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FAULT DIAGNOSIS AND IDENTIFICATION IN THE DISTRIBUTION NETWORK USING THE FUZZY EXPERT SYSTEM

IDENTYFIKACJA I DIAGNOZA BŁĘDÓW W ELEKTROENERGETYCZNEJ SIECI ROZDZIELCZEJ Z WYKORZYSTANIEM ROZMYTEGO SYSTEMU EKSPERCKIEGO

In this paper, a fuzzy expert off-line system has been developed for fault diagnosis in the distribution network based on the structural and functional operation of the relay and circuit breakers. Functional operations (correct operation, false operation and failure to operate) of the relays and circuit breakers are described by fuzzy logic. Input data for the proposed fuzzy expert fault diagnosis system (FDS) are status and time stamps of the alarms, associated with relays and circuit breakers. The diagnostic system from a huge number of alarms sets, logically organizes and quantifies the diagnosis. FDS can diagnose correct operation, false operation and failure to operate of the relays and circuit breakers. Also, it can identify and quantify fault location based on the Hamacher's operator of a fuzzy union. The additional contribution of this paper is in modeling unknown information using linear fuzzy membership function. Statuses of certain components may be unknown due to telemetry failures or are simply unavailable to the operator and proposed FDS can make diagnosis in such a situation. Developed fuzzy expert FDS is tested on the two examples of faults in real life distribution network.

Keywords: *fault diagnosis, alarm processing, fuzzy logic, expert system, distribution network.*

W prezentowanym artykule opracowano rozmyty system ekspercki typu off-line do diagnozowania błędów w elektroenergetycznej sieci rozdzielczej. System bazuje na strukturze i działaniu przekaźnika i wyłączników automatycznych. Działanie (prawidłowe działanie, błędne działanie i brak działania) przekaźników i wyłączników opisano za pomocą logiki rozmytej. Dane wejściowe do proponowanego rozmytego eksperckiego systemu diagnostyki błędów (FDS) stanowią stany i sygnatury czasowe alarmów, związane z przekaźnikami i wyłącznikami. System diagnostyczny logicznie porządkuje i określa ilościowo diagnozę na podstawie ogromnej liczby zestawów alarmów. FDS pozwala zdiagnozować prawidłowe działanie, błędne działanie oraz awarię (brak działania) przekaźników i wyłączników. Ponadto umożliwia identyfikację i lokalizację błędów w oparciu o sumę Hamachera. W artykule dodatkowo omówiono metodę modelowania informacji nieznanych przy użyciu liniowej funkcji przynależności dla zbiorów rozmytych. Stany niektórych elementów mogą być nieznane z powodu awarii telemetrii lub mogą być po prostu niedostępne dla operatora. Proponowany FDS umożliwia postawienie diagnozy w takich sytuacjach. Opracowany rozmyty ekspercki FDS testowano na dwóch przykładach błędów powstałych w funkcjonującej sieci rozdzielczej.

Słowa kluczowe: *diagnoza błędów, przetwarzanie alarmów, logika rozmyta, system ekspercki, sieć rozdzielcza.*

1. Introduction

Nowadays, electric power systems around the world are becoming more and more complex, and their operation is often close to their limits. Uninterrupted supply of electricity is an important factor influencing a series of events and relationships within the society itself. Disruption of the power systems caused by faults results in significant financial damage due to unsupplied electricity (possible consumers' lawsuits for damage caused by interruption of electricity supply). One of the ways of dealing with the mentioned problems is automating and systematically handling of the information which help power system operators make the right decisions. The nature of this type of problem is diagnostic, and the general term is a failure diagnosis. According to Sekine [26], ″fault diagnosis of power systems involves identifying the location and cause of faults occurring in the power system due to lightning strokes, and so on″. With occurrence of a few hundred alarms in a short period of time, the situation for a power system operator is complicated and it is very difficult to find a section of a failure and a cause of a failure. This prevents the operator from reacting in a proper way and to establish initial topology of the network thus making operator's assumptions erroneous. Due to such situations, various methods for analysing the alarms are used. In order to assist operators in making decisions and diagnosis, automated fault-diagnosis and decision-making systems are being developed. Off-line systems for the diagnosis of faults are primarily developed. On-line systems for fault diagnosis, often called alarm processing, is developed from the off-line systems [29]. Interesting examples of fault diagnosis in complex systems can be found in the literature [6, 8, 10]. Modern online diagnostic systems work in the form of advanced DMS (Distribution System Management) applications. The current situation in the Croatian distribution system is such that most diagnostics are carried out by the operator (human) on the basis of received alarms that are generated in the case of the fault. In many parts of the distribution network, equipment is not connected to the local dispatching centre and operators are often faced with a lack of information. The first step towards the establishment of a modern on-line diagnostic system is a communication connection of all relevant equipment with a control center. This is the way towards the development of the so-called smart grid where it will rely less and less on the network operator response and failures will be addressed through a network self-recovery.

Artificial Intelligence (AI) has proven to be successful in solving diagnosis problems when compared to traditional numerical methods [32]. Expert systems (ES) are one of the AI methods which are commonly used to solve these problems. They use and import methods developed in the area of qualitative reasoning [13]. ES possesses a lack of generality in an application for failure diagnosis and restoration, which is not considered as a negative characteristic in such an extensive and combinatorial problem, since the system requires: understanding, flexibility and high performance [18]. ES emulates the solution, which means that the solution can be closer to the reality than the solution obtained by simulation [11]. However, some problems remain, such as shortcomings or complete lack of information, quantifying fault identification and black-and-white thinking. For such a type of problem, fuzzy rule-based expert systems are suitable.

In [12] fuzzy set is developed to deal with the uncertainty involved in the process of locating faults in distribution networks. The fuzzy set theory has been introduced as a mechanism to incorporate uncertainties and qualitative judgments in the status of relays and circuit breakers as well as correctness or incorrectness of their operations in the research papers [4, 20]. An integrated fuzzy expert system is presented in [15] to diagnose faults in a transmission network and substations. Besides the application in power system, fuzzy expert systems are widely used for diagnosing problems in many fields [1]. Methods by which researchers are trying to overcome the shortcomings of fuzzy expert systems are: artificial neural networks (ANNs) combined with the fuzzy logic systems [3, 24], genetic algorithms (GA) [2, 14], fuzzy Petri net [34], mixed integer programming model [21], multi-agent systems [25] etc. A detailed review of articles on intelligent systems used for fault diagnosis in transmission networks can be found in the literature [7]. On the other hand, trends in the fault diagnosis in distribution systems include systems with distributed generation (photovoltaics, wind generation etc.) [17, 27, 28, 30, 33, 35, 36].

