Improved Method for Modeling the Universal High Impedance Arcing Faults with RLC Circuit in MATLAB/Simulink®

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Abstract - *High impedance (HiZ) fault is an unwanted operating condition of Power Distribution Companies (PDCs) which rarely effect the continuity of supply but poses a potential electrocution hazards for human beings and animals and fire hazards for public assets. Detection of HiZ faults with 100 % accuracy still needs improvement in existing algorithms and methods. In this paper different HiZ arc model techniques are reviewed and a modified arcing model is proposed, modeled in MATLAB/Simulink and the results show that proposed method is reliable for modeling arcing based HiZ faults.*

Keywords: *High impedance faults, Arc model, Simulation, Public safety, PDS, PDCs.*

INTRODUCTION

A HiZ fault in primary distribution system (PDS) of 11 kV and more voltage is considered as an abnormal operating condition which posses a potential electrocution hazard for human beings, animals and fire hazard for public assets, crops and forests. Utilities rarely face an operational issue during HiZ fault, as in-service conventional protection system takes it as normal increase in loading condition, but quite oftenly faces litigation issues and have to bear compensation money for loss of public lives, properties. HiZ faults may or may not cause arcing. Arc is produced due to non-solid contact between energized conductor and touching surfaces and presence of high voltage at these contact points. Over grown trees and vegetation, building touching the PDS energized conductors, cracked insulators and excessively sagged or broken energized conductors are major events which usually become HiZ faults. Current produced during these types of faults, in almost all type of cases known to date , are mostly less than 80A and conventional over current and earth fault relays are unable to detect such low current faults. Decreasing earth fault sensitivity was an option for such type of faults but it was rejected after mal-operation of relays and alarmingly increase in PDS reliability indices (SAIFI,SAIDI etc)[1]. Detection of 100% HiZ faults with reasonable confidence is yet impossible. Researchers & protection engineers around the globe are trying their best to reach the ultimate goal. Many universities and utilities researchers have studied the features of HiZ faults and collected the data using staged faults. HiZ faults have non-linearity and asymmetry during faulty condition and buildup and shoulder after that. Korean utility (KEPCO) [2], Texas university (TAMU) and other researchers [3,4] staged fault data

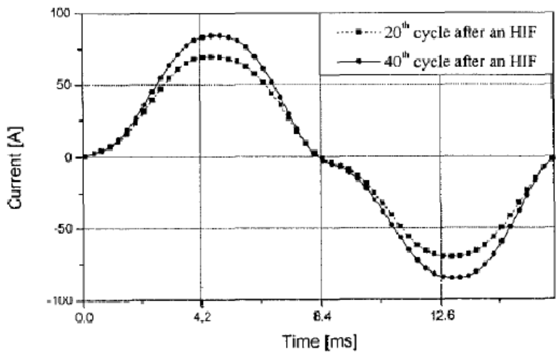

Figure 1. Currents for the 20th and 40th cycle after HiZ (asymmetry) [4]

shows these main characteristics of HiZ faults. KEPCO carried out thirty two experiments with 10 kHz sampling frequency and recorded data at fault location instead of at relaying point. Currents of 20th and 40th cycle plotted in figure 1, after occurrences of HiZ fault and both currents show these characteristics [2]. V-I characteristics of these faults is shown in

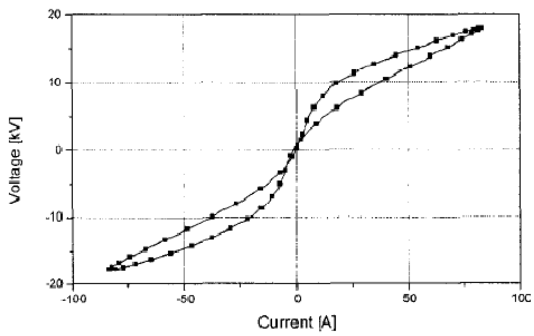

Figure 2. Voltage-current characteristic curve for one cycle in the steady state after HiZ (nonlinearity) [4]

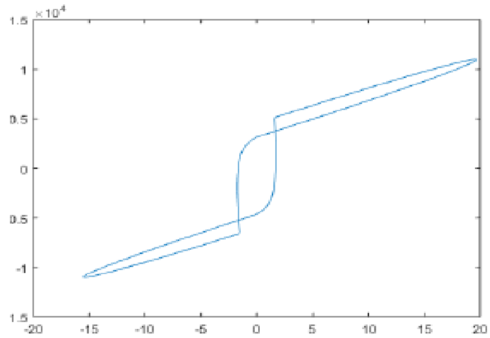

Figure 2(a) V-I Charectrestics of proposed model

Figure 2. As the staged faults study involves huge operational & financial implications therefore modeling of these HiZ arcing faults in simulation tools gaining popularity worldwide. This paper reviews the arc models ,their simulation results, waveforms and comparison with well established characteristics and then discusses the different aspects of newly proposed RLC based modified Emanuel arc model.

