International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:8, No:6, 2014

ANFIS Approach for Locating Faults in Underground Cables

Magdy B. Eteiba, Wael Ismael Wahba, Shimaa Barakat

***Abstract*—**This paper presents a fault identification, classification and fault location estimation method based on Discrete Wavelet Transform and Adaptive Network Fuzzy Inference System (ANFIS) for medium voltage cable in the distribution system.

Different faults and locations are simulated by ATP/EMTP, and then certain selected features of the wavelet transformed signals are used as an input for a training process on the ANFIS. Then an accurate fault classifier and locator algorithm was designed, trained and tested using current samples only. The results obtained from ANFIS output were compared with the real output. From the results, it was found that the percentage error between ANFIS output and real output is less than three percent. Hence, it can be concluded that the proposed technique is able to offer high accuracy in both of the fault classification and fault location.

***Keywords*—**ANFIS, Fault location, Underground Cable, Wavelet Transform.

I. INTRODUCTION

UNDERGROUND cables have been widely implemented due to their reliability and limited environmental concerns. To improve the reliability of a distribution system, accurate identification of a faulted segment is required in order to reduce the interruption time during a fault. Therefore, a rapid and accurate fault detection method is required to accelerate system restoration, reduce outage time, minimize financial losses and significantly improve the system reliability.

Various fault location algorithms for underground cables have been developed so far. For example, Ningkang and Yuan introduced a mathematical model that is based on calculating the impedance across a tested transmission line to localize all fault locations [1].

Although their model was satisfactory, they only used the post-fault phase magnitude current to identify the fault location; however, their method is not applicable to the distribution system due to asymmetrical network. An alternative approach to identify the fault location for a radial cable employed wavelet transform to extract valuable information from transient signals and eventually localize faults through a fuzzy logic system is presented in [2]. Javad implemented another approach locate faults in a combined overhead transmission line with underground power cable using ANFIS [3]. The wavelet transform is used to obtain the current patterns in [4]; the proposed methodology consists of training the ANFIS system with a fault database registers obtained from the power distribution system. The performance of the ANFIS nets was good and the 99.14% of the current patterns were correctly classified.

Here, we build upon previously presented methods and describe a fast and accurate method that to detect fault location in underground cables. The proposed method uses a novel wavelet-ANFIS combined approach. The ANFIS is used to extract information from the available Discrete Wavelet Transform coefficients to obtain coherent conclusions regarding fault location. Similar to any rule-based system, the rules are gathered through a fuzzy inference system (FIS) [5]. The efficacy of the proposed model was validated under different fault conditions.

II. PROPOSED FAULT LOCATION METHOD

The proposed method consists of two main stages, namely, fault type classification and exact fault location. The presented algorithm contains five ANFISs. The first network is for fault type classification, while the remaining four networks are for accurate fault location (one for each fault type).

A. Features Extraction Using DWT

Here, we used the line current signals as the input to the DWT. Daubechies DB4 wavelet, is employed since it has been demonstrated to high performance. The fault transients of the study cases are analyzed through discrete wavelet transform at the level five. Both approximation and detail information related fault current are extracted from the original signal with the multi-resolution analysis .

When a fault occurs in the cable, its effect can be observed as variations within the decomposition coefficient of the current signals that contain useful fault signatures. Fig. 1 shows the DWT detailed coefficients at level 1 to level 5 for a particular type of fault studied in the work. The nature of the plot of detailed coefficients at level 1 reveals a sharp spike which corresponds to the fault initiation process. According to DWT theory, this spike represents the highest frequency within the fault signal. It is, however, not practical to identify a fault based on this spike only since such spikes will occur every time there is a sudden change in the cable current signal. This will thus not be able to clearly differentiate between the faults of different types and at different locations.

Shimaa Barakat is with the Electrical Engineering Department, Faculty of Industrial Education, Beni Suief University, Beni Suief, Egypt. (phone: +20 01115153369; fax: +20 822241932; e-mail: shimaabara@yahoo.com).

Magdy B. Eteiba and Wael Ismael Wahba are with the Electrical Engineering Department, Faculty of Engineering, Fayoum University, Fayoum, Egypt. (e-mail: eteiba@yahoo.ca, waelwahba@gmail.com).