Based on the literature review, it can be concluded that most commonly used methods for fault diagnosis in distribution networks include expert systems, neural networks (NN), fuzzy logic (FL) and genetic algorithms (GA). The strengths of the ES are in the representation of expert knowledge and the interpretation of causative-consequence relationship. The shortcomings of the ES are in the lack of generality, inability to learn and adapt. On the other hand, NN and GA are superior in the case of learning and adapting and dealing with uncertainty and missed data. The disadvantages of NN and GA lie in poor expert knowledge representation and interpretation. The FL is very good in dealing with uncertainty and missed data while it is weaker regarding learning and adapting. Research trends show that solutions related to fault diagnosis in the distribution network are found in the hybridization of different methods in order to combine the strengths of each method and overcome weaknesses. A combination of ES and FL has been shown to be effective and it is chosen in this paper.

It is noticed that fuzzy expert systems developed in [4, 12, 15, 20] for fault diagnosis use information only in the form of relays and circuit breakers (CBs) status and they do not use the alarm time stamp. Also, the expert base of knowledge are not shown by the functional activity of the relay and CB. In this paper, a model for functional activity of the relay and the circuit breaker, described by fuzzy logic, is presented and incorporated in off-line fault diagnosis system (FDS) for application to electric distribution system. Fuzzy expert FDS uses relay and CB statuses and their timestamps as input data. The diagnostic system sets, logically organizes and quantifies the diagnosis from a huge number of alarms. Developed fuzzy expert FDS successfully diagnoses the correct operation, false operation and failure to operate of the relay and CB. It also has the ability to locate and quantify the fault on the basis of the operator of the fuzzy union, which is expressed as Hamacher's union operator [37]. Locating and quantifying the fault refers to finding a section of distribution network which is faulted and quantifying this diagnose with a certain probability. In addition, it also successfully deals with telemetry breakdowns by using a new way of modeling non-existent information using a linear time-dependent fuzzy membership function. Since faults in telemetry, noise or lack of connection can make certain statuses of relays or CBs unknown, modeling of non-existent information enables successful diagnosis even in these cases. Developed fuzzy expert FDS is tested on the two examples of faults in real life distribution network.

The structure of this paper is as follows: first, a detailed mathematical description of the developed fuzzy expert FDS is done in Section 2. Modeling of the real-life distribution network is briefly described in Section 3. In Section 4, examples of the diagnoses for the real-life events are presented. Short conclusion and comments are made at the end of the paper.

2. Mathematical description of the developed fuzzy expert FDS

2.1. General description of the model

The flow chart diagram of a developed fuzzy expert FDS is shown in Fig. 1. The diagram starts with the input data relating to the alarms with their statuses and time stamps. Alarms used for fault diagnosis are related to relays and CBs and they consist of statuses and time stamps. Data are in linguistic and numerical form. The linguistic form describes component status (for example relay is activated or relay starts) - R_{start}, relay trip - R_{trip}, circuit breaker open – CB_{open} and circuit breaker closed – CB_{closed}). Numerical form is time-stamp.

The input data are then transferred to the expert knowledge database which is composed of the three parts: the network model, the fuzzy expert database for relays and the fuzzy expert database for circuit breakers. The network model is composed of individual sections. The expert databases for relays and CBs are modeled using fuzzy rules outlined by functional knowledge and causative-consequent mode of component functioning. Since it is not possible to make a diagnosis when only one component status is available (this can be often in practice), a nonexistent status is modeled. The part of the knowledge database is modeled with fuzzy rules that use the model of nonexistent information to model the functionality of components with one known and one unknown information. Thus developed fuzzy expert FDS can diagnose relay and CB operation even when only one status is known because it uses the model of nonexistent information.

After the expert knowledge databases (Fig. 1), the diagnosis of the relay and CB operation is made using fuzzy membership functions in order to diagnose the correct operation, false operation and failure to operate of the appropriate component. A detailed description of the used fuzzy rules can be found in the Chapters 2.2 and 2.3. Once, when the diagnosis of relay and CB operations are made, using Hamacher's fuzzy union operator, the last diagnosis is made i.e. the fault is identified and quantified.

The above-mentioned system can diagnose the correct operation, false operation and failure to operate of the relay and CB and it makes a quantitative diagnosis by the numerical amount of membership function in order to rank a different diagnosis thus helping the operator make the right decision.

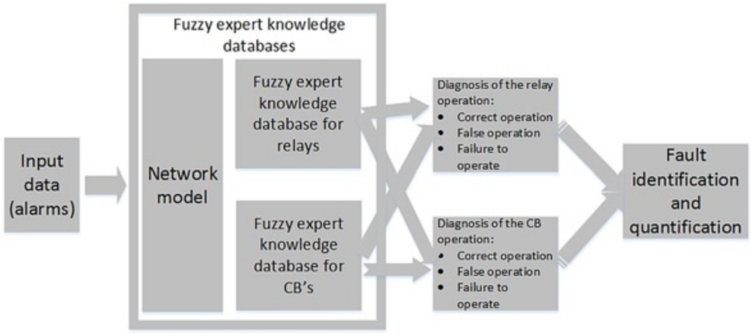


Fig. 1. Block diagram of the developed fuzzy expert FDS

2.2. Fuzzy model for the relay operation diagnosis

The functional operation of the relay is described by means of correct operation, false operation and failure to operate. Expressions (1) and (2) represent a functional description of these operations based on the cause and effect of the fault and related relay and are referred to as logical equations of operations [16, 22]:

$$R_{operate} = R_{start} \cap R_{trip} \quad (1)$$

$$R_{failure\_to\_operate} = R_{start} \cap N_o R_{trip} \quad (2)$$

where: $R_{operate}$ – correct operation of the relay, R_{start} – relay status when it is activated i.e. active relay status, R_{trip} – relay status when it trips, $R_{failure\_to\_operate}$ – failure to operate of the relay and N_0R_{trip} – non-existent trip status of the relay (the relay has not sent the signal for switch off to CB).

Relation (1) represents the correct operation of the relay which means that after the relay is activated R_{start} (at the moment t_{start} when fault occurs) it waits for a certain time and then at the moment that is defined by the so-called setup tripping time t_{sup} it sends the tripping signal R_{trip} to associated CB to open. In the practice, actual trip time of the relay t_{trip} can be slightly different from the set up time t_{sup} (most often t_{trip} is in the time interval ±10% of t_{sup}). Relation (2) is the failure to operate of the relay which means that relay is activated but it has not sent the signal to the circuit breaker. In this case, status R_{trip} is not available, thus the new non-existent trip status N_0R_{trip} is modeled. The second functional operation of the relay i.e. false operation means that relay tripped but outside of the allowed time interval. In practice most commonly allowed time interval is $0.9t_{sup} – 1.1t_{sup}$. This functional operation can't be modeled by previously introduced logical equations but it is modeled using fuzzy logic.

