Fuzzy Logic Based Approach for Faults Identification and Classification in Medium Voltage Isolated Distribution Network

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Abstract. Power system faults are unwelcome events which pose a safety, technical and social hazard. Power system operators are under increasing pressure from customers and regulators to maintain high levels of power system reliability. Appropriate fault identification and classifications is a crucial part of power system operation and management. This paper proposes a method for identification and classification of faults in 10 kV isolated distribution network. The proposed method uses three line voltages, available at the substation as input variable and returns the fault code as the output variable for all ten shunt fault types, as the output variable. Classification is based on the fuzzy system with three input variables and one output variable. Results show that proposed system can detect low resistance faults with 100% accuracy for all then shunt fault types that can occur in electric power distribution network. The input data (voltage waveforms) are generated in simulations performed on a model of realistic distribution system in Bosnia and Herzegovina.

1 Introduction

Electrical power systems are more frequently operated close to their technical limits due to the increase of renewable energy systems and distributed generation. Therefore they become more prone to fault occurrences. Especially the medium voltage grid is affected since it experiences the most significant changes. Therefore fault detection identification and localization are of great concern for the distribution grid operators. Fault identification and localization mainly includes the following aspects: type, direction, and distance. It is generally independent from protective relaying. The purpose is not to protect assets through a short-term generation of a trip signal to de energize a faulted section as fast as possible. The objective is to supply the grid operator with information about the fault prior to an on-site investigation. Transmission lines are most prone to occurrence of fault. Fault detection, direction estimation and faulty phase selection play a critical role in the protection for a transmission line. Accurate and fast fault detection and classification under a variety of fault conditions are important requirements of any protective relaying scheme [1].

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This paper aims to provide a contribution toward more effective identification and classification of earth faults in 10 kV isolated network. The investigated network modelled in accordance with realistic distribution network data in Bosnia and Herzegovina. The main characteristic of Bosnian 10 kV distribution network is lightly loaded, long overhead distribution lines which run through the harsh mountain terrain and supply electricity to remote communities. These feeders are often run from the same substation, which is used to supply electricity to urban areas and industrial customers via shorter, but more heavily loaded underground cables. Most of 10 kV distribution system in Bosnia and Herzegovina still operates with an isolated neutral point. This mode of operation has numerous advantages (as well as disadvantages) over the other methods of neutral point treatment, as shown in Table 1. The main advantage of an isolated system is the ability of uninterrupted operation under the fault conditions which is good for systems in the early stages of their development (such as the Bosnian system in 1960s and 1970s). However, as the system develops and as the new sections and feeders are added, the earth fault currents increase and overvoltage during fault becomes a serious issue, causing an ongoing debate on the benefits and challenges of the existing configuration.

Table 1. Overview of advantages and disadvantages of isolated system

Neutral point treatment: isolated system	
Advantages	Disadvantages
Can continue to operate during the earth fault and increase the system reliability	Overvoltage to the ground and rise of a voltage of "healthy" phases
It has low fault current	Potential hazard
It is can be identified by observing the voltage waveform	Difficult to locate the fault
Very suitable for systems in the early stages of development	Might not be cleared by the protection and cause additional stress to the equipment
It is simple and relatively inexpensive The self-healing system as arc can be extinguished by the system	Not suitable for developed system since fault current increases and arc extinction is less likely to occur

2 Overview of Earth Fault Fundamentals

In the past 20 years, there has been a rapid development in various fields concerning the detection, classification and location of faults in power systems. The advances in signal processing techniques, artificial intelligence and machine learning, global positioning system (GPS) and communications have enabled more and more researchers to carry out studies with high breadth and depth in that the limits of traditional fault protection techniques can be stretched [2]. Earth fault is a type of power system fault which occurs when contact is established between conducting phase and the earth in the system with isolated neutral point of a transformer. Since in the isolated system, there is no direct connection with the earth, the only connection that can be established is due to the ground level capacities of transmission lines. When the earth fault is developed in an isolated network, currents flow through earth capacities of healthy phases and the earth fault current is dependent on the fault resistance and network capacitance [3]. Figure 1 represents an illustration of basic distribution network parameters during the earth fault. With reference to Fig. 2 and defining the V_0 as the neutral point voltage, the general representation of the earth fault current can be derived as follows:

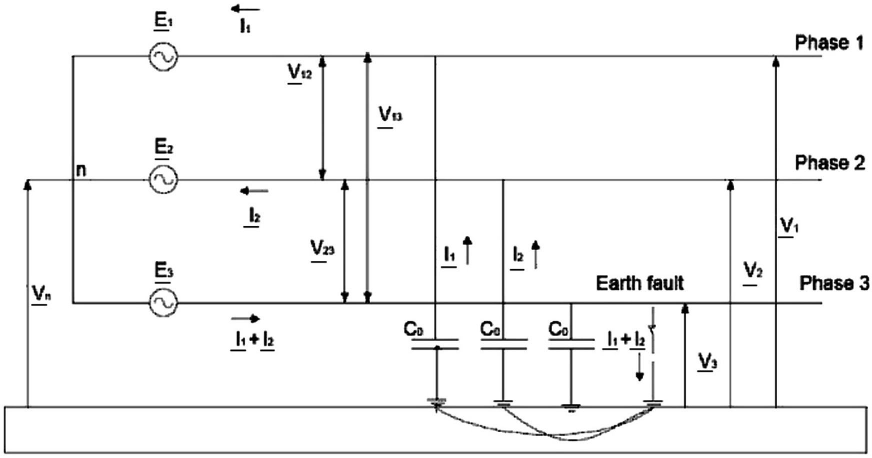

Fig. 1. Illustration of basic power distribution network parameters during the earth fault

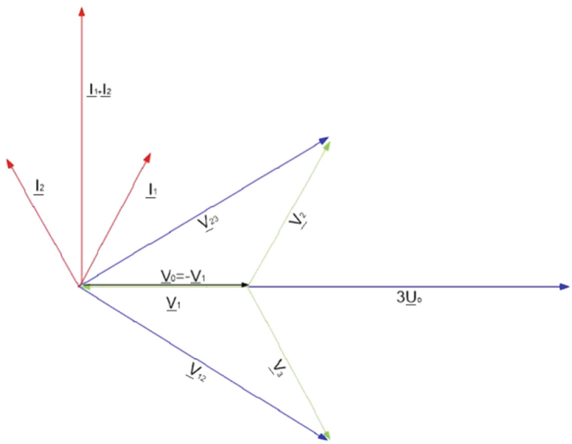

Fig. 2. Phasor diagram during earth fault in an isolated system

$$\underline{V_1} = \sqrt{3}V_n e^{j150^\circ} \tag{1}$$

$$\underline{V_2} = \sqrt{3}V_n e^{j210^\circ} \tag{2}$$

$$\underline{I_1} = V_1 j\omega C_0 = \sqrt{3}V_n \omega C_0 e^{j150^\circ} e^{j90^\circ} = \sqrt{3}V_n \omega C_0 e^{j240^\circ} \tag{3}$$

$$\underline{I_2} = V_2 j\omega C_0 = \sqrt{3}V_n \omega C_0 e^{j210^\circ} e^{j90^\circ} = \sqrt{3}V_n \omega C_0 e^{j300^\circ} \tag{4}$$

$$\begin{aligned} \underline{I_f} &= \underline{I_1} + \underline{I_2} = \sqrt{3}V_n \omega C_0 e^{j240^\circ} + \sqrt{3}V_n \omega C_0 e^{j300^\circ} \\ &= \sqrt{3}V_n \omega C_0 (e^{j240^\circ} + e^{j300^\circ}) \\ &= \sqrt{3}V_n \omega C_0 (\cos 240^\circ + j\ \sin 240^\circ + \cos 300^\circ + j\ \sin 300^\circ) \\ &= \sqrt{3}V_n \omega C_0 (\frac{1}{2} - j\frac{\sqrt{3}}{2} - \frac{1}{2} - j\frac{\sqrt{3}}{2}) = -jV_n 3\,\omega C_0 \end{aligned} \tag{5}$$