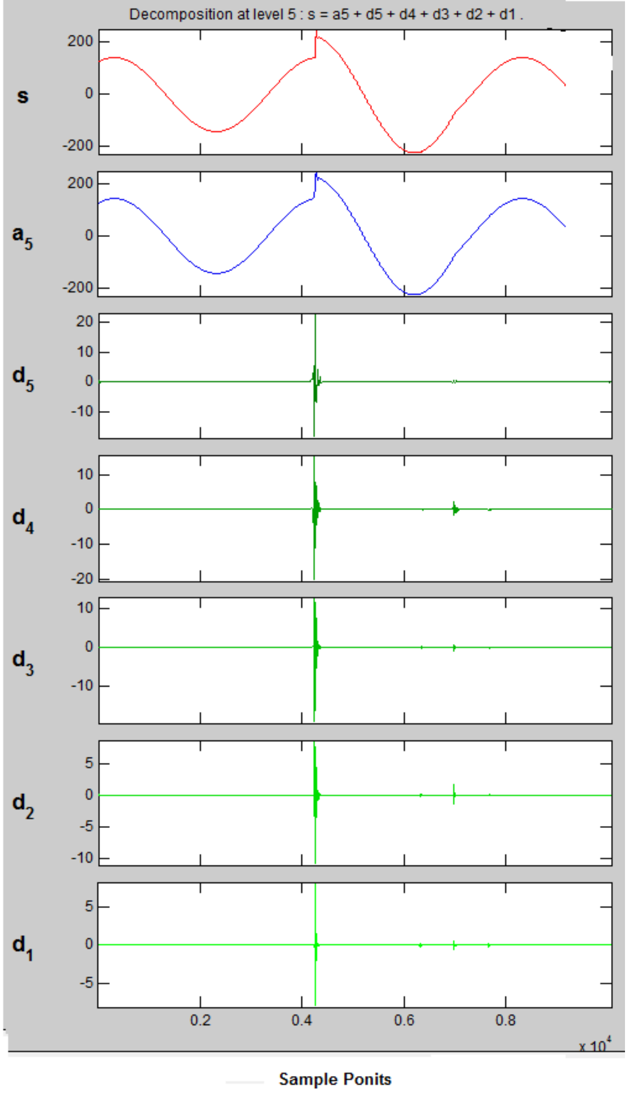


Fig. 1 The DWT detailed coefficients at level 1 to level 5 for a three phase to ground fault (Decomposition of phase A, with fault resistance=100Ω, Inception Angle =90 (and fault location=1. 375Km)

The nature of level 5 detailed coefficients (Figs. 2 and 3) shows that along with the high spike, there is a certain side band containing some smaller spikes. The nature of this side band along with the dominant spike has been observed to change appreciably with variations in fault types and locations. Detailed coefficients at still higher levels, however, have been found to contain much wider side bands that complicated correlation with possible fault types and locations.

Therefore, we decided to start with, extracting some meaningful features from the level 5 detailed coefficients that can be correlated to possible fault types and locations. With this in mind, the maximum detailed energy of three phase and zero sequence currents have been used as features of the fault classification and location scheme. The proposed methodology consists of training the ANFIS system with a fault database obtained from the simulation of the cable.

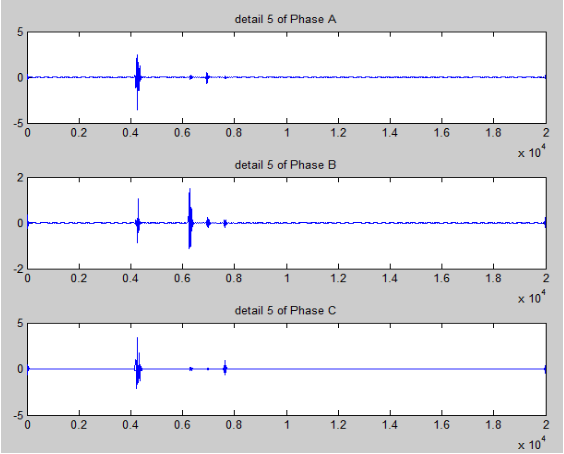


Fig. 2 Level 5 detailed coefficients of Three Phase to Ground Fault case

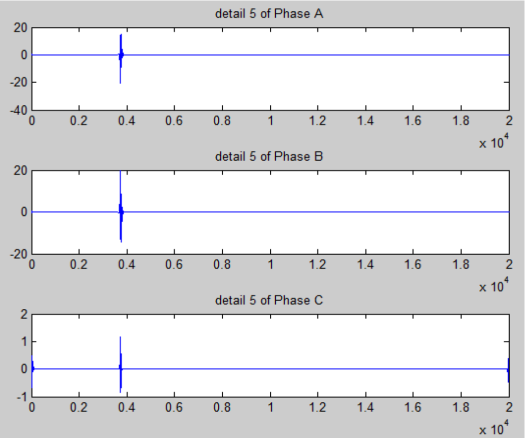


Fig. 3 Detailed coefficients of Line to Line Fault case

B. *Fault Classification Scheme*

In order to design an ANFIS, it is crucial to train it efficiently and correctly. The training set must be carefully chosen such that it can include a diversity of fault conditions such as different fault inception angles, different fault resistances and different fault locations are considered. The performance of the ANFIS is then tested using both patterns within and outside of the training set.