A new way of modeling the functional operation of the relay by fuzzy logic in the time domain is described by the following expressions:

$$\mu_{R\_operate}(t) = \mu_{Rstart}(t) \cap \mu_{Rtrip}(t)\ ,\ t \in \left(0.9t_{\sup}, 1.1t_{sup}\right) \quad (3)$$

$$\mu_{R\_false\_operation}(t) = \mu_{Rstart}(t) \cap \mu_{Rtrip}(t)\ , t \in \left[t_{start}, t_{sup}\right) \cup \left(t_{\sup}, 2t_{\sup}\right] \quad (4)$$

$$\mu_{R\_failure\_to\_operate}(t) = \mu_{Rstart}(t) \cap \mu_{NoRtrip}(t)\ , t \in \left[t_{start},\ \ t_1\right) \quad (5)$$

where: $\mu_{R\_operate}(t)$ – fuzzy membership function that represents the correct operation of the relay, $\mu_{Rstart}(t)$ – fuzzy membership function of the active relay status, $\mu_{Rtrip}(t)$ – fuzzy membership function of the trip relay status, t_{sup} – setup tripping time of the relay, $\mu_{R\_false\ operation}(t)$ – fuzzy membership function that represents the false operation of the relay, t_{start} – the time when relay is activated (relay activation time), $\mu_{R\_failure\ to\ operate}(t)$ – fuzzy membership function that represents the failure to operate of the relay, $\mu_{NoRtrip}(t)$ – fuzzy membership function of the non-existent trip status of the relay and t_1 – arbitrary chosen time which needs to be larger than double setup tripping time t_{sup}.

In order to obtain intersection of fuzzy sets, standard fuzzy intersection defined by the relation (6) is chosen in this paper:

$$\mu_{A \cap B} = \min(\mu_A, \mu_B) \quad (6)$$

where: μ_A – membership function of the fuzzy set A and μ_B – membership function of the fuzzy set B.

Fuzzy membership functions of the active relay status and trip relay status are modeled as trapezoidal shape membership functions. For the fault diagnosis in power system using fuzzy-expert systems, researchers mostly use triangular fuzzy membership function in order to model non-existent state (or alarm signal) [20]. In some other application, the constant membership function is also used [23]. For FDS developed in this paper, a new way of modeling non-existent information consists of using linear membership function (as time passes the value of the membership function to the non-existent state linearly increases) for relay non-existent trip status. The background of this model consists of a combination of deductive (logical) insertion, regression insertion and longitudinal insertion expressed in fuzzy logic and is based on the theory of missing data explained in [5, 31]. The fuzzy membership function of the non-existent trip status of the relay is defined:

$$\mu_{NoRtrip}(t) = \frac{t}{t_1} + a \quad (7)$$

where: a – is intersection of linear membership function and y-axes, $1/t_1$ is the slope of the liner membership function.

Unknown time stamp (unknown time t_n) of this non-existent relay signal can be found from:

$$t_n = \frac{\int_0^{t_1} t \cdot \mu_{NoRtrip}(t)\,dt}{\int_0^{t_1} \mu_{NoRtrip}(t)\,dt} \quad (8)$$

Correct operation of the relay is defined by the membership function $\mu_{R\_operate}(t)$ (relation (3)) which is equal to the standard fuzzy intersection of the relay active status membership function $\mu_{Rstart}(t)$ and relay trip status membership function $\mu_{Rtrip}(t)$ in the time interval of $\pm 10\%$ of the relay setup tripping time. Example of the fuzzy memebership function that describes correct operation of overcurrent protection of the relay is shown in Fig. 2. False operation of the relay is defined by the membership function $\mu_{R\_false\_operation}(t)$ (relation (4)) which is equal to the standard fuzzy intersection of the relay active status membership function $\mu_{Rstart}(t)$ and relay trip status membership function $\mu_{Rtrip}(t)$ in the time interval that starts with the relay activation time t_{start} and ends with double setup tripping time $2t_{sup}$. Because the value of membership function $\mu_{Rtrip}(t)$ in the moment $t=t_{sup}$ is one, setup tripping time t_{supp} is excluded from this time interval. Failure to operate of the relay is defined by the membership function $\mu_{R\_failure\_to\_operate}(t)$ (relation (5)) which is equal to the stan-

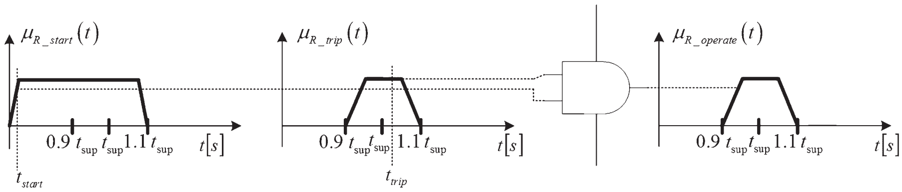


Fig. 2. Example of correct operation of the relay overcurrent protection relay

dard fuzzy intersection of the relay active status membership function $\mu_{Rstart}(t)$ and relay non-existent trip status membership function $\mu_{NoRtrip}(t)$ in the time interval that starts with the relay activation time t_{start} and ends with time t_1 which is arbitrary chosen time (it needs to be larger than double time t_{sup}).

2.3. Fuzzy model for the circuit breaker operation diagnosis

The relays and circuit breakers in the power system are causal-consequently connected due to their functional operation. During the fault, the relay sends signal R_{trip} to the circuit breaker to switch off (to open) and circuit breaker opens the faulted section (line, transformer etc.). The functional operation of the CB is described by means of correct operation, false operation and failure to operate. These actions are described by the logical equations (9-11) derived from the [16, 22]. All relations are combinations of relay status and CB status:

$$CB_{operate} = R_{trip} \cap CB_{open} \tag{9}$$

$$CB_{false\_operation} = N_O R_{trip} \cap CB_{open} \tag{10}$$

$$CB_{failure\_to\_operate} = R_{trip} \cap CB_{close} \tag{11}$$

where: $CB_{operate}$ – correct operation of the circuit breaker, CB_{open} – CB status when it opens or switch off (open status), $CB_{false\_operation}$ – CB false operation, $CB_{failure\_to\_operate}$ – failure to operate of the CB and CB_{close} – CB status when it close (closed status).

Relation (9) represents the correct operation of CB which means that CB opens when it receives the corresponding signal from the connected relay. Expression (10) represents the false operation of CB which means that CB opens without the signal from the connected relay. Expression (11) represents the failure to operate of CB which means that CB receives the signal from the connected relay but it doesn't open.

