

A New Model for High Impedance Fault in Electrical Distribution Systems

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Abstract— A new High Impedance Fault (HIF) model in electrical distribution systems is presented in this paper. Developed model parameters is calculated based on Emanuel arc model, HIF characteristics and experimental data. Signal processing methods are used for extracting, selecting and comparing of features. Fast Fourier Transform (FFT) is used for features extracting and Principal Component Analysis (PCA) is used for data reduction. Also Bonferroni method is applied for comparing simulated model with real current features. Proposed HIF model contains 5 arc models based on Emanuel arc model. Presented model is simulated with ATP/EMTP and probability switch is used for simulating of random state of HIF feature. 5 different models are developed for several amplitude of HIF current. Results show all presented models have high accuracy for simulation of HIF current.

Keywords-Bonferroni Method; Electrical Distribution System; High Impedance Fault; Principal Component Analysis;

I. INTRODUCTION

HIFs occur when a conductor such as a distribution line make contact with poor condition a surface or substance and a current lower than nominal current follows from the line at the fault location. Therefore, conventional relay can't be detected the HIFs and it may be leads to potential hazards to human and fire hazards [1].

HIFs on electrical power distribution systems involve arcing and nonlinear characteristics of fault impedance which cause a stochastic nonlinear current. HIFs have characteristics in transient and steady state sections that make them identifiable.

Many researchers proposed various detection methods. A detection technique is reliable and secure when it is capable of perfectly identifying and distinguishing the HIFs from other transients in networks. Several researchers have presented many techniques aimed at detecting HIF more effectively. Some detection methods are based on experimental data [2-6], and other methods are based on simulated HIF models [7-15]. An accurate modeling method for HIF is essential for the development of reliable detecting algorithms. The HIF model's data must be contain the complex characteristics of HIF such as nonlinearity, asymmetry and the low frequency of HIF currents. Many models are introduced with respect to some HIF features as explained in next section.

In order to obtain a good model for HIF, the experimental data was collected on a 20 kV distribution network. The total number of experiments data was 40, with sampling rate 24.670 kHz.

The proposed model is applied based on previous experiment and some new features that extracts from collected data.

Some HIF models are explained in next section, in the third section a background of proposed method of HIF models are introduced. HIF data collection is explained in the fourth section and the fifth section shows HIF model and simulation method. Results explained in the sixth section.

II. INTRODUCE OF HIF MODEL

Because of stochastic behavior and complex characteristic of HIF, researchers introduce different models for HIF. These models try to cover some its features. Most of the previous HIF models are based on Emanuel model that was introduced in 1990. Emanuel HIF model is based on laboratory measurements and theoretical components, as shown in Fig. 1 [8].

In that model, the arc in HIF is modeled using two DC sources, connected as anti-parallel by two diodes. Many researchers have been used this model and tried to complete it. A review of these models can be fined in [16].

Some researchers introduced others model, for example in 2001 and 2008, two models are proposed that employs two series time varying resistors for representing the various characteristics of HIFs [11], [17].

Similarly Elkalashy et al. introduce an arc model based on experimental laboratory tests that depends on thermal equilibrium, in the form of a first order differential equation [18]. In 2010, another HIF model was introduced [19]. The proposed HIF arc model combines between the simplicity of MODELS and the flexibility of TACS.

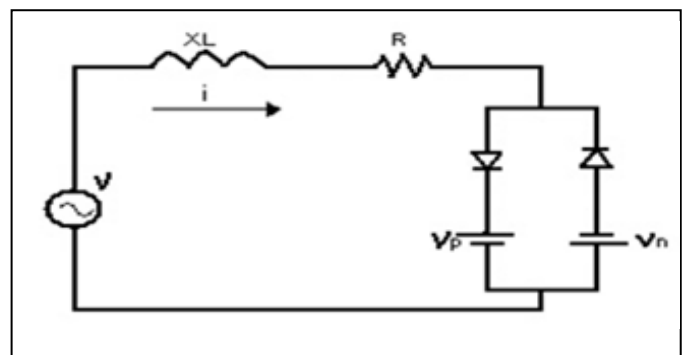


Figure 1. Emanuel arc model

III. BACKGROUND OF THE PROPOSED METHOD

In this section the Principal component analysis and Bonferroni method as mathematical methods used in proposed model are addressed.

