High Impedance Fault Arc Analysis on 11 kV Distribution Networks

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ABSTRACT: This paper presents a study of high impedance fault (HIF) arc analysis on 6 km 11 kV distribution network from New Haven to New NNPC, Enugu State. These HIF currents have low fault current ratings and are not readily detected by the distribution sub-station relays and protective equipment. This was realized with the aid of MATLAB. Firstly, the HIF was modelled based on the electric arc theory method for single line-to-ground and double line-to-ground faults, when the 11 kV New-haven to New NNPC Enugu distribution line interfaces with a dry asphalt ground surface. The HIF was incident on the midpoint of the distribution line between the switching times of the circuit breaker from 0.02 to 0.05 seconds. The results showed that for single line-to-ground and double line-to-ground faults, a peak current magnitude of 12.4 A and 2280 A were seen respectively and initial spikes due to arcing in the system voltages at the initial switching times of 0.02 seconds. The corresponding residual currents I_b and I_c are very small with a peak spike of 0.3 A and 1.9 A for double line-to-ground fault (BC-G). These spikes are because of the impact of the initial transients caused by the arc flames as its quenches and re-ignites.

KEYWORDS: High Impedance faults, Electric arc, Transients, Single-line-to-ground fault, Double-line-to-ground fault.

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I. INTRODUCTION

High impedance fault (HIF) is the type of fault that arises from the conductor touching a poorly conducting or high impedance surface. These faults occur when a live conductor makes contact with an object or ground surface that reduces the levels of current below the detection level of typical protection devices. These types of faults (HIF) frequently take place when a live overhead line experiences a break or a cut and drop to the ground surface or an object, causing a grave public hazard. Protecting distribution systems from HIF is very tedious since the fault current is usually very small to be detected by over-current relays. (Jena and Pradhan, 2012; Kavaskar and Mohanty, 2019).

High impedance fault (HIF) detection remains a serious opposition for electrical engineers up to date due to the nonsymmetric, random and nonlinear nature of the fault current and more methods of detection have certainly been developed and employed over time though it has been generally acknowledged by researchers that no method will be able to detect all HIF (Iurinic *et al*., 2016; Sarwar *et al*., 2020). HIFs are classified into two major types: the active and passive HIFs. The active HIFs are usually pursued by arc and drawn currents much less than the protection units set while the passive HIFs do not make an electric arc. They are very risky to human and animal life considering the fact that there is no statement of the energization case of the conductor (Sulaiman *et al*., 2013).

Recent growth in digital technologies on fault detection has shown some modes of detecting most HIF even though it is not possible to detect all the faults due to the periodic nature and randomness of these low faults current. Several mechanical devices have been developed in the past decades to handle a broken transmission or distribution line; however, they are costly and fail reliability test. One of such tests is circuit breaking mechanism which can be achieved by lowering the instantaneous trip settings of the circuit breaker to a level not higher than what is needed to avoid nuisance tripping under healthy conditions (Gonen, 2014; Gonen, 2016).

Another example is power line communication (PLC) device which continually monitors the feeder impedance and detects the fault when an abrupt change in the high frequency impedance is asserted. This falls short of reliability test due to the fact that it requires knowledge of the impedance and resonant frequencies of the system for the best narrow frequency range selection (Gomes and Ozansoy, 2020). The method of high impedance fault detection is generally categorized into mechanical and electrical detection techniques. The mechanical method of detection involves forcing the line to touch down with a solid ground to permit the operation of overcurrent protection (Vico *et al*., 2010) while the electrical method involves the use of classical or heuristical approaches. The classical approach is made up of wavelet transform, high-frequency spectrum, and low order harmonics while the heuristical method comprises expert system, neural network, neur-fuzzy network, fuzzy logic, and generic algorithm (Sedighizadeh *et al*., 2010).