Earth fault modulus can be represented as:

$$|I_f| = V_n 3\omega C_{tot} \tag{6}$$

3 Method and Data Collection

The input data (voltage waveforms) are generated in simulations performed on the model of a realistic electric power distribution system in Bosnia and Herzegovina. The single line diagram of power distribution network used in this study is shown in Fig. 3. Figures 4 and 5 show the relevant electrical data of the underground cable and overhead line conductors used to create the power distribution network model, respectively. This is a typical 35/10 kV zone substation with eight, 10 kV feeders. The first four are underground cables, while feeders 5–8 are modelled as overhead lines. Normal mode (steady state) operations and fault conditions, for each of the ten shunt fault types are simulated and voltage waveforms for three line voltages at 10 kV substation bus bar are reported. The types of faults are shown in Table 2. The value of an earth fault current in an isolated network is independent from location. As shown in Eq. 5. earth fault depends only on voltage and total line capacitance (which, obviously is related to line lengths). Notwithstanding this, simulations are performed for faults in different parts of the network in order to provide same diversity of input data. It was observed that some difference in voltage at the faulted line measure at 10 kV substations is present as a function of fault locations. For example, voltage in phase 1 drops to zero at the fault locations, and increases to some 10% of nominal value as we move away from the network.

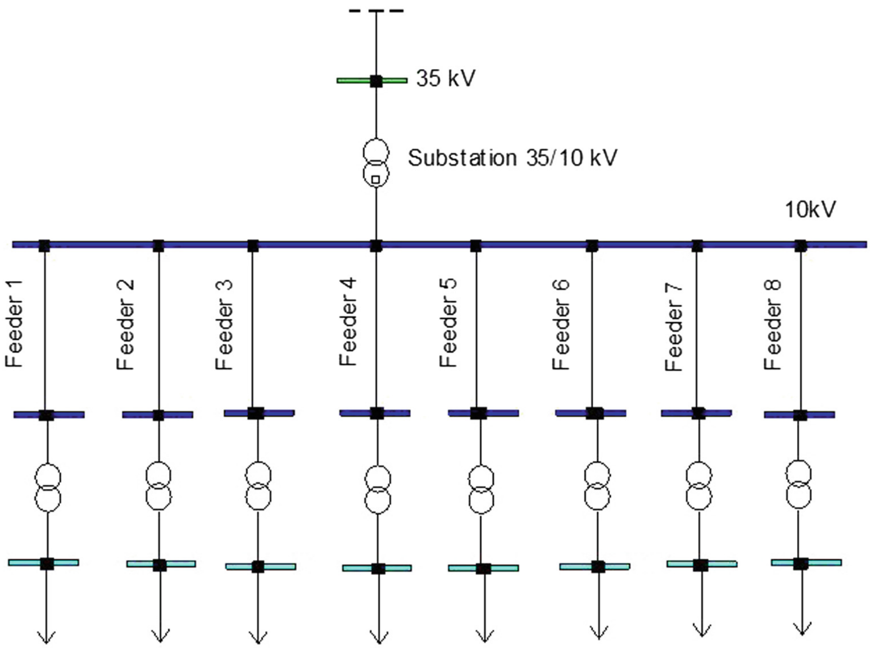

Fig. 3. Single line diagram of power distribution system used in this study

Rd[ohm/km]	0,206	Ro[ohm/km]	0,795
Xd[ohm/km]	0,15	Xo[ohm/km]	0,57
Gd[uS/km]	0	Go[uS/km]	0
Bd[uS/km]	81,6399	Bo[uS/km]	81,6399

Fig. 4. Relevant electrical data for underground cables used in the model

Rd[ohm/km]	0,61	Ro[ohm/km]	0,76
Xd[ohm/km]	0,355	Xo[ohm/km]	1,7
Gd[uS/km]	0	Go[uS/km]	0
Bd[uS/km]	3	Bo[uS/km]	1,6

Fig. 5. Relevant electrical data for the overhead line conductor used in the model

3.1 Development of Fault Classification and Identification System

Figure 6 represents schematic representation of the proposed system for fault identification and classification. It is conveniently divided into four logical parts which might be considered as stages of the proposed system. The first stage is concerned with signal generation and the obtained txt files contain signal time series are stored in the database. The following stage is named signal processing and is used to store values of each line phase as a separate vector. The next step in the signal processing stage is the calculation of root mean square value for each vector. The obtained values are fuzzified and used as inputs into a fuzzy inference engine. The output of a fuzzy inference procedure is a fuzzy variable which needs to be defuzziffied in order to give a final, single valued quantity which represents the fault code. The final values of the system are represented by two vectors *a* and *b*, where *a* contains the information on fault code and b on the number of repetitions for each fault code [4]. The proposed system procedure is concluded by the output formatting and reporting stage which is used to graphically represent the output data. Following subsections provide some more details.