An acceptable and simple criterion that we used here is that the ANFIS input should provide more information for fault location than those not selected. Therefore, for fault type classification (ANFIS1), the maximum detailed energy of three phases and zero sequence currents are selected as inputs and the desired output is the fault type as set in Table I.

The Matlab code used for calculating the maximum detailed energy is:

```
[Ea0,Ed0] = wenergy (C0,L0);
Ed0_max = max (Ed0);
```

```
[Eaa,Eda] = wenergy(Ca,La);
Eda_max = max (Eda);
[Eab,Edb] = wenergy(Cb,Lb);
Edb_max = max (Edb);
[Eac,Edc] = wenergy(Cc,Lc);
Edc_max = max (Edc);
```

where:

Ea: The percentage of energy corresponding to the approximation.

Ed: The vector containing the percentages of energy corresponding to the details.

TABLE I
TRAINING TARGET FOR ANFIS1 FAULT TYPE CLASSIFICATION

Fault Type	ANFIS Target
Three Phase to ground (ABCG)	1
Double line to ground (ABG)	2
Line to line (AB)	3
Single line to ground (AG)	4

C. Fault Location Scheme

At this stage, four different ANFISs are trained for fault location based on the knowledge of the fault type. Once the fault is classified, the relevant ANFIS for fault location is activated. The inputs for these networks are the same as those for the inputs of ANFIS1. The output, however, is the distance of the fault point from the sending end of the cable in Km.

III. TESTS AND RESULTS

A. Test System

The Alternative Transient Program (ATP) is used to simulate medium voltage underground cable model [6] with a sampling frequency of 200 KHz. The single line diagram is shown in Fig. 4 while the cable configuration is shown in Fig. 5. The components that we used are the three phase voltage source, a tested cable and a fixed load. The specifications of cable material for 11 Kv are presented in Table II.

- Three phase voltage source: V= 11KV with f = 50 Hz
- Load: Three-Phase 2 MVA Grounded-Wye load with parallel R, L elements (power factor = 0.85, R = 71.157 Ω, L = 365.475mH).

Simulation of MV underground cable faults depends on four main fault parameters (fault type, fault distance, fault resistance, inception angle).

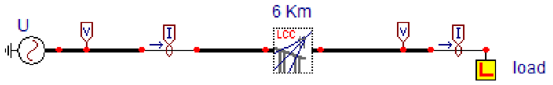


Fig. 4 Single line diagram for underground cable model

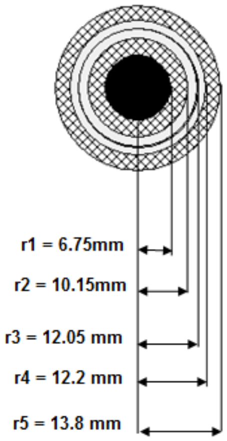


Fig. 5 Cable Configuration

TABLE II
SPECIFICATION OF CABLE MATERIAL FOR 11KV

Specification of MV underground cable material (XLPE Stranded Copper Conductor - 6 Km - Bergeron model)	
Radius (mm)	r1= 6.75, r2 = 10.15, r3 = 12.05 r4 = 12.2, r5 = 13.8
Core conductor	ρ = 1.7 E-8 Ω.m , μ = 1.0
Insulation	μ = 1.0 , ε = 2.7
Sheath	ρ = 2.5 E-8 Ω.m , μ = 1.0

ρ : Resistivity of the conductor material.

μ: Relative permeability of the conductor material.

μ (ins.): Relative permeability of the insulating material outside the conductor.

ε (ins.): Relative permittivity of the insulating material outside the conductor.