HIFs are influenced by several factors which include the

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material of the ground surface, level of voltage, surface dampness, type of feeder layout, type of load and weather conditions. Among these, the two main dominant factors considered on the HIF attribute are dampness and material surface conditions. It has been shown that higher humidity or damp surface gives rise to higher fault current breadth. Hence, HIF occurs on several materials with different results on current-voltage properties. The materials that mostly come in contact with down-conductors are tree branches, asphalt, stout gravel, thin gravel, crushed stone, lawns, gravel, concrete, sand, board blocks, and cement (Ghaderi *et al*., 2017). The inability of HIF detection technique to detect the fault occurrence can lead to endangerment to public safety due to the likelihood of electrocution from live conductors producing deleterious step or touch voltages, and initiation of fire (Milioudis *et al*., 2011) as can be seen in Figures 1 and 2.

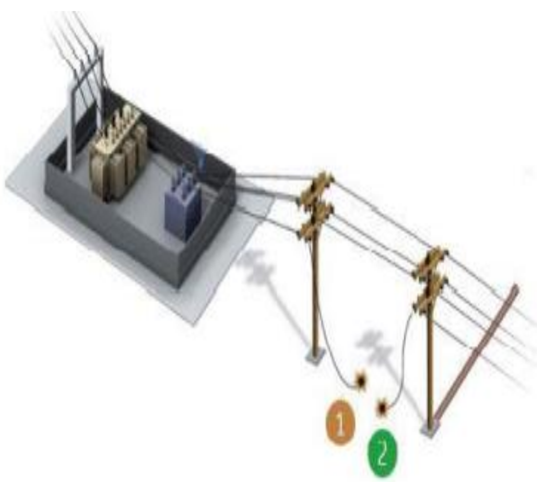

Figure 1: Source-end and load-end downed conductors on asphalt surface (Theron *et al*., 2018)

Figure 2: Energized downed conductors on asphalt surface (Wu, 2015).

Several researchers have worked on high impedance fault analysis and identification on transmission and distribution lines. Obtaining alienation coefficients by collocating half period of the signals of unrestrained voltage by the use of moving window technique were used in the classification and perception of high impedance faults in a transmission line (Shah *et al*., 2018). They instituted that alienation coefficient is a fitting variable for discerning the HIFs from other possible transmission line faults. Congruous analysis of voltage and current contours at converter terminals was used to determine and locate HIFs in the direct current (DC) link (Hoseinzadeh *et al*., 2018). Analysis of single-phase HIF protection for low-resistance grounded distribution system was presented by (Tang *et al*., 2018). In their analysis, compound power of every one of the feeders which is made up of the complex and conjugate power was explained, and a HIF protection technique based on the compound power of each of the feeder was presented which showed that the technique employed is not obliged to check the polarities of the zero-sequence current transformers and is capable of isolating faulty feeder assuredly.

A new deep learning method using 2-D function maps extracted from wavelet packet entropy was used in detecting HIFs on overhead transmission lines which showed that the wavelet packet entropy-based 2-D function map is well fitted for ascertaining HIFs (Sirojan *et al*., 2018). A novel HIF detection method using a convolutional neural network (CNN) in distribution network systems was analyzed by (Fan and Yin, 2019). A neural network approach and discrete wavelet transform method were used to detect high impedance transmission line fault with the aid of Matlab/Simulink (Ogboh *et al*., 2019). Their results showed that the wavelet transform method is more accurate in detecting the various faults of a transmission line than any other signal analysis techniques.

Detecting high impedance faults is one of the most important challenges for the protection of DC micro-grids network (Taheri *et al*., 2019). They proposed a new routine for determining high impedance fault in DC network using Group Method of Data Handling (GMDH) neural network which has the ability to detect fault impedance value up to 700 ohms. A wavelet-based routine for solving the issues of determining low and high impedance fault and categorization in transmission lines was presented by (Paul and Debnath, 2020) with the aim of developing an adaptive fault determination and categorization scheme for distinguishing between the two types of fault. This was made possible with the aid of discrete wavelet transform (DWT) algorithm. An online monitoring system embedded with machine learning analytics was proposed by (Wang and Dehghanian, 2020). This is known as a pseudo continuous quadrature wavelet transform (PCQ-WT) in addition to a modified Gabor wavelet and a compact CNN-based event determination method.