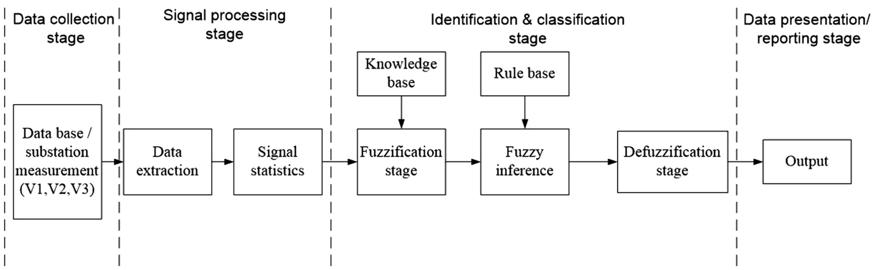

Fig. 6. Schematic representation of the system for fault identification and classification

3.1.1 Data Collection

The generated waveforms are sampled at a rate of 1000 Hz and saved in database as txt files. The total of 900 simulations was run, which produced 900 text files. Table 2 provides a summary of simulations performed for each type of fault and normal operation conditions.

3.1.2 Fuzzification

If define $\mu_{\tilde{A}}(x) \in [0, 1]$ as membership function and X as a Universe or universe of discourse, a fuzzy set $\tilde{A}$ in *X* is expressed as a set of ordered pairs [5]:

$$\tilde{A} = \left\{ \left(x, \mu_{\tilde{A}}(x)\right) | x \in X \right\} \qquad (7)$$

Fuzzy logic models are particularly useful in applications which require the description of imprecise and complex processes. Such descriptions are performed with the use of fuzzy sets used in the process of fuzzy logic control [6]. In the proposed

Table 2. Number of generated samples, and binary and decimal binary code

Type of fault	Number of samples	Binary code	Decimal code
none	100	0000	0
a–g	100	1001	8
b–g	100	0101	5
c–g	100	0011	3
abc	100	1110	14
ab–g	100	1101	13
ac–g	100	1011	11
bc–g	100	0111	7
ab	50	1100	12
ac	30	1010	10
bc	20	0110	5

fuzzy system, input and output linguistic variables are described by an expert knowledge and represented by sets $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ and $\tilde{O}$ which contain single terms A_i, B_j, C_l i O_k [6]:

$$\begin{aligned}
\tilde{A} &= \{A_1, A_2, \ldots, A_i, A_{i+1}, \ldots, A_n\} \\
\tilde{B} &= \{B_1, B_2, \ldots, B_j, B_{j+1}, \ldots, B_m\} \\
\tilde{C} &= \{C_1, C_2, \ldots, C_l, C_{l+1}, \ldots, C_z\} \\
\tilde{O} &= \{O_1, O_2, \ldots, O_k, O_{k+1}, \ldots, O_f\}
\end{aligned} \tag{8}$$

Terms A_i, B_j, C_l and O_k are fuzzy sets defined as [6]:

$$\begin{aligned}
\tilde{A}_i &= \left\{\left(x, \mu_{\tilde{A}_i}(x)\right) \middle| x \in \tilde{A}_i \subset U_1\right\}, i = 1, \ldots, n \\
\tilde{B}_j &= \left\{\left(y, \mu_{\tilde{B}j}(y)\right) \middle| y \in \tilde{B}_j \subset U_2\right\}, j = 1, \ldots, m \\
\tilde{C}_l &= \left\{\left(z, \mu_{\tilde{C}_l}(z)\right) \middle| z \in \tilde{C}_l \subset U_3\right\}, l = 1, \ldots, z \\
\tilde{O}_k &= \left\{\left(w, \mu_{\tilde{O}_k}(z)\right) \middle| w \in \tilde{O}_k \subset U_4\right\}, k = 1, \ldots, f
\end{aligned} \tag{9}$$

In particular, in the proposed model input variables are values the root mean square of three line voltage, represented by Eqs. 10–16. Graphical representation of input variables is presented in Fig. 7 while the output variable is presented in Fig. 8. Some of the values are sub normalized in order to improve the classification accuracy.