A. Principal Component Analysis

The objective of dimension reduction is to reduce the dimension of feature vector as much as possible with minimum loss of information. Principal component analysis (PCA, also called K - L transformation) is one of the most widely used dimension-reduction techniques in most practical cases [20-21]. PCA finds the linear subspace that best represents data without using information of class labels, which is usually called unsupervised dimension reduction method. In PCA a vector is first decomposed into a linear combination of orthogonal basis functions in which the combination coefficients are uncorrelated, and then the dimension of the feature vector is reduced as described below.

Supposing the distribution of data is Gaussian, the variance-covariance matrix of the feature vectors C is:

$$C = \frac{1}{N} \sum_j X_j X_j^T - mm^T \quad (1)$$

Where N is the number of feature vectors, X is the feature vector and m is the mean of feature vectors. C is symmetrical and positive definite. Thus there exists a matrix similar to C which is diagonal, (called C^*). For this purpose a A matrix is constructed such that,

$$C^* = ACA^T = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_k) \quad (2)$$

Where λ_i is the i th eigenvalue of C , and i th row of A is the corresponding normalized eigenvector.

A is a transformation matrix that converts the original features into new space with uncorrelated features. If the distribution of data is not Gaussian, the feature in new space will be correlated.

It can be shown that the optimum properties of PCA are satisfied if the rows of transformation matrix A are chosen as the m (out of k) normalized eigenvectors corresponding to the largest eigenvalues of diagonal covariance matrix C^* . The ratio of eigenvalues to sum of eigenvalues expresses the percentage of MSE (mean square error) introduced by the elimination of the i th eigenvector.

So the dimension of feature vectors can be reduced until a desired accuracy is achieved.

$$MSE = \frac{\lambda_i}{\sum_{j=1}^N \lambda_j} \quad (3)$$

B. Bonferroni Method

The Bonferroni method is a simple method that allows many comparison statements to be made (or confidence intervals to be constructed) while still assuring an overall confidence coefficient is maintained [22].

This method applies to an ANOVA situation when the analyst has picked out a particular set of pair wise comparisons or contrasts or linear combinations in advance. This set is not infinite, as in the Scheffé case, but may exceed the set of pair wise comparisons specified in the Tukey procedure.

The Bonferroni method is valid for equal and unequal sample sizes. We restrict ourselves to only linear combinations or comparisons of treatment level means (pair wise comparisons and contrasts are special cases of linear combinations). We denote the number of statements or comparisons in the finite set by g .

Formally, the Bonferroni general inequality is presented by:

$$P\left(\bigcap_{i=1}^g A_i\right) \geq 1 - \sum_{i=1}^g P[\bar{A}_i] \quad (4)$$

where A_i and its complement \bar{A}_i are any events.

In particular, if each A_i is the event that a calculated confidence interval for a particular linear combination of treatments includes the true value of that combination, then the left-hand side of the inequality is the probability that all the confidence intervals simultaneously cover their respective true values.

The right-hand side is one minus the sum of the probabilities of each of the intervals missing their true values. Therefore, if simultaneous multiple interval estimates are desired with an overall confidence coefficient $1-\alpha$, one can construct each interval with confidence coefficient $(1-\alpha/g)$, and the Bonferroni inequality insures that the overall confidence coefficient is at least $1-\alpha$.