This was done in order to avoid the damaging results of HIFs by ensuring an accurate, timely and quick detection of HIFs in power transmission network. Electromagnetic time reversal (EMTR) procedure for high impedance fault location was presented by (An *et al*., 2020); whereby double-ended signals were simultaneously injected in the network and EMTR technique was used to achieve an accurate location for high-impedance fault. A susceptibility analysis of high impedance fault done by Velmurugan and Chattopadhayay, (2020) was considered indispensable because small fault current signals cannot be rightly exploited from high transformation ratio current transformers due to the domineering load currents in real power systems. Their results established that when the discernment of HIF in the field is difficult, then neutral impedance emerges as a vital framework for calibrating the system. High impedance fault in transmission line was examined by Bhakat *et al*., (2021) with a modified S-transform method. They used the IEEE 34-bus test distribution network for simulation in EMTP-RV software and S-transform analysis in Matlab software.

It is seen from the reviewed literature that analysis and observation of high impedance fault on 11 kV distribution line with focus on single line-to-ground fault and double line-to-ground fault were not captured in their analysis. As a result, this research analysis focused on the determination of high impedance fault with the cases of single line-to-ground and double line-to-ground fault. This is done in order to ascertain the peak magnitude of fault current, system voltage and arc behaviour of the high impedance fault.

II. METHODOLOGY

The detailed schematic network for the analysis of high impedance fault on 11 kV distribution line between New Haven and New NNPC, Enugu State is shown in Figure 3, while Figure 4 shows the Matlab/Simulink model used in the HIF analysis. A realistic approach and illustration for the fault is dominant in developing of a suitable methodology to ascertain and localize HIFs on 11 kV distribution lines. High impedance fault models are illustrated based on the equations of electric arc as stated by (Torres *et al*., 2013; Maximov *et al*., 2014) which are depicted in Eqns. 1 to 10:

$$\frac{d\, In\, g}{dt} = \frac{1}{\tau(v,i)}\left(\frac{vi}{P(v,i)} - 1\right) \qquad (1)$$

where g = i/v is arc conductance

v is arc voltage

i is arc current

$\tau(v,i)$ is the time constant

P(*v*, *i*) is the cooling power.

P is the power due to heat dissipation

The heat dissipation power is given in Eq. (2).

$$P = P_0 + V_0|i| \qquad (2)$$

As a result, the arc conductance equation gives:

$$\frac{dg}{dt} = \frac{G(i) - g}{\tau} \qquad (3)$$

The steady state conductance as a basis of the arc current is given as;

$$G(i) = \frac{i^2}{P_0 + V_0|i|} \qquad (4)$$

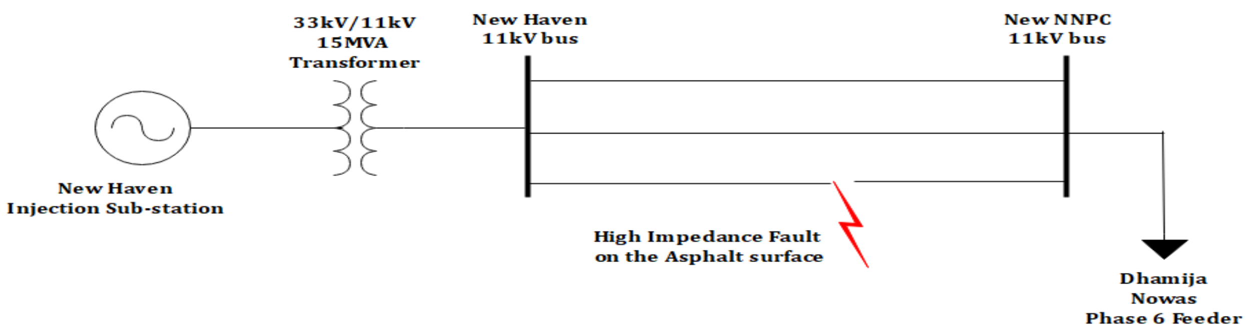

Figure 3: Detailed schematic network for the analysis.