II. LITERATURE REVIEW

Non-bolted contact of medium voltage energized conductors of PDS with different HiZ surfaces causes arcing & glowing phenomenon as a result of electric

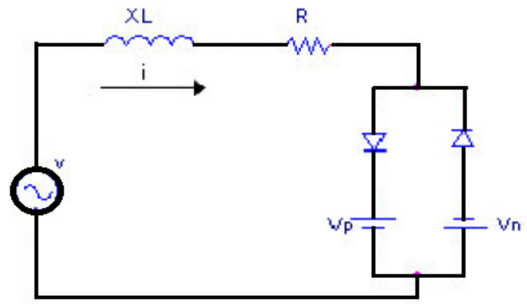

Figure 3. The Emanuel arc model

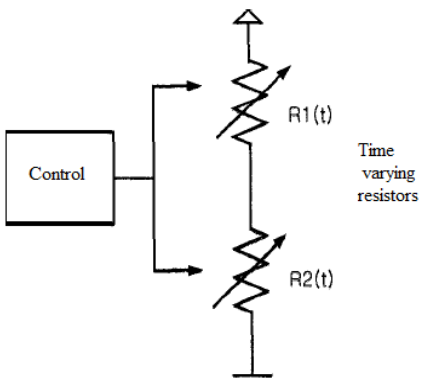

Figure 4. Modeling of HiZ as two series connected TVRs

discharge. Asymmetrical, non-linear, dynamic and random behavior of arc makes it difficult to model. Emanuel proposed a HiZ fault model & is based upon two anti-parallel diodes & DC supply sources and shown in the Figure 3 [5]. Asymmetry is modeled by different resistance values and presence of diodes ensures the non-linearity and zero crossing periods arcing in each half cycle. Some researcher's uses single variable resistor for non-linearity and some also used two variable resistors in model shown in

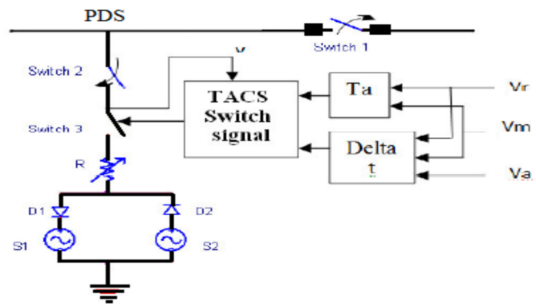

Figure 5. The HiZ model based on arc essences

Figure 4[2]. A more refined type model based on arc theory was proposed in 1998 which have impedances, voltage sources and TACS based control. Saw tooth waveform was used instead of sinusoidal and is shown in Figure 5[6]. A new universal type decision tree based model was proposed by Sheng which can simulate the HiZ faults caused by different surfaces [7]. Some models have good results of asymmetry and no-linearity whereas lacks in buildup and shoulder properties and only few have all the properties with some limitations.

III. MODELLING HIZ ARCING FAULTS

KEPCO staged HiZ fault currents have different characteristics in steady and transient states. In steady state non-linearity and asymmetry are visible whereas transient state shows two more feature viz. build up and shoulder as shown in Figure 6 a & b [2]. Every model which is proposed or yet to be propose must have all these features and also comparable THD, harmonic content & zero crossing distortion of

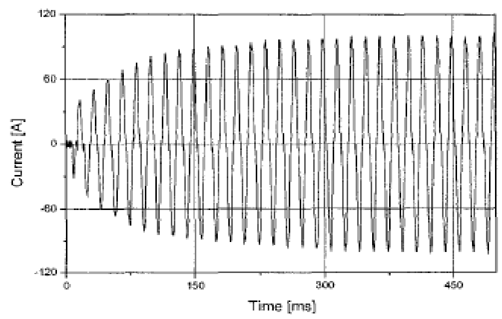

Figure 6(a). A current waveform of HiZ on crushed pebbles [6]

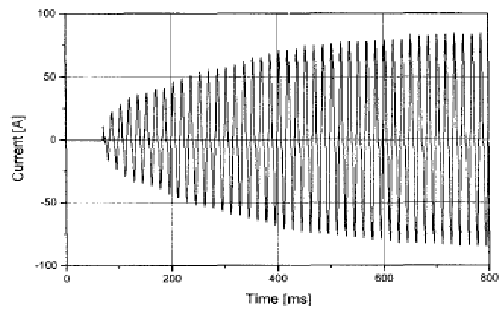

Figure 6(b). A current waveform of HiZ on robust pebbles [6] current waveform. Model proposed for now has two anti-parallel diodes, voltage sources of different