In summary, the Bonferroni method states that the confidence coefficient is at least $1-\alpha$ that simultaneously all the following confidence limits for the g linear combinations C_i are "correct" (or capture their respective true values):

$$\hat{C}_i \pm t_{\alpha/2g; N-r} S_{\hat{C}_i} \quad (5)$$

Where:

$$S_{\hat{C}_i} = \hat{\sigma}_e \sqrt{\sum_{i=1}^r c_i^2 / n_i} \quad (6)$$

IV. HIF DATA COLLECTION

In this research HIF current data was gathered from tests on a real network [2-4]. For HIF data collection a radial 20kV feeder in Qeshm Island, Iran, was chosen for high-impedance fault tests. Feeder length is 19.5 km and HIF locations were approximately 8.5km from the source end. The feeder was energized from another 20kV feeder through two distribution transformers (20/0.4kV, 100kVA) connected back-to-back. The high- and low-voltage connections of transformers were D and Y, respectively. The high-voltage sides are connected to feeders and the low-voltage sides are connected together through the low-voltage switch. Three phase voltages and currents were recorded using Hall-effect current transformers (CT), a resistive voltage divider (PT), power analyzer and computer. Sampling rate of recorded data was 24.670 kHz and total recorded time was 15 s for each test. A schematic of the connections is shown in Fig. 2, and the site is shown in Fig. 3.

For a HIF test a conductor was connected to one phase of the feeder and for each test it was dropped to the ground as shown in Fig. 4.

The fault studies were conducted on seven types of surfaces (wet and dry asphalt, cement and soil, and dry tree) at two locations, approximately 8209 and 8446m from the site. Three tests were conducted for each type of surface at each location for a total of 42 data sets. For the reason that two data set were not recorded correctly, 40 data sets are used in this work. Faulted phase current signal on various conditions are shown in Fig. 5.

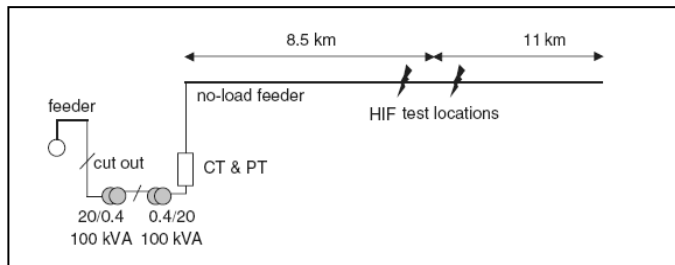


Figure 2. Schematic of instrument connection



Figure 3. The experiment site



Figure 4. Connection of a conductor to one phase

V. HIF MODEL AND SIMULATION METHOD

At the first, some characteristic of HIF are explained. These features are based on research and considerations that presented in previous papers [23].

- Nonlinearity phenomena of ground impedance affect on HIF current curve. The most noticeable is that the initial current is only about 60% of the final value, growing to final value in about three to four cycle. This reduced initial current is due to a smaller effective initial contact between the conductor and the ground. When the contact area is small, as via a small arc, the density of the current at the arc/ground interface, and hence the voltage gradients will be large. This will result in localized arcing and ionization. The arc will then penetrate the ground between the earth particles thus enlarging the effective contact with the ground. That is, when a conductor arcs to the surface of ground, the arc will not stay terminated at exactly the surface of the ground, but will cause ionization within the earth and so penetrate the ground, thus enlarging the effective area of the equivalent electrode.
- A second nonlinear effect occurs within the earth based on silicon carbide composition of earth. This nonlinearity is not identical to that of the arc. This character is not occurring in the first cycles of HIF current.
- Resistance of the earth is the third character of HIF nonlinearity current. That affect from earth kind, genus and humidity of it.
- Fault current has different waveforms for positive and negative half cycle.
- The voltage and current of HIF have the same phase, so resistance is inherent in HIF.