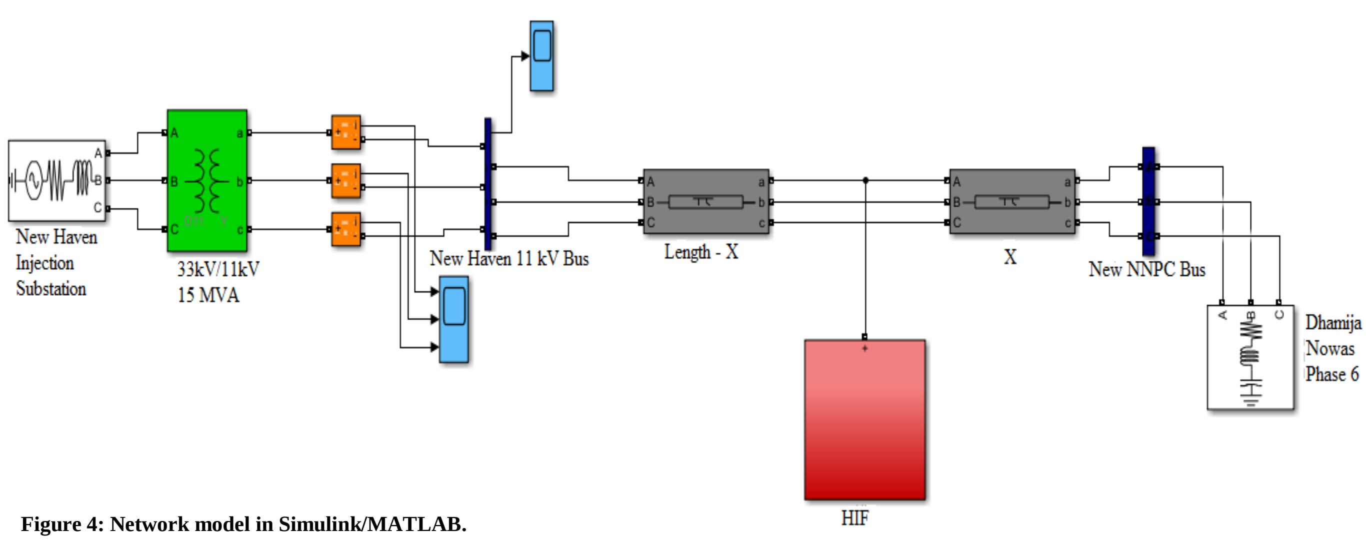

Figure 4: Network model in Simulink/MATLAB.

where $g = i/v$ is arc conductance

v = arc voltage

i = arc current

$\tau(v, i)$ is the time constant

$P(v, i)$ is the cooling power.

P is the power due to heat dissipation

Given that the electric arc current in the steady state expression of the conductance is in form sinusoid with angular frequency $\omega = 2\pi/T$, then the equilibrium state conductance expression is a recurrent basis with angular frequency 2ω, which can be broaden in Fourier series with the even harmonics stated in (Maximov *et al.*, 2014) as:

$$\mathrm{G(t)} = \sum_{\mathrm{n}=-\infty}^{\infty} \mathrm{G_n e^{j2nwt}} \tag{5}$$

Assuming the period of (3) $\tau \gg (T/2)$, then the equilibrium conductance expression is the emplacement of the constant part G_0 and the speedily oscillating part (t) which is given as:

$$\mathrm{G(t)} = \mathrm{G_0} + \delta\mathrm{G(t)} \tag{6}$$

where the speedily oscillating part can be filtered by the operation:

$$\bar{G}(t) = \frac{1}{T}\int_0^T G(t)dt = G_0 \tag{7}$$

Substituting Eqn. (6) in (3), the arc conductance (t) can be constituted as a sum of the “slow” part $\bar{\mathrm{g}}(\mathrm{t})$, which does not vary appreciably in the course of one period T and the swiftly oscillating component $\delta g(t)$ is given as follows:

$$g(t) = \bar{g}(t) + \delta g(t) \tag{8}$$

The equation for the slow part of the arc conductance is given as follows:

$$\frac{d\bar{g}}{dt} = \frac{G(i) - \bar{g}}{\tau} \tag{9}$$

While the solution of the equation in time domain is given as follows:

$$\bar{g} = G_0\left(1 - e^{-\frac{t}{\tau}}\right) \tag{10}$$

where *G(i)* is the steady state conductance

G(t) is equilibrium conductance

g(t) is arc conductance

III. RESULTS AND DISCUSSION

A. *Case I: Single line to ground fault (phase A-G).*

In this case, the results when a HIF is incident on a single phase (A) to ground of the 11kV distribution line from New Haven to New NNPC is shown in Figure 5, the HIF was applied at the midpoint of the 6 km 11 kV distribution line and a fault current with a peak magnitude of 12.4 amps between the switching times of 0.02 to 0.05 secs. The waveform represents a similar characteristic of the electric arc phenomena. The HIF current waveform in Figure 5 presents invisible zero-crossing rest after ignition and extinction. Little fault current is generated and reignition by arc occurs. Figure 6 shows the system voltage when HIF is incident on the midpoint of the New Haven to New NNPC distribution line. The system voltage waveform shows spikes in its waveform after the fault is introduced at t = 0.02 secs, these spikes occur initially on phases A and C at 0.02 secs when the system voltage waveform is sinusoidally above zero when arc reignition instants occur as shown in Figure 6.

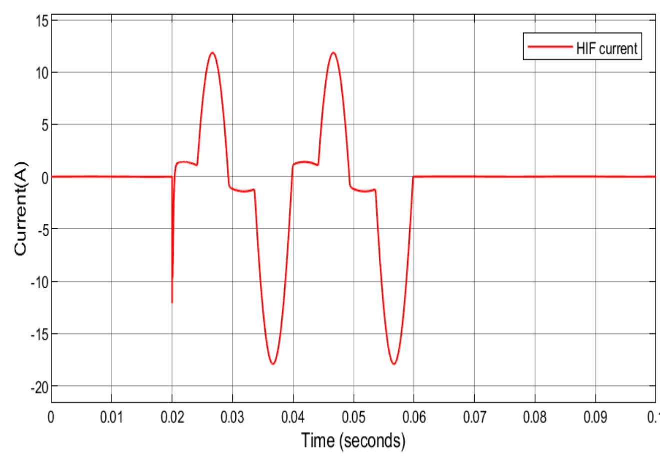

Figure 5: High impedance fault current on phase A-G.

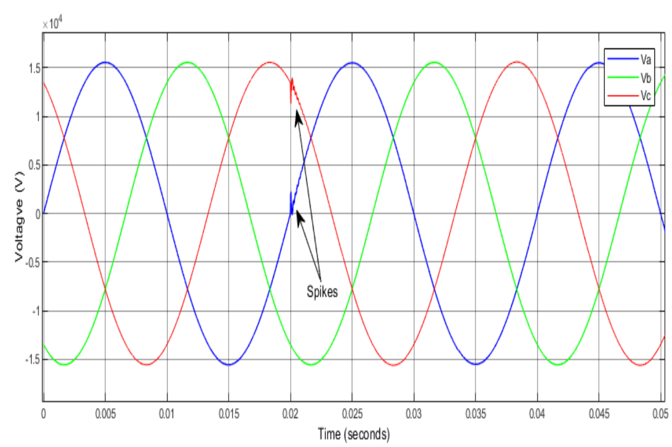

Figure 6: System voltage showing spikes.

Figure 7, shows the plot of the system phase currents, phase A HIF current is large with respect to phases B and C. Arbitrary current transients occur at 0.02 secs - at the introduction of HIF, and these current transients show the uncertainty in amplitude in the case of high impedance fault which represents arcing. Figure 8 shows an enlarged view of phases B and C currents at 0.02 secs which is the switching time of the HIF. The corresponding residual currents Ib and Ic are very small with a peak spike of 0.3 A and 1.9 A respectively before the spike reduces and normalizes. The impact of the initial transients due to the arc reignition is noticeable after each zero-crossing. As this arcing is an eruption of energy in form of light and heat when the 11 kV distribution line conductor A strikes the asphalt surface.