A new way of modeling the functional operation of the relay by fuzzy logic in the time domain is described by the following expressions:

$$\mu_{CB\_operate}(t) = \mu_{Rtrip}(t) \cap \mu_{CBopen}(t)\ ,\ t \in \left(0.9t_{\mathrm{sup}} + t_{CBopen}, 1.1t_{sup}\right) \tag{12}$$

$$\mu_{CB\_false\_operation}(t) = \mu_{NoRtrip}(t) \cap \mu_{CBopen}(t)\ ,\ t \in \left[0.9t_{\mathrm{sup}} + t_{CBopen}, t_1\right) \tag{13}$$

$$\mu_{CB\_failure\_to\_operate}(t) = \mu_{Rtrip}(t) \cap \mu_{CBclosed}(t)\ ,\ t \in \left(0.9t_{\mathrm{sup}}, 1.1t_{sup}\right) \tag{14}$$

where: $\mu_{CB\_operate}(t)$ – fuzzy membership function that represents the correct operation of the CB, $\mu_{CBopen}(t)$ – fuzzy membership function of the CB open status, t_{CBopen} – time needed CB to open, $\mu_{CB\_alse\_operation}(t)$ – fuzzy membership function that represents the false operation of CB, $\mu_{CB\_failure\ to\ operate}(t)$ – fuzzy membership function that represents the failure to operate of the CB, $\mu_{CBclose}\ (t)$ – fuzzy membership function of the CB closed status.

The fuzzy membership function of the open CB status is modeled as gamma membership function. Correct operation of the CB is defined by the membership function $\mu_{CB\_operate}(t)$ (relation (12)) which is equal to the standard fuzzy intersection of the relay trip status membership function $\mu_{Rtrip}(t)$ and CB open status membership func-

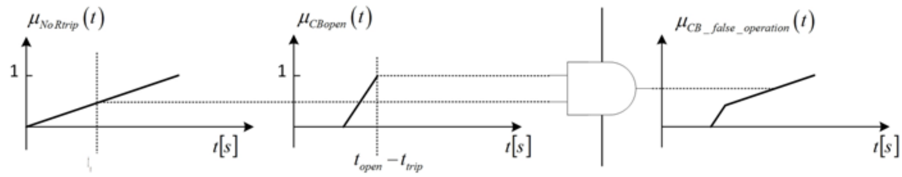


Fig. 3. Example of false operation of the CB

tion $\mu_{CBopen}(t)$ in the time interval that starts with $0.9t_{sup}+t_{CBopen}$ and ends with $1.1t_{sup}$. False operation of the CB is defined by the membership function $\mu_{CB\_false\_operation}(t)$ (relation (13)) which is equal to the standard fuzzy intersection of the relay non-existent trip status membership function $\mu_{NoRtrip}(t)$ and membership function of the CB open status $\mu_{CBopen}(t)$ in the time interval that starts with $0.9t_{sup}+ t_{CBopen}$ and ends with arbitrary chosen time t_1 (it needs to be larger than double tripping time t_{sup}). Failure to operate of the CB is defined by the membership function $\mu_{CB\_failure\_to\_operate}(t)$ (relation (14)) which is equal to the standard fuzzy intersection of the relay trip status membership function $\mu_{Rtrip}(t)$ and membership function of the CB closed status $\mu_{CBclosed}(t)$ in the time interval that starts with $0.9t_{sup}$ and ends with $1.1t_{sup}$. Example of the fuzzy membership function that describes the false operation of the CB is shown in Fig. 3. Fig. 3 shows that fuzzy membership function of the non-existent trip status of the relay is linear.

2.4. Fuzzy model for the fault identification and quantification

Fault identification is defined by the action of the relay and circuit breaker since their combination will protect a particular section or component in the electric distribution network. Knowing the information about the functional operation of the relay and/or circuit breaker, the faulted section of the network can be identified. The identification of the fault with proposed FDS is possible even when only one information is known. Nevertheless, if the information about both the relay and the CB are known, the probability that the failure occurred on a particular section that is protected with these specific relay and CB is greater than if only information for one component (CB or relay) is available. Fault identification and quantification using fuzzy logic are defined by the union of fuzzy sets of all CBs and all relays that are activated due to fault based on the expression [4, 12]:

$$\mu_{FDI}(t) = \mu_{R\_operate}(t) \cup \mu_{CB\_operate}(t) \tag{15}$$

where: $\mu_{FDI}(t)$ – fuzzy membership function that represents fault identification and quantification.

Fault identification presented with expression (15) is defined by the union of two fuzzy sets. Many alternative fuzzy union operators (t-conorms) are used for fault identification in electric networks. Standard fuzzy union operator (or maximum operator) is used in [4, 20]. Yager, Hamacher, Dubois and Dombi union operators are used in [19]. For FDS developed in this paper, Hamacher's union operator is chosen:

$$U(\mu_{R\_operate},\mu_{CB\_operate})=\frac{\mu_{R\_operate}+\mu_{CB\_operate}+(r-2)\cdot\left[\mu_{R\_operate}\cdot\mu_{CB\_operate}\right]}{r+(r-1)\cdot\left[\mu_{R\_operate}\cdot\mu_{CB\_operate}\right]} \tag{16}$$

where: $U(\mu_{R\_operate},\mu_{CB\_operate})$ – Hamacher's union of two fuzzy sets (first set is consisted of all relays that are activated due to fault and second set is consisted of all CBs that are activated due to a fault), r – is a positive number (r > 0) which is in this paper set to a value of 1.01.

3. Application of fuzzy expert FDS to the real distribution network

3.1. Model of the distribution network

The distribution network that is used as a model for developed fuzzy expert FDS is shown in Fig. 4 (part of 35 kV and 10 kV real distribution network in Croatia). The network consists of two 35 kV bus (B2 and B3) connected by a 35 kV transmission line (L2), two transformers 35/10 kV (T3 and T4), 10 kV bus (B4) and four 10 kV transmission lines (L3, L4, L5 and L6). The transmission line L2 (35 kV) is protected by the overcurrent (I>), short circuit (I>>) and earth fault protection (U_0I_0) incorporated in relay R1 that controls circuit breaker CB1. Circuit breaker CB2 is manual and it is not controlled by the any of the relays. The 35/10 kV transformers (T3 and T4) are protected by the overcurrent (I>) and differential (3DI) protection incorporated in relays R2 and R3 that control pairs of circuit breakers CB3-CB5 and CB4-CB6 respectively. 10 kV transmission lines (L3 – L6) are protected by the overcurrent (I>), short circuit (I>>) and earth fault protection (U_0I_0) incorporated in relays R4, R5, R6, and R7. These relays are connected to the appropriated circuit breakers (CB7, CB8, CB9, and CB10). Transformers in the 110/35 kV substation (T1 and T2) are the responsibility of the transmission system operator so their relays and circuit breakers are not considered in this paper. The time settings for the protection are shown in Fig. 4. The number of rules that are introduced in FDS for presented distribution network is 78. In this paper, only part of distribution network presented in Fig. 4 is modeled because this part makes one operational and functional section which is connected to one transmission transformer station (110/35 kV). This functional section is radially supplied from the transmission transformer station and is independent of the rest of the distribution network. The whole distribution network consists of many similar sections that are standard. In the practice, fault diagnosis is done for each section individually because the fault in one section doesn't affect other sections. Thus proposed FDS is tested for only one section. For the modeling fuzzy expert fault diagnosis system Prolog software tool is used.