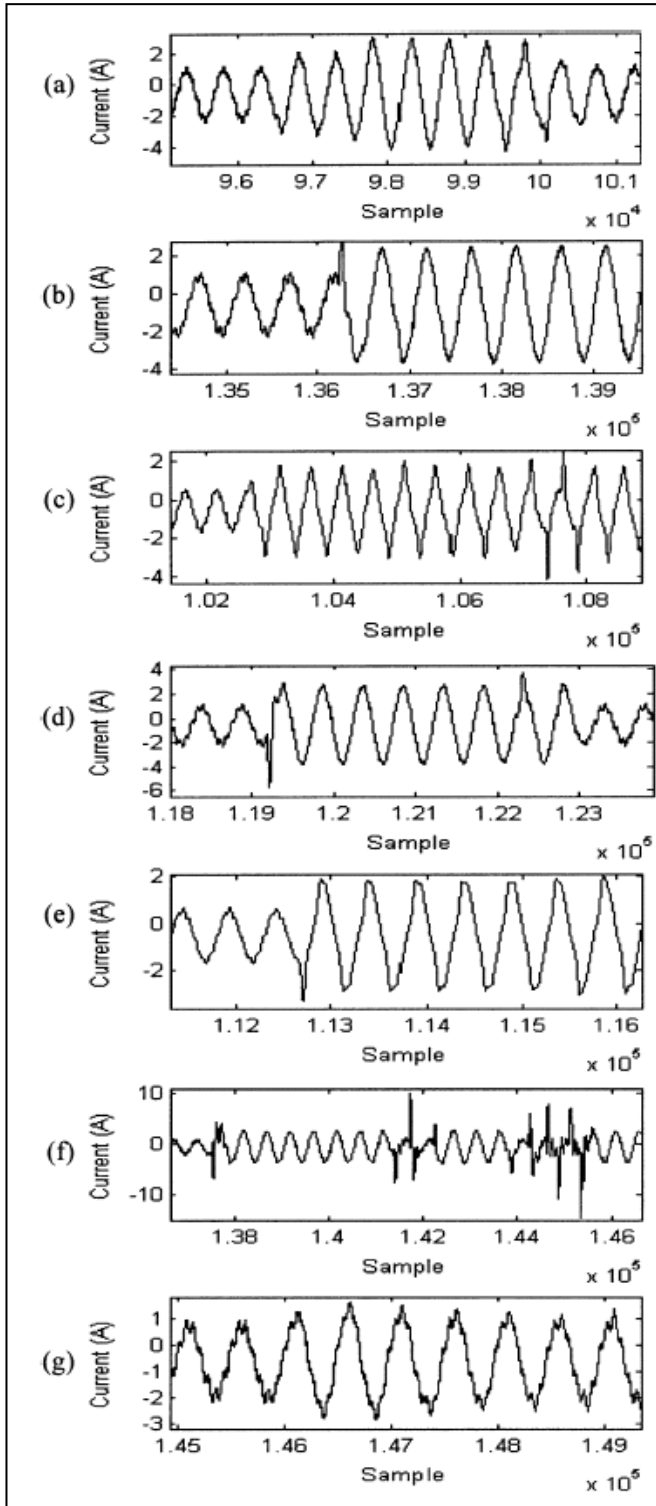


Figure 5. HIF current waveforms on different surface
 a) Dry asphalt. b) Wet asphalt. c) Dry cement. d) Wet cement. e) Dry soil
 . f) Wet soil. g) Dry wood.

In this paper the first eight cycle of HIF current is simulated and the first and third feature, which explained above, are used in presented model. Also by using 40 recorded current as explained in previous section, this model support all frequency component of recorded HIF current. In previous

research, all models are based on Emanuel arc model and researchers changes parameters of that model and received to HIF model. With notice to Fig. 6(a,b), many arcs will occur when a conductor fall on the earth.

So we can use several arc model in parallel that combined of them produce HIF current. Fig. 7 shows this HIF model.

Random state of HIF is shown using statistic switch in EMTP. Arcs parameters in the introduced model determine based on recorded current and voltage data. As shown in Fig. 8 voltage and current have the same phase after fault occurred, and resistance of earth can be derive from it.

V_p and V_n , DC voltage source, can be derive from $v-i$ curve of HIF as introduced in Fig. 9, based on explanation in [8].

Using switch time regulation and other parameters the amplitude of current in one simulation can be controlled from 60% of the final value until to final value after 50~60 *ms*.