B. Case II: Double line to ground fault (phase BC-G)

Figure 9 displays the system voltage when HIF is incident on phases B and C of the New Haven to New NNPC distribution line. The figure shows transients in its waveform after the fault is introduced initially at t =0.02 secs, these transients occur initially on phases A and C and are present whenever arc reignition instants occur as shown. It also shows reduced phase B voltage due to fault occurrence. Figure 10, displays the substation transformer neutral current during HIF which appears like an electric arc reigniting as it quenches and re-ignites.

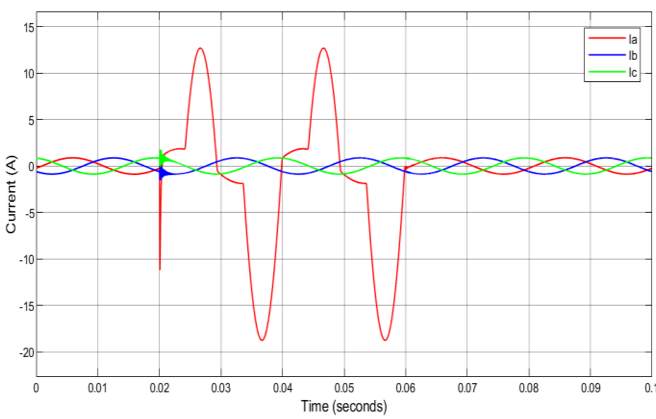

Figure 7: System phase A, B and C currents.

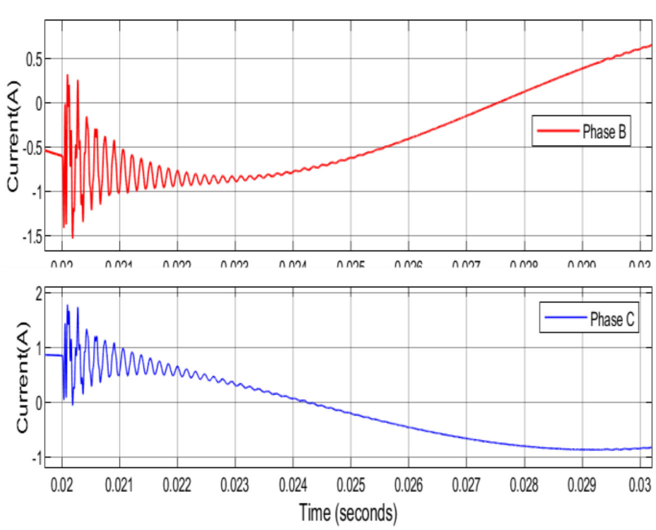

Figure 8: Enlarged view of phase B and C currents at 0.02 seconds.

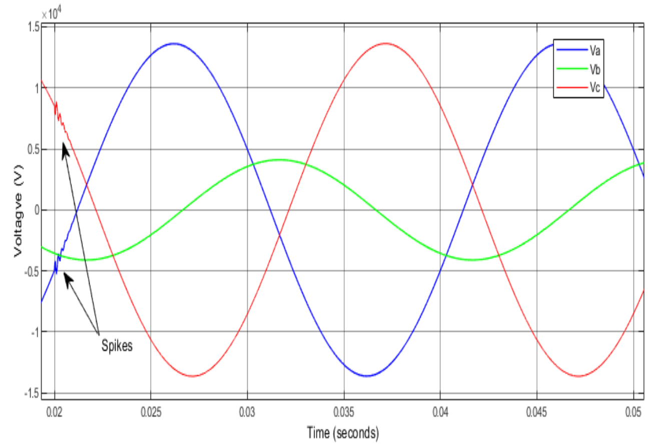

Figure 9: System voltage showing voltage spikes.

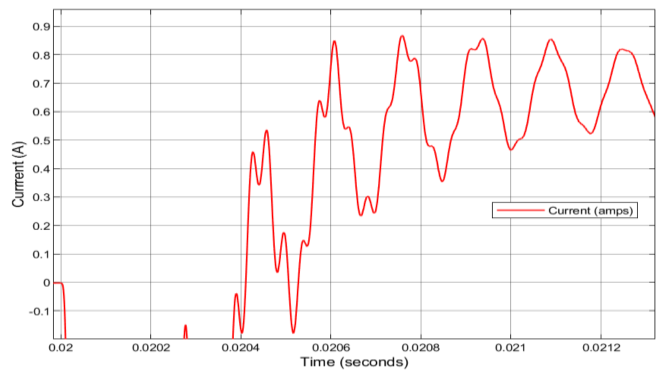

Figure 10: Transformer neutral current during HIF.