1. Training Scenarios for the Simulation

Fault type

- Single line to ground (AG)
- Double line to ground (ABG)
- Line to line (AB)
- Three phase to ground

Fault resistance: {0, 10, 30, 50, 100, 200 Ω}

Inception angle: {0° , 45 °, 90 °, 135 °, 180 °}

Fault distance:

- Training: [0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, 3.75, 4, 4.25, 4.5, 4.75, 5, 5.25, 5.5] Km from the sending end.
- Testing: [0.625, 0.875, 1.125, 1.375, 1.625, 1.875, 2.125, 2.375, 2.625, 2.875, 3.125, 3.375, 3.625, 3.875, 4.125, 4.375, 4.625, 4.875, 5.125, 5.375] Km from the sending end.
- Table III shows the number of simulations used in this work.

TABLE III
NUMBER OF SIMULATIONS

	Training	Testing
Three phase to ground	630	120
Single line to ground (AG)	630	180
Line to line (AB)	630	120
Double line to ground (ABG)	630	120
Total	2520	540

B. ANFIS Fault Type Classification Results

Table IV lists part of the fault classification training output results for the three phase to ground fault. As shown, the obtained predicted values are quite similar to that of the training target values. This demonstrates that ANFIS is able to recognize and classify the fault correctly.

TABLE IV
THREE PHASE ANFIS FAULT TYPE CLASSIFICATION TRAINING RESULTS WITH FAULT RESISTANCE = 0 Ω

*X (KM)	Target	ANFIS Output IA = 0°	ANFIS Output IA = 45°	ANFIS Output IA = 90°	ANFIS Output IA = 135°	ANFIS Output IA = 180°
0.5	1	1.004	0.978	0.977	1.054	1.021
0.75	1	1.004	0.988	1.001	1.022	1.012
1	1	1.002	0.992	1.008	0.991	1.003
1.25	1	1.002	1.000	1.010	0.964	0.995
1.5	1	1.001	1.008	1.012	0.959	0.992
1.75	1	1.000	1.014	1.009	0.958	0.990
2	1	0.999	1.019	1.005	0.960	0.989
2.25	1	0.998	1.021	1.003	0.976	0.991
2.5	1	0.998	1.022	0.999	0.989	0.992
2.75	1	0.997	1.019	0.996	1.006	0.994
3	1	0.997	1.014	0.995	1.017	0.997
3.25	1	0.997	1.008	0.995	1.028	1.000
3.5	1	0.997	0.998	0.994	1.035	1.003
3.75	1	0.997	0.990	0.995	1.039	1.005
4	1	0.999	0.983	0.997	1.044	1.007
4.25	1	0.998	0.978	0.997	1.035	1.007
4.5	1	1.000	0.978	0.999	1.024	1.007
4.75	1	1.001	0.981	1.001	1.012	1.005
5	1	1.001	0.990	1.001	0.989	1.002
5.25	1	1.005	1.006	1.002	0.963	0.999
5.5	1	1.005	1.025	1.003	0.935	0.991

* X(KM): Actual fault location .
* IA: Inception Angle

C. Fault Location System Tool

Development of the fault location system tool (FL) is based on Matlab GUI as shown in Fig. 6. The purposes of building the GUI tool are to:

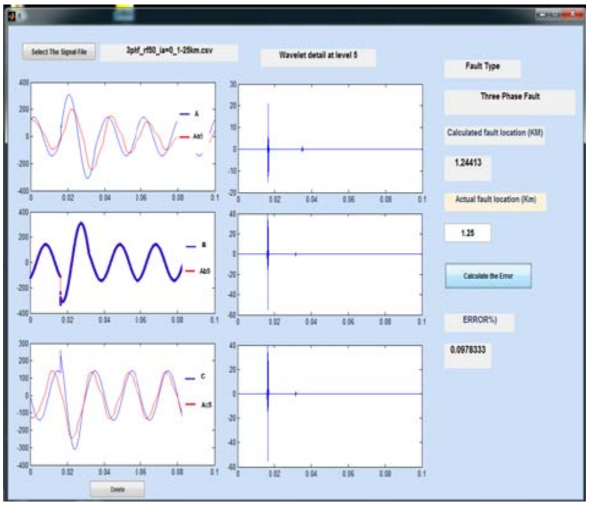
- Test the data using ANFIS models,
- Display the original signal, the wavelet approximation and detail coefficients at level 5,
- Produces fault types,
- Calculate fault location and
- Calculate the percentage error.

The FL needs only a standard data format of three-phase current as an input to pinpoint the fault.