$$\tilde{V}_1 = \{A_1, A_2, A_3, A_4\} \tag{10}$$

$$\tilde{V}_1 = \{\text{verylow}, \text{low}, \text{normal}, \text{high}\} \tag{11}$$

$$\tilde{V}_2 = \{B_1, B_2, B_3, B_4\} \tag{12}$$

$$\tilde{V}_2 = \{\text{verylow}, \text{low}, \text{normal}, \text{high}\} \tag{13}$$

$$\tilde{V}_3 = \{C_1, C_2, C_3, C_4\} \tag{14}$$

$$\tilde{V}_3 = \{\text{verylow}, \text{low}, \text{normal}, \text{high}\} \tag{15}$$

$$\tilde{F} = \{O_1, O_2, O_3, O_4, O_5, O_6, O_7, O_8, O_9, O_{10}, O_{11}\} \tag{16}$$

$$\tilde{F} = \{\text{none}, \text{ag}, \text{bg}, \text{cg}, \text{abc}, \text{abg}, \text{acg}, \text{bcg}, \text{ab}, \text{ac}, \text{bc}\} \tag{17}$$

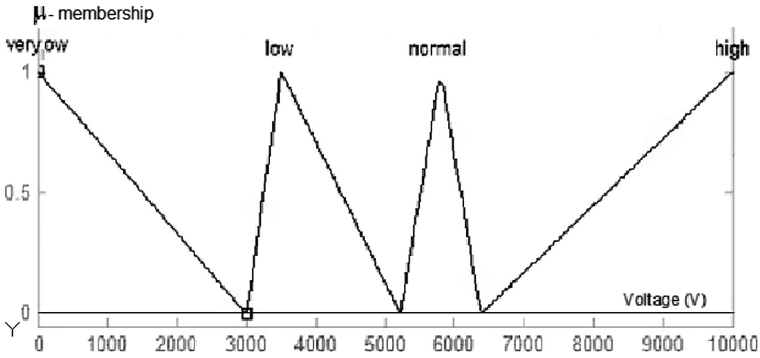

Fig. 7. Graphical representation of fuzzy to represent input variables

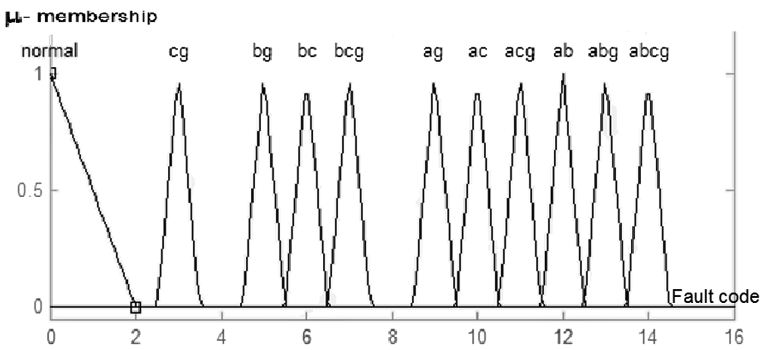

Fig. 8. Graphical representation of fuzzy set used to represent output variable

3.1.3 Inference

The inference model used in this paper is Mamdani type inference with three inputs (root mean square of three line voltage) and one output (fault code) variable [7]. Schematic representation of the proposed inference model is shown in Fig. 9.

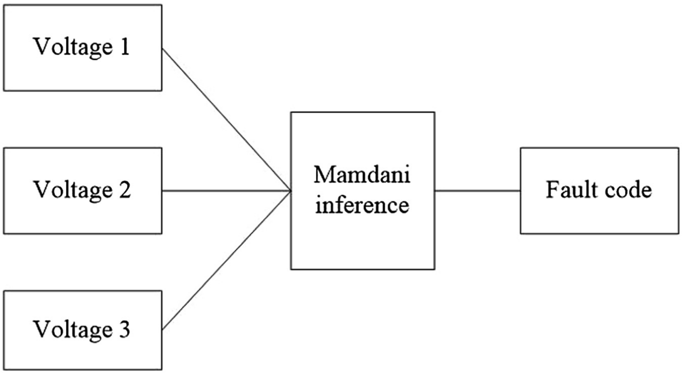

Fig. 9. Schematic representation of fuzzy inference system with three inputs and one output variable

3.1.4 Rule Base

A total of eleven IF…AND…THEN rules are created on the bases of expert knowledge. They form a rule base and can be represented as shown in Table 3.