3.2. Example of sagittal diagram for the test network

Sagittal diagrams were introduced for the first time in a power system fault diagnosis in 1997 [9]. They describe the causative consequence relationship of the alarm with the fault location. Most commonly, this causal connection is called the alarm path. In the background of the alarm path, there is a functional connection (cause-and-effect connection) of the fault and the relay and also of the relay and the CB. Sagittal diagrams represent a unified view of the alarm (membership function to a particular state) and fault identification.

Figure 5 shows the example of the sagittal diagram for the 10 kV transmission line L6 (see Fig. 4). The direction from the cause to the consequence goes from the left side to the right, marked by the arrow. The diagram consists of six functional operations; three of them are related to relays, and the remaining three are related to the CBs (correct operation, false operation and failure to operate).

The correct operation of the relay, false operation and failure to operate is shown for all three protections (overcurrent protection, short circuit protection and earth fault protection) that are incorporated in relay R7. Two alarms (states) are required for the diagnosis of functional operation, and these alarms are differently colored in Fig. 5. Light gray rectangles indicate the presence of these alarms on the alarm log, and diagnosis of the functional operation, in that

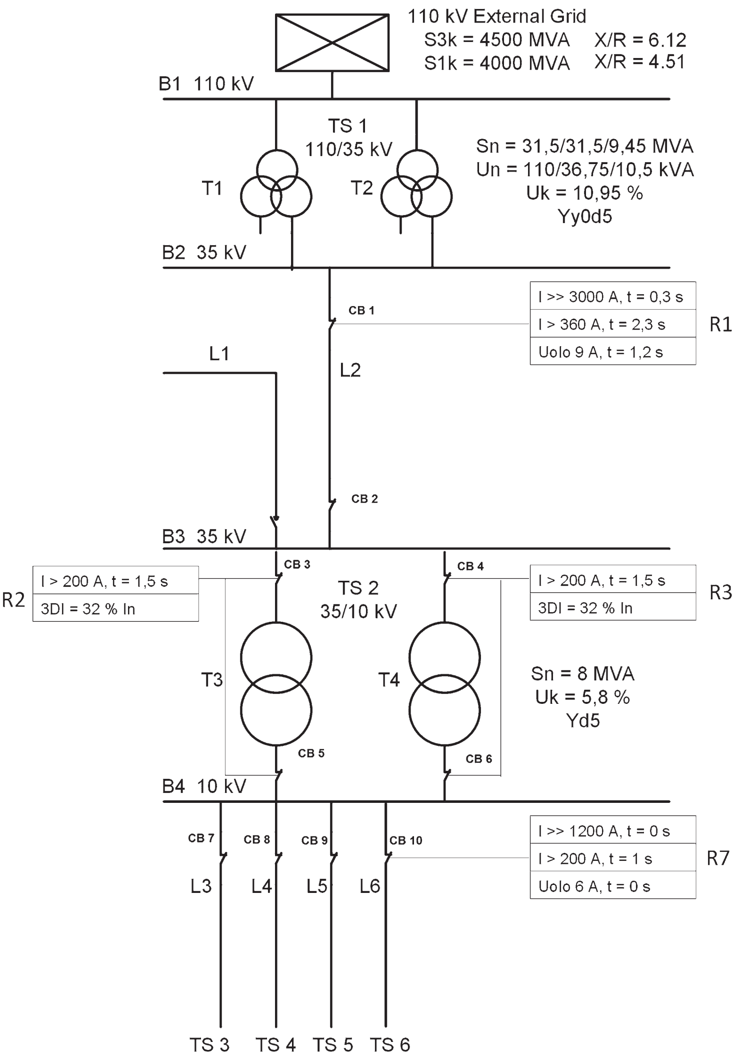


Fig. 4. Single line diagram of the analyzed distribution network

case, is simple. The situation is complicated when one of the necessary alarm is missing, which can happen in the actual distribution networks. In order to make diagnosis in such a situation, non-existent information is modeled as it is explained in section 2.2. Dark gray rectangles represent non-existent alarms (non-existent information;

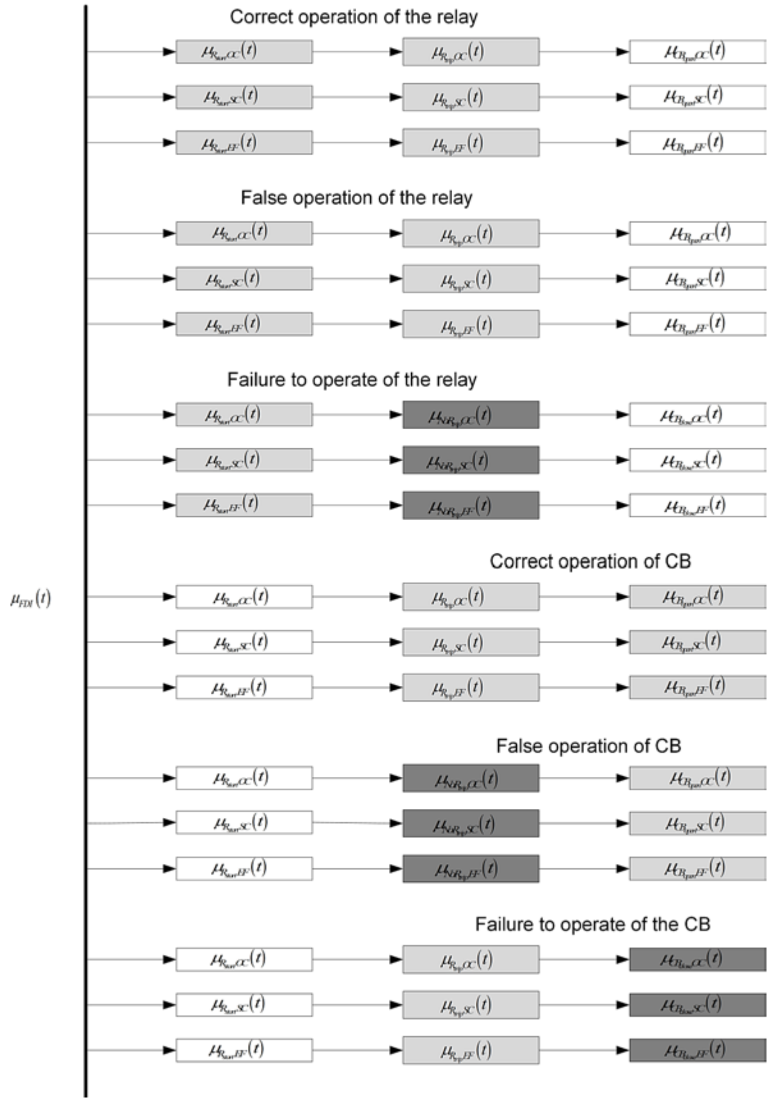


Fig. 5. Sagittal diagram for the line L6

membership function of non-existent state). White rectangles indicate alarms (state, membership function of the state) that are not used in diagnosis, and appear at the beginning or at the end of the alarm path.