1. Components of the Fault Location System Tool

The fault location system tool (FL) consists of three sections:

- *Section 1:* It shows the original three phase signals (A, B and C) and the corresponding wavelet approximation signals at level 5 (Aa5, Ab5 and Ac5).
- *Section 2:* It shows the wavelet detail signals at level 5 (Da5, Db5 and Dc5).
- *Section 3*: It displays the fault types ,calculate the fault location and finally calculate the percentage error.



3phf_rf50_ia=0_1-25km.csv

Fault Type: Three Phase Fault

Calculated fault location (KM): 1.24413

Actual fault location (Km): 1.25

ERROR%): 0.0978333

Fig. 6 The application window of fault location system tool

D. ANFIS Fault Location Estimation Training Results

In ANFIS Fault Location Estimation, all the four types of fault (ABCG, ABG, AB and AG) were trained separately. As a result, a total of four networks was used to estimate the fault distance. The results for each network are presented below.

The location error is defined as [7]:

$$\%Error = \left|\frac{Exact\ Distance - ANFIS\ output}{Total\ cable\ Length}\right| \times 100\%$$

$$where\ , \qquad Total\ cable\ Length = 6\ Km$$

2. Three Phase to Ground ANFIS Fault Location Model

It can be noticed from Fig. 7 that the Percentage error of three phase to ground fault is less than 1.65%.

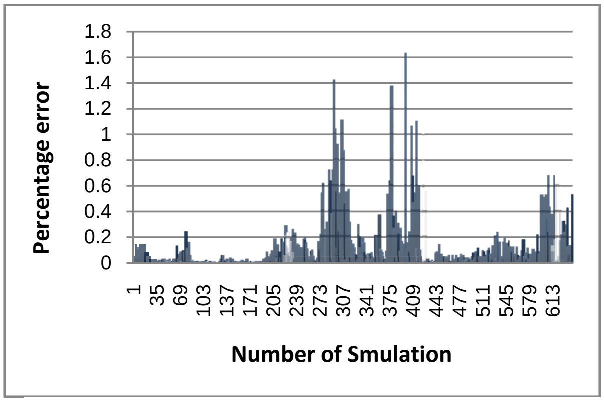


Fig. 7 Percentage error of three phase to ground fault (training)

3. Double Line to Ground ANFIS Fault Location Model

It can be noticed from Fig. 8 that the Percentage error of double Line to ground fault is less than 1%.

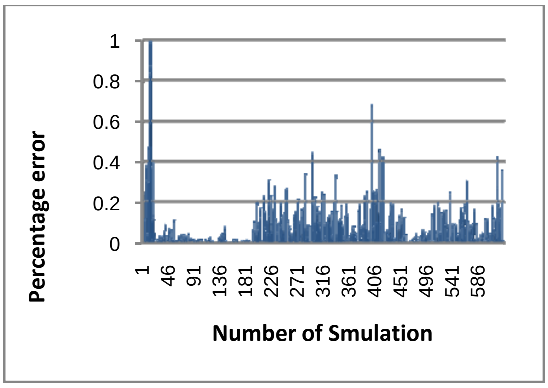


Fig. 8 Percentage error of double Line to ground fault (training)

4. Line To Line ANFIS Fault Location Model

It can be noticed from Fig. 9 that the Percentage error of Line to Line fault is less than 2%.

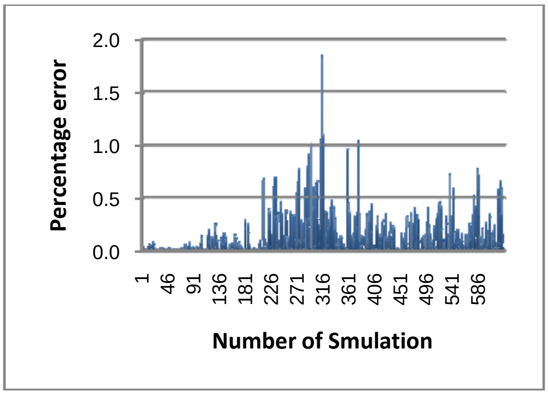


Fig. 9 Percentage error of Line to Line fault (training)

5. Single Line to Ground ANFIS Fault Location Model

It can be noticed from Fig. 10 that the Percentage error of Single Line to ground fault is less than 3%.

