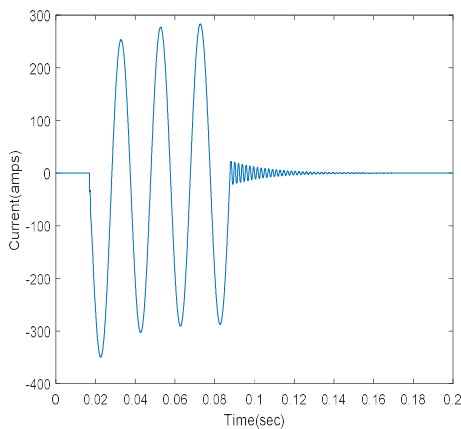


Figure 10: Waveform of Neutral current for single line to ground fault

Figure 11 represents the current waveforms of a three-phase supply over a period of 0.2 seconds, where the current is measured in amperes and time in seconds. Each phase exhibits a sinusoidal waveform, which is typical for AC currents there is a noticeable variation in amplitude among the three phases, suggesting an imbalance. The waveform corresponding to the yellow phase has a significantly higher amplitude initially and then drops dramatically. The other two phases (blue and red) maintain a more consistent amplitude but with noticeable oscillations. The dramatic change in amplitude for the yellow phase indicates the presence of a high impedance fault. High impedance faults typically result in irregular

current flow, often causing significant deviations in the amplitude of the affected phase. The frequency of the waveforms remains constant, indicating the supply frequency has not been affected by the fault. The stability of the waveforms in the non-faulted phases suggests the system is still operational, albeit with a fault present.

Figure 12 presents the neutral current waveform of a three-phase supply system over a period of 0.2 seconds, with the current measured in amperes and time in seconds. This waveform illustrates the behavior of the neutral current under a high impedance fault condition. At the beginning (0 to ~0.02 seconds), the waveform shows a significant initial surge in current, reaching values as high as 30 amperes and dropping to -40 amperes. This large oscillation is characteristic of the transient response immediately following the fault inception. From ~0.02 to 0.08 seconds, the waveform exhibits damped oscillations. The amplitude of these oscillations decreases over time, indicating the transient effects are diminishing. After approximately 0.08 seconds, the waveform transitions into a more stable sinusoidal pattern with an amplitude of around ± 20 amperes. This indicates that the system has settled into a steady-state condition post-fault, albeit with continued oscillations reflective of the high impedance fault.

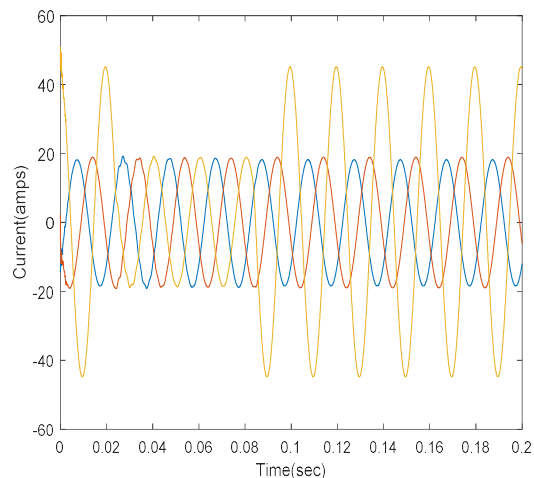


Figure 11: Waveform of High impedance fault condition wave form

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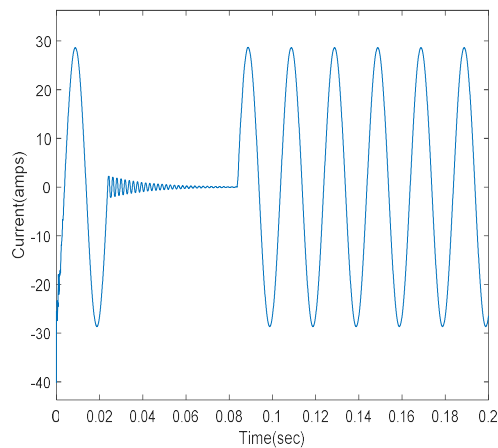


Figure 12: Neutral current wave form for high impedance condition.

CONCLUSION

The simulation results presented in this study demonstrate the distinct behaviors of a three-phase electrical system under normal operating conditions, single-phase to ground fault, and high impedance fault scenarios. Under normal conditions, the sinusoidal and symmetrical nature of the current waveforms across the three phases confirms a balanced system, with negligible neutral current, as evidenced by the minimal harmonic distortions (Figure 7 and Figure 8). The small neutral current magnitude, in the order of 10^{-11} A, further supports the absence of any significant imbalances or distortions in the system. However, when a single-phase to ground fault occurs, as depicted in Figure 9 and Figure 10, a noticeable disturbance is observed, particularly in the faulted phase. The significant increase in current amplitude and the corresponding distortion in the neutral current waveform indicate the severity of the fault. The behavior of the system post-fault shows residual disturbances, indicating that while the system begins to stabilize, the effects of the fault persist.

In the case of a high impedance fault, illustrated in Figure 11 and Figure 12, the current waveforms show a more complex behavior, characterized by irregularities in the amplitude of the affected phase. The yellow phase exhibits significant deviations in current amplitude, typical

of high impedance faults, while the other phases remain relatively stable. The neutral current waveform under the high impedance fault condition shows a pronounced transient response immediately following the fault, with oscillations gradually diminishing as the system stabilizes over time.

These results highlight the challenges of detecting high impedance faults due to their subtle but potentially hazardous nature. The simulations confirm that while the system can maintain operational stability post-fault, significant distortions and imbalances in the current, particularly in the neutral wire, persist. This underscores the need for advanced detection and protection mechanisms to address the limitations of conventional methods in identifying and mitigating the effects of high impedance faults.

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