Figure 11, shows the plot of the system phase currents; phases B and C currents are large with respect to phase A reaching a peak of 2280 Amps due to the HIF. The measured current phase A wave has some harmonic distortions due to the nonlinear behavior of the arc and its current peak value is 0.81 A. Arbitrary current transients occur at 0.02 secs - at the introduction of HIF, which shows the uncertainty in amplitude in the case of high impedance fault and represents arcing.

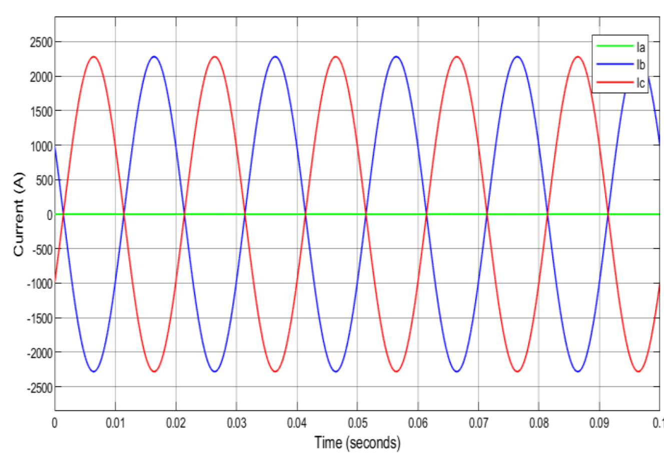

Figure 11: System phase A, B and C currents during HIF.

Figure 12 shows the enlarged view of phase A current waveform at the initial switching time of 0.02 secs. As this arcing is an eruption of energy in form of light and heat when the 11 kV distribution line conductors B and C strike the asphalt surface.

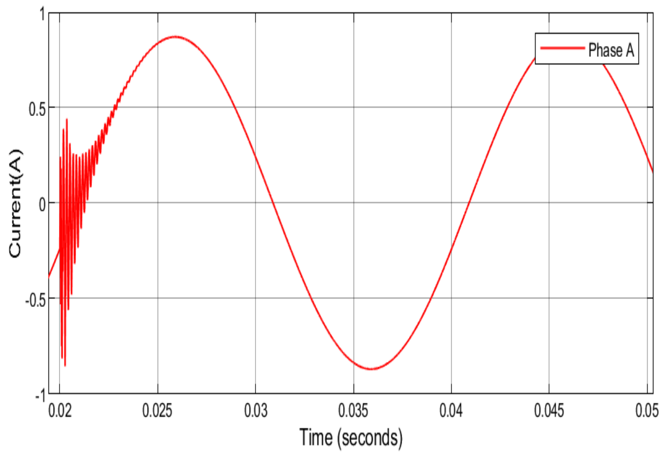

Figure 12: Enlarged view phase "A" currents.

IV. CONCLUSION

High impedance faults (HIF) are low fault currents with very high impedance due to the interface with the ground resulting in arcing. These arcs result in heat and burst of energy causing initial transients at the switching time of 0.02 secs as seen in the work. The HIF currents were consistent with the electric arc theory. The HIF currents seen were 12.4 A and 2280 A for single line to ground (A-G) and double line to ground (BC-G) respectively.

These arbitrary current transients which occurred at 0.02 secs - at introduction of HIF show the uncertainty in amplitude in case of high impedance fault which represents arcing which is seen as light and heat on the asphalt tarmac surface. Also reduced currents of 0.9 A and transients were noticed in the other phases that weren't faulted as seen in Figure 7: System phase A, B and C currents. These fault currents showed unique similarities with the electric arc theory and are small and not detected by the station's overcurrent protective devices whose minimum fault current detection limit are set at 5 KA and hence need to be detected further.

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