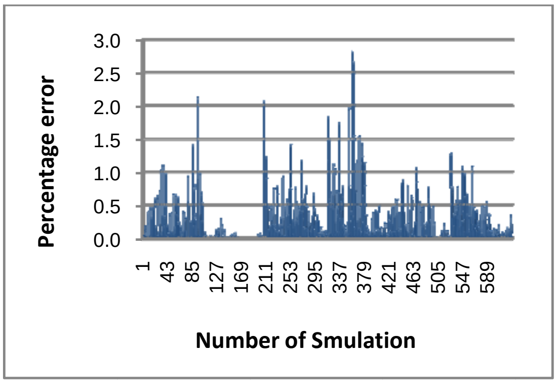


Fig. 10 Percentage error of Single Line to ground (training)

E. ANFIS Fault Location Estimation Testing Results

1. Three Phase To Ground Fault

It can be noticed from Fig. 11 that the Percentage error of three phase to ground fault is less than 0.7%.

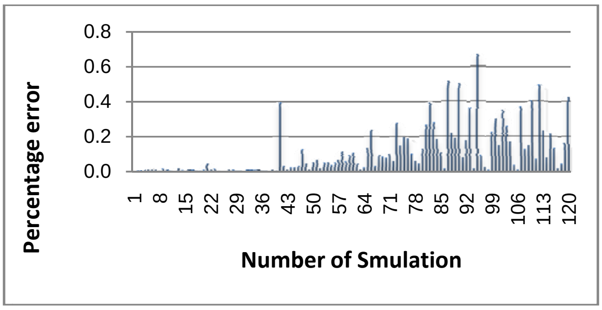


Fig. 11 Percentage error of three phase to ground fault (testing)

2. Double Line to Ground Fault

It can be noticed from Fig. 12 that the Percentage error of double Line to ground fault is less than 1.7%.

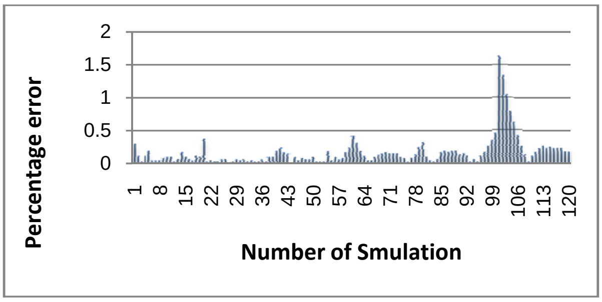


Fig. 12 Percentage error of double Line to ground fault (testing)

3. Line To Line Fault

It can be noticed from Fig. 13 that the Percentage error of Line to Line fault is less than 1.8%.

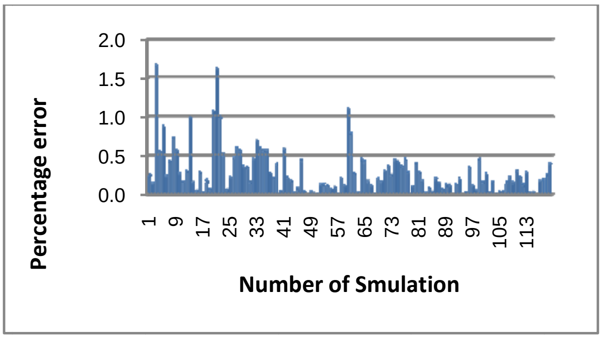


Fig. 13 Percentage error of Line to Line fault (testing)

4. Single Line To Ground Fault

It can be noticed from Fig. 14 that the Percentage error of Single Line to ground fault is less than 3 %.

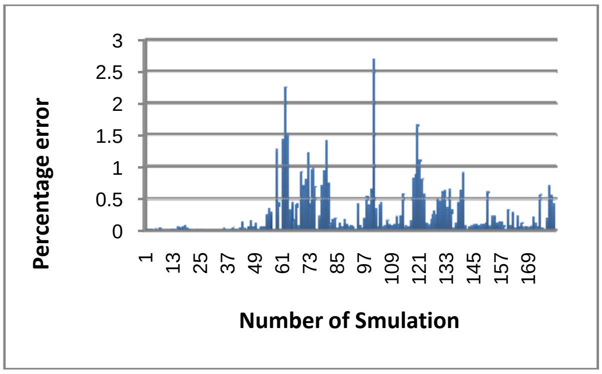


Fig. 14 Percentage error of Single Line to ground fault (testing)

IV. CONCLUSION

This paper presented an application of fault location method to localize faults in a medium voltage underground cable based on the theory of Wavelet and Adaptive Network Fuzzy Inference System (ANFIS). The Proposed ANFIS uses only post-fault three-phase currents as inputs. It predicts the distance of the fault from the sending endpoint. The results show that the approach can accurately identify the fault types and locate the faults.

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