The simulated current and recorded current compare as explained in the following:

- The first eight cycle of recorded current with sampling rate 224.67 kHz are used.
- Using FFT, all frequency components (2048) are extracted.
- Based on main frequency component all amplitudes are normalized.
- Number of extracted feature at this state are 4096 (amplitude and phase).
- The features are reduced to 38 using PCA, with 98.3 energy saving.
- For mean of each 38 features, Bonferroni intervals are acquired with $\alpha = 0.0001$.
- For simulated current, steps 1~5 are repeated.
- If all 38 simulated current features in step 7, stand in Bonferroni interval in step 6, then the simulated current is alike HIF current. Otherwise some parameters of HIF model will be reclaim and go to step 7.



Figure 6. (a) Arcs in HIF test on cement surface

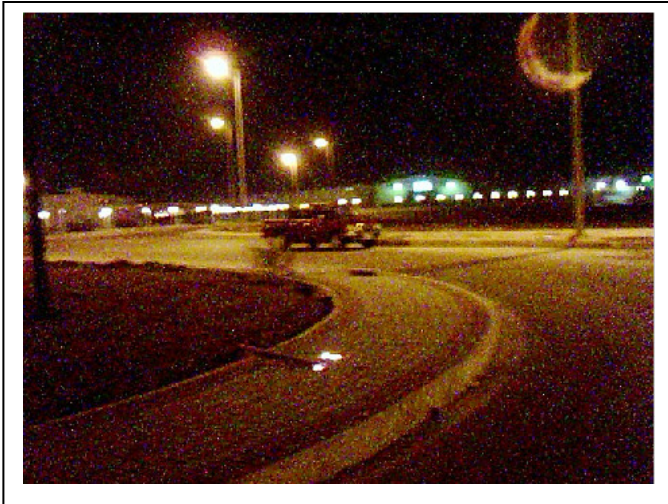


Figure 6. (b)Arcs in HIF test on cement surface

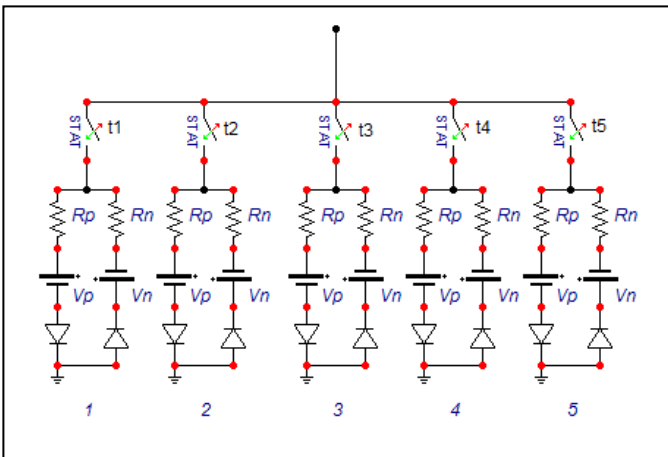


Figure 7. New HIF model based on several Emanuel arc model

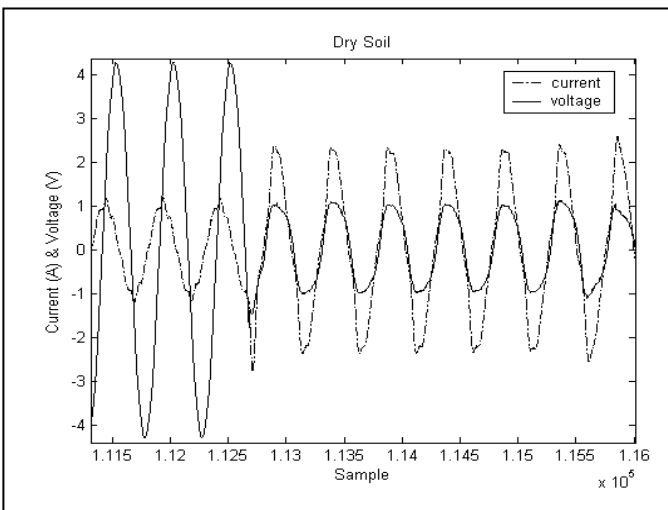


Figure 8. HIF current and voltage

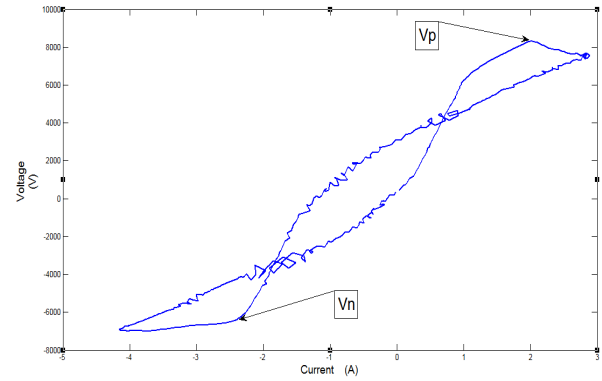


Figure 9. v-i curve of HIF

VI. RESULTS

Based on explained procedure in previous section, 5 models for HIF current are introduced with several amplitudes (9~90 A) for various surfaces. In each HIF model five arc models are used.

All parameters of each arc model are appointed based on recorded HIF current. STATISTIC switches with Gaussian distribution are used for access to random state of HIF current.

Several sample of simulated HIF current are illustrated in Fig. 10 .

Fig.11 shows voltage and current of the first state in a curve, as shown voltage and current have the same phase after fault occurred.

Simulated HIF v-i curve of the first state is shown in Fig. 12.

All parameters for 5 presented model and their arcs are shown in Table I.

As explained, each arc connect to the model with a statistical switch that have mean time as show in Table I, with Gaussian distributed function with $\sigma = 3.3\text{mS}$.

VII. CONCLUSION

In this paper a novel HIF model is presented. This new model is based on Emanuel arc model. Several arc models is used together until simulated HIF currents have similar to real recorded HIF current. FFT is used for extracting, HIF current features and PCA for dimension reduction of them. Simulated and recorded current compared with Bonferroni interval method.

ElectroMagnetic Transient Program (EMTP) is used for simulation of HIF model and statistical switches are used for producing random HIF current. Results show high similarity between simulated current and real recorded current.