From top to bottom in Fig. 5 the correct operation of the relay R7 is shown first. The diagram is further divided into three groups depending on the type of the associated protection: overcurrent (OC), short circuit (SC) and earth fault (EF). After the correct operation, false operation as well as failure to operate of the relay R7 are shown in Fig. 5. Relay R7 is connected to CB10 thus functional operations of CB10 are also shown.

4. Examples of the diagnosis for the real life events

Two examples of fault diagnosis for the real distribution network (Fig. 4) are shown in order to verify the developed FDS. The examples are based on the real-life events and they illustrate the possibilities and effectiveness of the proposed FDS. Fault activates the relay protection that isolates the faulted section by sending tripping to associated circuit breakers. Also, alarms are send to the dispatch center. There the operator can see the alarms through the SCADA system (Supervisory Control and Data Acquisition) which alongside having a possibility of remote management, measurement and control, also has a chronological events recorder (CER). The alarms that reach the dispatch center are visible in the CER and are retained there [38]. The operator needs to make decision how to reconfigurate the network and minimize the consequence of the faults (the intention is that the number of end consumers without the electricity due to fault is minimum while the network is repaired). Exact location of the faulted section is of vital importance for the quick intervention and developed FDS can help the operator in making decision. Actual fault diagnosis in the presented examples is done manually by the operator.

4.1. Example A

The fault occurs on the 10 kV transmission line L6 (actual fault location – AFL at Fig. 6a) and it started a series of alarms that are coming to the distribution network operator that are shown at Fig 7. The fault occurs due to the damage of insulator on a one 10 kV transmission line tower – it is single phase short-circuit.

After the fault occurs, overcurrent protection of the relay R7 reacts first (R_{trip}) and sends a signal to CB10 which opens (CB_{open}) after 47 ms. But overcurrent protection in relay R1 also reacts after 200 ms and sends a signal to the CB1 which opens after 60 ms. Two causes for this kind of events are possible: first, the fault is on the 10 kV line L6 (possible fault location – PFL1 at the Fig. 6a) and second, the fault is on the 35 kV line L2 (PFL2 at Fig. 6a). The operator starts the routine by disconnecting all the 10 kV lines (L3-L6) together with the associated end consumers and then starts to reclose all the equipment one by one in order to find the faulted section. This activated the whole sets of alarms that are shown in Fig. 7. The entire procedure lasted from 20:49:15 till 21:26:15 – approximately 37 minutes. As can be seen from the Fig. 7 at 10:26:15 the same four alarms appeared as in the beginning. This is the signal for the operator that faulted section was found. Fig. 7 shows original alarm list extracted

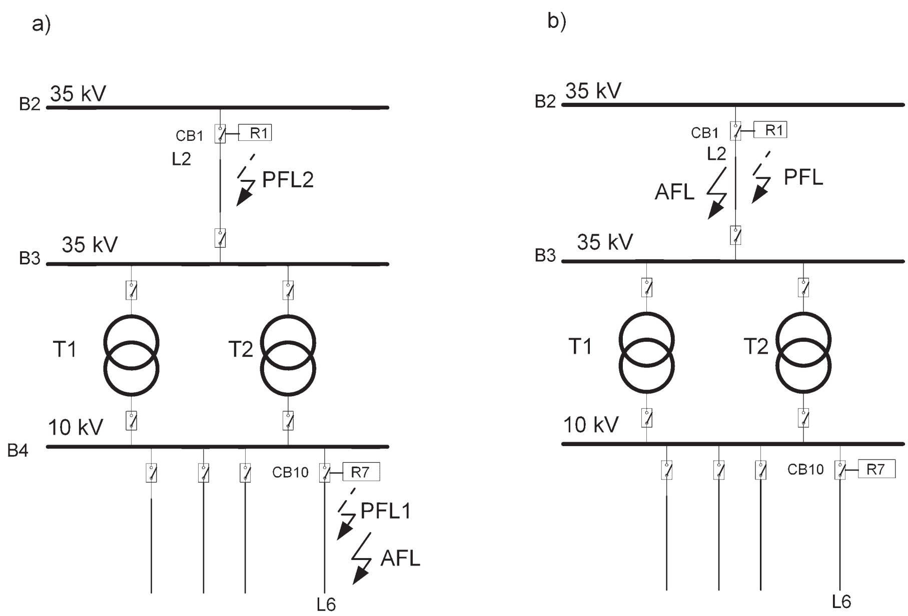
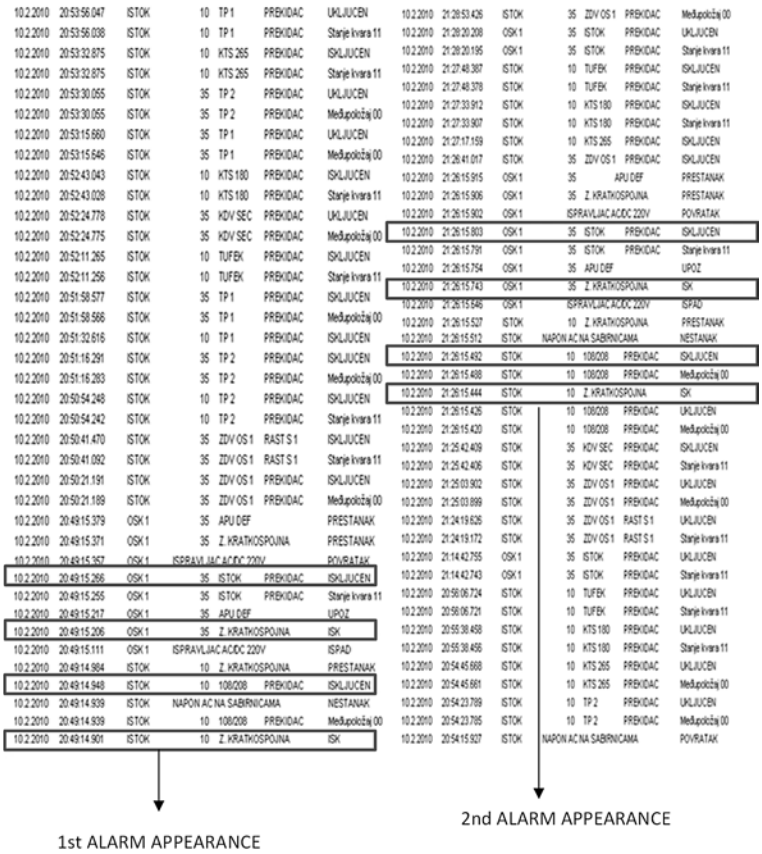