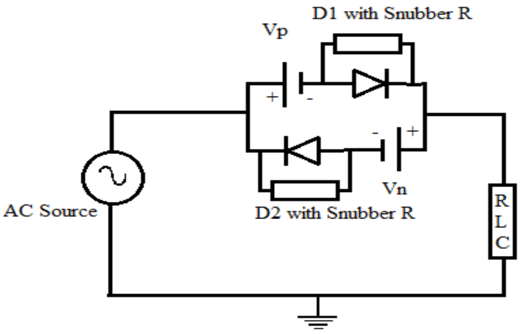

Figure 7. Proposed HiZ Arc Fault Model

magnitudes and an RLC circuit as shown in the Figure 7. Resistor in the circuit serves the purpose of resistance involved in the arcing phenomenon and resistance of contacting surface. Presence of energy storage elements (capacitors and inductors) are causing non-linaer behavior of V-I characteristics of HiZ arcing faults,
behaves as a filter for harmonic content of arcing current as it has a fixed band width involved and

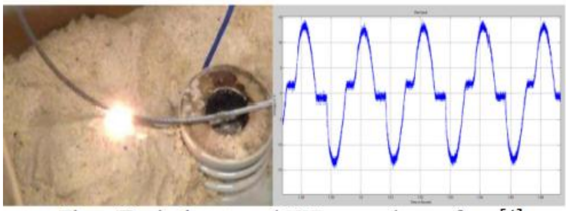

Fig **8**. Typical wet sand HIF arc and waveform[4]

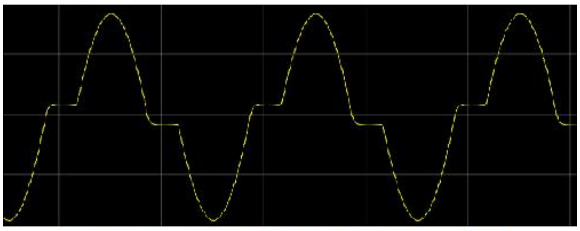

Figure 8(a) Propsed Model current Similar to wet sand

Fig. 9 Typical soil HIF arc and waveform

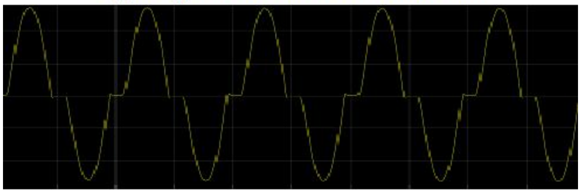

Figure 9(a) Proposed Model current waveform

have RC, RL behavior at all other frequencies and behaves only as R at critical frequency. DC sources in the circuit are equivalent to high voltages across the HiZ surfaces during the fault duration. HiZ fault current flows to the ground when PDS AC voltage

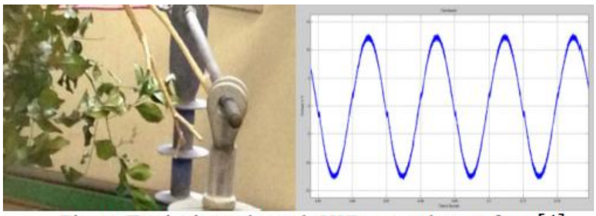

Fig. 10 Typical tree branch HIF arc and waveform[4]

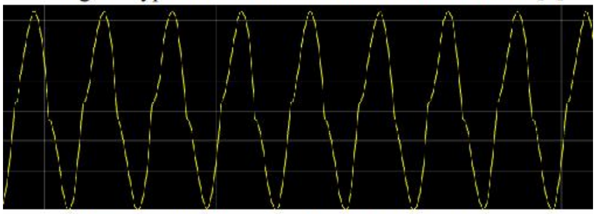

Figure 10(a) Proposed model Current

becomes greater than DC source voltages in each half cycle. Current waveform of arcing HiZ fault of proposed model is shown in Figure 8. By using suitable values of RLC circuit, all the waveforms as staged by [4] can be obtained.

V-I characteristics of all these modeled arcing waveforms are non-linear, have different shapes according to active power, inductive and capacitive reactive powers of RLC circuit.