Table 3 Rule base

Rule 1	if (v1 is normal) and (v2 is normal) and (v3 is normal) then: no fault
Rule 2	if (v1 is very low) and (v2 is high) and (v3 is high) then: ag fault
Rule 3	if (v1 is high) and (v2 is very low) and (v3 is high) then: bg fault
Rule 4	if (v1 is high) and (v2 is high) and (v3 is very low) then: cg fault
Rule 5	if (v1 is very low) and (v2 is very low) and (v3 is very low) then: abc sym fault
Rule 6	if (v1 is very low) and (v2 is very low) and (v3 is high) then: abg fault
Rule 7	if (v1 is very low) and (v2 is high) and (v3 is very low) then: acg fault
Rule 8	if (v1 is high) and (v2 is very low) and (v3 is very low) then: bcg fault
Rule 9	if (v1 is low) and (v2 is low) and (v3 is normal) then: ab fault
Rule 10	if (v1 is low) and (v2 is normal) and (v3 is low) then: ac fault
Rule 11	if (v1 is normal) and (v2 is low) and (v3 is low) then: bc fault

3.1.5 Defuzzification

The last component of fuzzy system is defuzzification stage, sometimes also called decoding. The purpose of this stage is to produce a non-fuzzy control output which adequately represents the membership function $\mu_{agg}(z)$[6]. There are numerous defuzzification methods and in this paper, center of gravity method is chosen as defuzzification method [8]. It is important to note that one can refrain from computerized defuzzification, which means that one characterizes the faulty situation by a gradual representation rather than by a yes-no statement [9].

4 Results and Discussion

The output values of the proposed identification and classifications systems are two vectors *a* and *b* which contains data on fault type and occurrence (in the form of decimal fault code). Figure 10 show a graphical representation of these vectors. Results shown in Fig. 10 are the output result of the proposed system, which for each fault type gives occurrence rate. It can be seen, by comparing results in Fig. 10 with results presented in the second column of the Table 2 that the proposed system is capable to identify and classify the events with 100% accuracy.

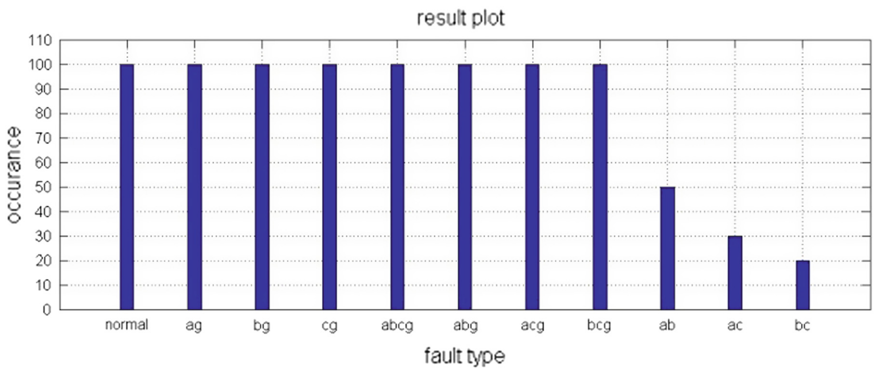

Fig. 10. Output results of the proposed system—fault types and occurrence

5 Limitations and Future Work

This paper proposed a promising system for identification and classification of power distribution network faults. The study focused signal processing of voltage waveforms, used as input variables in the fuzzy system for identification and classification of power distribution network faults. Proposed system proved to be very efficient for identification and classification of low impedance faults. Further investigation is required to take into consideration fault resistance. The proposed system could be extended to include identification and classification algorithms that are capable to account for different network configurations (neutral point treatment). Particularly interesting would be investigation of hardware implementation possibilities of the proposed system.

6 Conclusion

This paper proposed a fuzzy logic based approach to classification and identification of isolated power distribution network. It was demonstrated that the proposed system is able to identify the phase(s) involved in all ten types of shunt faults that may occur in an electric power distribution system and to use this information to perform fault classification. The proposed method uses three line voltages, available at the substation as input variable and returns the fault code as the output variable. The input data (voltage waveforms) are generated in simulations performed on a model of realistic distribution system in Bosnia and Herzegovina.

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