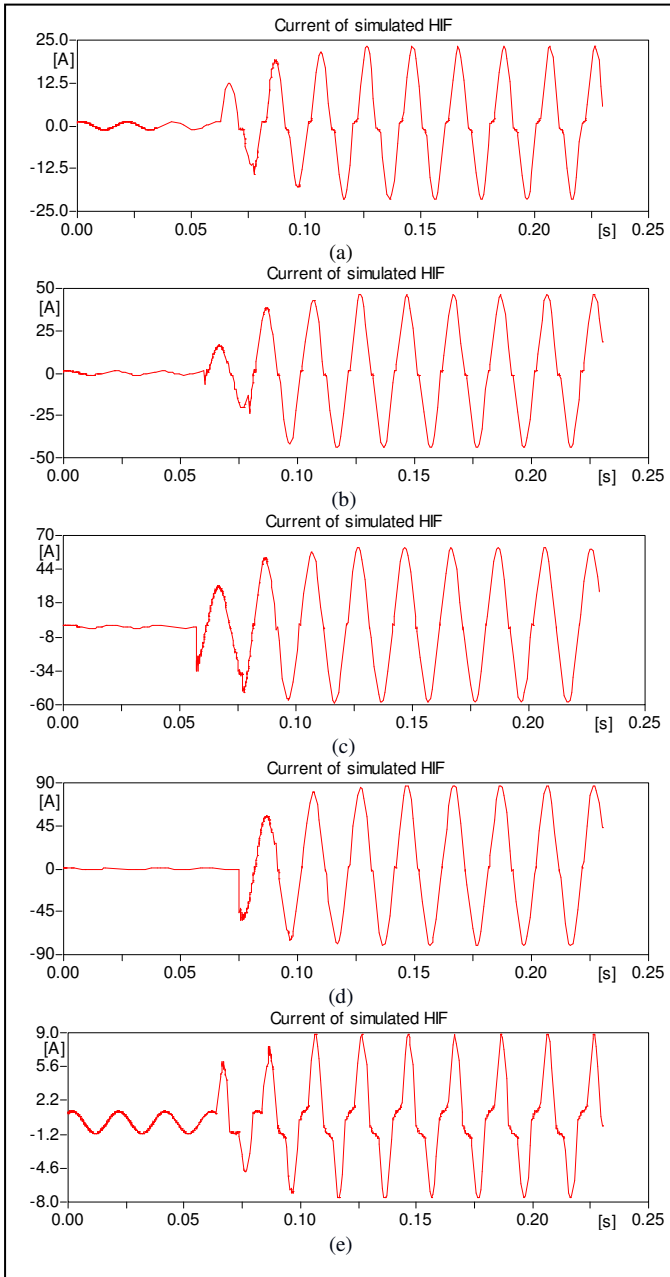


Figure 10. Simulated HIF currents

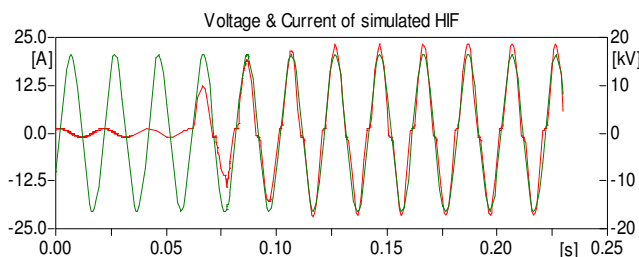


Figure 11. Simulated HIF voltage and current of the first

State	parameter	Arc 1	Arc 2	Arc 3	Arc 4	Arc 5
1	<i>t</i>	0.062	0.077	0.1	0.114	0.083
	<i>R_p</i>	1000	2900	3500	3700	4000
	<i>R_n</i>	1200	3000	3550	3750	4010
	<i>V_p</i>	4000	8000	7500	10000	490
	<i>V_n</i>	4500	8100	7600	10500	510
2	<i>t</i>	0.06	0.073	0.093	0.112	0.079
	<i>R_p</i>	900	2800	2500	2100	800
	<i>R_n</i>	905	2850	2550	2150	805
	<i>V_p</i>	1800	3000	4000	10000	2000
	<i>V_n</i>	1900	3500	4500	11000	2500
3	<i>t</i>	0.057	0.075	0.09	0.11	0.077
	<i>R_p</i>	500	2000	2500	1800	1000
	<i>R_n</i>	505	2050	2550	1900	1050
	<i>V_p</i>	900	2500	3000	11000	1000
	<i>V_n</i>	1000	2700	3200	11500	1100
4	<i>t</i>	0.075	0.096	0.111	0.131	0.09
	<i>R_p</i>	280	2000	2500	2700	800
	<i>R_n</i>	300	2500	2700	2750	805
	<i>V_p</i>	750	1800	3000	11300	950
	<i>V_n</i>	900	2800	4000	11500	1050
5	<i>t</i>	0.061	0.066	0.092	0.104	0.086
	<i>R_p</i>	1500	9000	6500	5800	10000
	<i>R_n</i>	1505	9600	7000	6500	11100
	<i>V_p</i>	9000	8000	11000	12000	2000
	<i>V_n</i>	10000	9000	11050	12500	2050

TABLE I. ARCS PARAMETERS OF HIFs MODELS

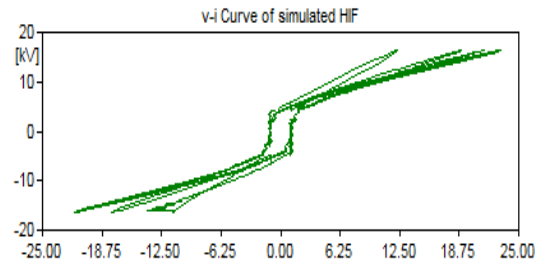


Figure 12. Simulated HIF v-i curve of the first state

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