Table-2 HiZ Faults and Model Parameters

Surface	Active Power (kW)	Q_L (kVAR)	Q_C (kVAR)	C_o (V)
Wet Sand	330	10	0.1	0
Soil	2665	360	110	50
Tree Branch	1800	2600	180	50
Tree Leaf	330	10	5	50

IV. MATHEMATICAL MODELLING

Non-homogeneous second order differential equations can be help full in developing the mathematical equation of proposed HiZ arcing fault model [10]. In positive and negative half

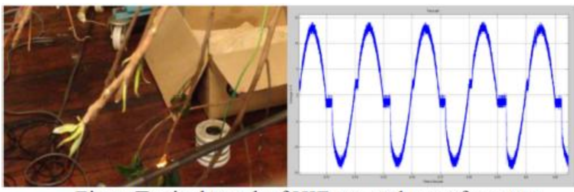

Fig.11 Typical tree leaf HIF arc and waveform [4]

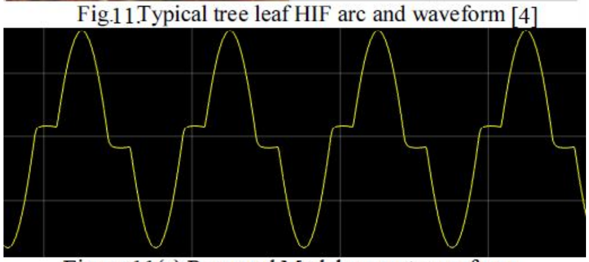

Figure 11(a) Proposed Model current waveform cycles, the circuit will be changed into an equivalent series RLC circuit (with ideal diode) with connected AC sinusoidal and DC sources.

As we know from basic physics and Kirchhoff's voltage law that

$$i(t) = dq/dt \quad (1)$$

$$V_s = V_o \sin(\theta+\varphi) \quad (2)$$

$$L(di^2/dt^2) + R(di/dt) + 1/C(i) = V_s \quad (3)$$

Its solution will be in the form of sinusoidal and terms with constant coefficients extracted from circuit parameters and their initial conditions. All the waveforms can be represented by the sum of sinusoidal functions (Fourier Series) and by using the curve fitting tool of MATLAB this can be easily determined with minimum error and maximum confidence interval. Table-2 shows the coefficients and other parameters including frequency/time period, phase angle and starting phase of all the four waveforms with their statistical data whereas equation (4) is the generalized equation for all the wave forms of proposed model given in figure 8-11 (a).

$$i(t) = a_1\sin(b_1t+c_1) + a_2\sin(b_2t+c_2) + a_3\sin(b_3t+c_3) + a_4\sin(b_4t+c_4) + a_5\sin(b_5t+c_5) + a_6\sin(b_6t+c_6) + a_7\sin(b_7t+c_7) \quad (4)$$

Surface	Wet sand	Soil	Tree Branch	Tree Leaf
a_1	14.15	113.7	143.9	14.14
b_1	314.2	314.2	314.1	314.2
c_1	0.03244	-0.095	-0.54	0.0403
a_2	3.982	31.56	19.32	3.973
b_2	942.5	942.5	942	942.5
c_2	2.881	2.781	0.767	2.906
a_3	1.175	9.242	7.029	1.167
b_3	1571	1571	1569	1571
c_3	2.696	2.629	0.1097	2.73
a_4	0.3033	56	31.83	2.639
b_4	0.8476	12.62	18.13	0.5032
c_4	4.614	-2.281	-2.804	-0.197
a_5	0.2921	1.967	3.463	0.2919
b_5	2827	628	2195	2827
c_5	-0.6994	1.356	-0.4104	-0.6355
a_6	0.2452	52.28	28.25	0.2692
b_6	3456	13.22	20.36	628
c_6	-0.9151	0.7735	0.0263	1.442
a_7	0.2086	1.863	1.912	0.2423
b_7	628.1	2827	2821	3456
c_7	1.42	-1.12	-0.847	-0.8386
Goodness of Fit				
R-square	0.9998	0.9993	0.9982	0.9997
Adjusted R-square	0.9998	0.9993	0.9982	0.9997
RMSE	0.1586	2.27	4.404	0.1847

V. HARMONIC CONTENT OF DIFFERENT WAVEFORMS

Fourier analysis of the data collected by researchers [2,4] shows that current waveform has major content of fundamental frequency, third and fifth harmonics in a considerable magnitude and THD value are 30.06% [9] which is the THD values found by the most of the researchers working on HiZ arcing faults shown in Figure 12,13 and 14.

As the FFT of current obtained from HiZ arcing fault model has harmonics upto 20th but the considerable magnitude are for upto 7th harmonic. Owning to this fact, sinusoidal equations in section IV are restricted to seven sinusoidal terms only which have shown reasonable statistical results in waveform modeling. It is evident from the FFT analysis that different HiZ surface causes different level of these harmonics but harmonics upto 7th remain remarkable as shown in Figures (12-15).