Fig. 6. Possible (PSF) and actual (AFL) fault locations for Examle A and Example B



10.2.2010	20:53:56.047	ISTOK	10	TP 1	PREKIDAC	UKLJUCEN
10.2.2010	20:53:56.038	ISTOK	10	TP 1	PREKIDAC	Stanje kvara 11
10.2.2010	20:53:32.875	ISTOK	10	KTS 265	PREKIDAC	ISKLJUCEN
10.2.2010	20:53:32.875	ISTOK	10	KTS 265	PREKIDAC	Stanje kvara 11
10.2.2010	20:53:30.065	ISTOK	35	TP 2	PREKIDAC	UKLJUCEN
10.2.2010	20:53:30.055	ISTOK	35	TP 2	PREKIDAC	Međupoložaj 00
10.2.2010	20:53:15.660	ISTOK	35	TP 1	PREKIDAC	UKLJUCEN
10.2.2010	20:53:15.646	ISTOK	35	TP 1	PREKIDAC	Međupoložaj 00
10.2.2010	20:52:43.043	ISTOK	10	KTS 180	PREKIDAC	ISKLJUCEN
10.2.2010	20:52:43.028	ISTOK	10	KTS 180	PREKIDAC	Stanje kvara 11
10.2.2010	20:52:24.778	ISTOK	35	KDV SEC	PREKIDAC	UKLJUCEN
10.2.2010	20:52:24.775	ISTOK	35	KDV SEC	PREKIDAC	Međupoložaj 00
10.2.2010	20:52:11.265	ISTOK	10	TUFEK	PREKIDAC	ISKLJUCEN
10.2.2010	20:52:11.256	ISTOK	10	TUFEK	PREKIDAC	Stanje kvara 11
10.2.2010	20:51:58.577	ISTOK	35	TP 1	PREKIDAC	ISKLJUCEN
10.2.2010	20:51:58.566	ISTOK	35	TP 1	PREKIDAC	Međupoložaj 00
10.2.2010	20:51:32.616	ISTOK	10	TP 1	PREKIDAC	ISKLJUCEN
10.2.2010	20:51:16.291	ISTOK	35	TP 2	PREKIDAC	ISKLJUCEN
10.2.2010	20:51:16.283	ISTOK	35	TP 2	PREKIDAC	Međupoložaj 00
10.2.2010	20:50:54.248	ISTOK	10	TP 2	PREKIDAC	ISKLJUCEN
10.2.2010	20:50:54.242	ISTOK	10	TP 2	PREKIDAC	Stanje kvara 11
10.2.2010	20:50:41.470	ISTOK	35	ZDV OS 1	RAST S 1	ISKLJUCEN
10.2.2010	20:50:41.092	ISTOK	35	ZDV OS 1	RAST S 1	Stanje kvara 11
10.2.2010	20:50:21.191	ISTOK	35	ZDV OS 1	PREKIDAC	ISKLJUCEN
10.2.2010	20:50:21.189	ISTOK	35	ZDV OS 1	PREKIDAC	Međupoložaj 00
10.2.2010	20:49:15.379	OSK 1	35	APU DEF		PRESTANAK
10.2.2010	20:49:15.371	OSK 1	35	Z. KRATKOSPOJNA		PRESTANAK
10.2.2010	20:49:15.357	OSK 1		ISPRAVLJAC AC/DC 220V		POVRATAK
10.2.2010	20:49:15.266	OSK 1	35	ISTOK	PREKIDAC	ISKLJUCEN
10.2.2010	20:49:15.255	OSK 1	35	ISTOK	PREKIDAC	Stanje kvara 11
10.2.2010	20:49:15.217	OSK 1	35	APU DEF		UPOZ
10.2.2010	20:49:15.206	OSK 1	35	Z. KRATKOSPOJNA		ISK
10.2.2010	20:49:15.111	OSK 1		ISPRAVLJAC AC/DC 220V		ISPAD
10.2.2010	20:49:14.984	ISTOK	10	Z. KRATKOSPOJNA		PRESTANAK
10.2.2010	20:49:14.948	ISTOK	10	108/208	PREKIDAC	ISKLJUCEN
10.2.2010	20:49:14.939	ISTOK		NAPON AC NA SABIRNICAMA		NESTANAK
10.2.2010	20:49:14.939	ISTOK	10	108/208	PREKIDAC	Međupoložaj 00
10.2.2010	20:49:14.901	ISTOK	10	Z. KRATKOSPOJNA		ISK