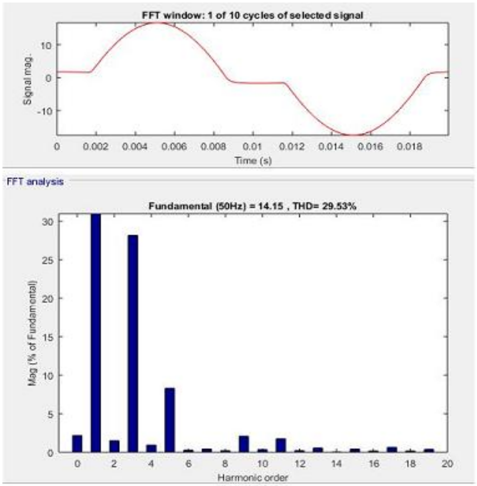

Figure-12: FFT Analysis of Wet Sand Current

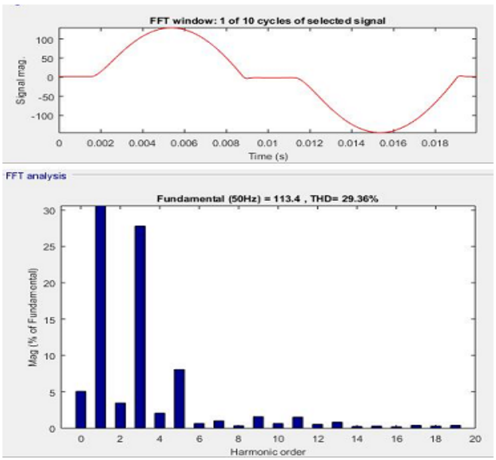

Figure-13: FFT analysis of Soil Current

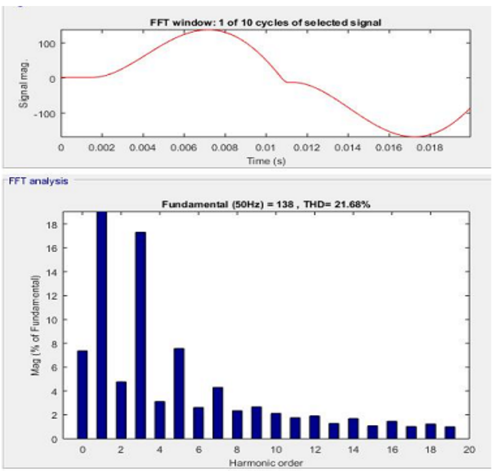

Figure-14: FFT of Tree branch current

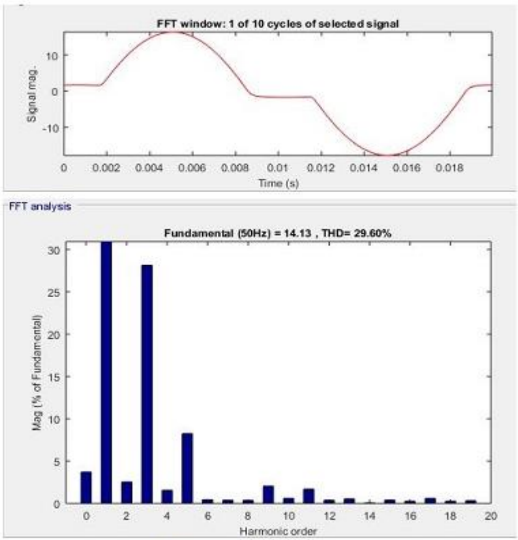

Figure-15: FFT of Tree Leaf current

VI. CONCLUSION

Modeling a HiZ arcing fault is a hot issue for researchers and utilities around the globe. Simulink® has wider user community [11] and comparable results as compared to other software packages employed for this task. In this paper different methods of modeling are reviewed and a new universal type model is proposed & the presence of non- linear V-I characteristics, Similarity between staged faults and proposed model waveforms, presence of same harmonics and similar THD level shows that proposed model can serve the purpose of universal type HiZ arcing fault model with changing simple RLC component values. Further work is in progress to obtain the relationship of these RLC parameters with HiZ surfaces

VII. ACKNOWLDGEMENTS

Author would like to acknowledge the support of the management of Gujranwala Electric Power Company (GEPCO) of Pakistan for providing me the study material, fault recorder data of modern digital feeder management relays and also the contribution of Mehran University of Engineering and Technology Jamshoro for providing labratory and library facility.

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