10.2.2010	21:28:53.426	ISTOK	35	ZDV OS 1	PREKIDAC	Međupoložaj 00
10.2.2010	21:28:20.208	OSK 1	35	ISTOK	PREKIDAC	UKLJUCEN
10.2.2010	21:28:20.195	OSK 1	35	ISTOK	PREKIDAC	Stanje kvara 11
10.2.2010	21:27:48.387	ISTOK	10	TUFEK	PREKIDAC	ISKLJUCEN
10.2.2010	21:27:48.378	ISTOK	10	TUFEK	PREKIDAC	Stanje kvara 11
10.2.2010	21:27:33.912	ISTOK	10	KTS 180	PREKIDAC	ISKLJUCEN
10.2.2010	21:27:33.907	ISTOK	10	KTS 180	PREKIDAC	Stanje kvara 11
10.2.2010	21:27:17.159	ISTOK	10	KTS 265	PREKIDAC	ISKLJUCEN
10.2.2010	21:26:41.017	ISTOK	35	ZDV OS 1	PREKIDAC	ISKLJUCEN
10.2.2010	21:26:15.915	OSK 1	35	APU DEF		PRESTANAK
10.2.2010	21:26:15.906	OSK 1	35	Z. KRATKOSPOJNA		PRESTANAK
10.2.2010	21:26:15.902	OSK 1		ISPRAVLJAC AC/DC 220V		POVRATAK
10.2.2010	21:26:15.803	OSK 1	35	ISTOK	PREKIDAC	ISKLJUCEN
10.2.2010	21:26:15.791	OSK 1	35	ISTOK	PREKIDAC	Stanje kvara 11
10.2.2010	21:26:15.754	OSK 1	35	APU DEF		UPOZ
10.2.2010	21:26:15.743	OSK 1	35	Z. KRATKOSPOJNA		ISK
10.2.2010	21:26:15.646	OSK 1		ISPRAVLJAC AC/DC 220V		ISPAD
10.2.2010	21:26:15.527	ISTOK	10	Z. KRATKOSPOJNA		PRESTANAK
10.2.2010	21:26:15.512	ISTOK		NAPON AC NA SABIRNICAMA		NESTANAK
10.2.2010	21:26:15.492	ISTOK	10	108/208	PREKIDAC	ISKLJUCEN
10.2.2010	21:26:15.488	ISTOK	10	108/208	PREKIDAC	Međupoložaj 00
10.2.2010	21:26:15.444	ISTOK	10	Z. KRATKOSPOJNA		ISK
10.2.2010	21:26:15.426	ISTOK	10	108/208	PREKIDAC	UKLJUCEN
10.2.2010	21:26:15.420	ISTOK	10	108/208	PREKIDAC	Međupoložaj 00
10.2.2010	21:25:42.409	ISTOK	35	KDV SEC	PREKIDAC	ISKLJUCEN
10.2.2010	21:25:42.406	ISTOK	35	KDV SEC	PREKIDAC	Stanje kvara 11
10.2.2010	21:25:03.902	ISTOK	35	ZDV OS 1	PREKIDAC	UKLJUCEN
10.2.2010	21:25:03.899	ISTOK	35	ZDV OS 1	PREKIDAC	Međupoložaj 00
10.2.2010	21:24:19.626	ISTOK	35	ZDV OS 1	RAST S 1	UKLJUCEN
10.2.2010	21:24:19.172	ISTOK	35	ZDV OS 1	RAST S 1	Stanje kvara 11
10.2.2010	21:14:42.755	OSK 1	35	ISTOK	PREKIDAC	UKLJUCEN
10.2.2010	21:14:42.743	OSK 1	35	ISTOK	PREKIDAC	Stanje kvara 11
10.2.2010	20:58:06.724	ISTOK	10	TUFEK	PREKIDAC	UKLJUCEN
10.2.2010	20:58:06.721	ISTOK	10	TUFEK	PREKIDAC	Stanje kvara 11
10.2.2010	20:55:38.458	ISTOK	10	KTS 180	PREKIDAC	UKLJUCEN
10.2.2010	20:55:38.456	ISTOK	10	KTS 180	PREKIDAC	Stanje kvara 11
10.2.2010	20:54:45.668	ISTOK	10	KTS 265	PREKIDAC	UKLJUCEN
10.2.2010	20:54:45.661	ISTOK	10	KTS 265	PREKIDAC	Međupoložaj 00
10.2.2010	20:54:23.789	ISTOK	10	TP 2	PREKIDAC	UKLJUCEN
10.2.2010	20:54:23.785	ISTOK	10	TP 2	PREKIDAC	Međupoložaj 00
10.2.2010	20:54:15.927	ISTOK		NAPON AC NA SABIRNICAMA		POVRATAK

Fig. 7. Original alarm list exctracted from the CER

from the CER and four important alarms are highlighted with the red rectangle. Detail analysis of the fault can be found in [38].

Table 1. Alarm list for the Example A

No	Status	Component	Possible fault location	Time
1.	R_{trip}	R7	L6	20:49:14.901
2.	CB_{open}	CB10	L6	20:49:14.948
3.	R_{trip}	R1	L2	20:49:15.206
4.	CB_{open}	CB1	L2	20:49:15.266

Out of a whole range of alarms (see Fig. 7), only four are relevant for FDS and they are shown in Table 1 together with their statuses, time stamps, component, and location.

Table 2. Diagnose results for the Example A

Diagnose	Membership function
Correct operation of CB10	0.8879
Correct operation of CB1	0.6796
Fault identification on L6	0.8879
Fault identification on L2	0.6796

Developed fuzzy expert FDS can help the operator to make the right decision in uncertain situations, such as in Example A. After the statuses and time stamps of the alarms (shown in Table 1) are entered in FDS, diagnosis results are obtained and presented in Table 2.

Finally, in order to decide at which location (L6 or L2) the fault occurred, the maximum selection criterion is used: based on the results from Table 2, most probable fault location is 10 kV line L6.

Comparing the time needed to diagnose a faulted section when using the proposed FDS and without it (when the diagnosis is performed by the operator manually) it can be concluded that the proposed FDS shortens the diagnosis time because the FDS needed only a few seconds for diagnosing while the operator needed 37 minutes.

4.2. Example B

Unlike Example A where the fault occurred at one location and four relevant alarms arrived, in Example B there was also fault at one location but only one alarm arrived at the operator. The actual location of the fault is 35 kV line L2 (AFL in Fig. 6b). The alarm that arrived is shown in Table 3. It is connected with short circuit protection of the relay R1 (R_{start}).

Table 4. Diagnosis results for the Example B

Diagnose	Membership function
Failure to operate of relay R1	0.663
Fault identification on L2	0.663

From the alarm in Table 3, it can only be concluded that the possible fault refers to the 35 kV line L2 but it is impossible to make a diagnosis about the relay operation with only one status known. Thus unknown trip status is modeled ($N_O R_{trip}$) as it is explained in Section 2.2. Diagnosis results are presented in Table 4.

Based on the results, the operator can conclude, that relay R1 most probably failed to operate (it didn't send a signal to CB1) and that actual fault was on the 35 kV line L2. Diagnosis is made only with one available alarm and its probability is 66.3%.

Table 3. Alarm list for the Example B

No	Status	Component	Possible fault location	Time
1.	R_{start}	R1	L2	14:23:17.129

4. Conclusion

This paper presents the fuzzy expert fault diagnosis system (FDS) for application to distribution networks. Alarms with their statuses and time stamps are used as an input data for diagnosis of correct operation, false operation and failure to operate of the relays and circuit breakers. In the next step, using Hamacher's fuzzy union operator, the diagnosis of the fault identification and quantification is done. The advantage of the proposed FDS is that it is able to make a diagnosis in a situation when only one information is known by modeling the unknown information using a linear fuzzy membership function. The usability of the developed FDS is presented in two examples of the fault diagnosis of the actual events in the real-life distribution network. The first example illustrates the situation when arrived alarms indicate two fault locations and it is necessary that operator makes the decision and chooses the right fault location. The second example illustrates the situation when only one alarm is available and the diagnosis is made using fuzzy modeling of unknown information. Further research and development of the proposed fuzzy expert FDS will seek to complete the diagnosis with other types of information. Further testing of developed FDS will be done on a technically more advanced distribution network which contains fault indicators and digital fault recorders. For that case, new information will be added to the FDS such as statuses of fault indicators as well as currents and voltages of digital fault recorders. There are possibilities to include non-electrical data such as

GPS location data. Also, the FDS will be upgraded in order to make a diagnosis in the distribution networks with a high penetration level of distributed energy sources (like photovoltaic power plants etc.).

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