Real-Time Circuit Breaker Availability Assessment in the Transmission Network

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Abstract: Circuit breakers (CBs) in the transmission network are the basic elements for energy flow control. CB diagnosis represents a decisive action for increasing power system reliability and safety. Their actual availability status and ability to perform major functions can sometimes be difficult to determine. This paper presents a general state estimation model based on fuzzy logic (FL), membership function (MF), and expert knowledge for diagnosis schemes to handle unclear information in the diagnosis procedure. The proposed model uses inputs from the Supervisory Control and Data Acquisition (SCADA) system, data on the position and state of the switch, changes in current in the network element CB (NECB), start or trip action of a protection relay on the NECB, and alarm status of the CB. For the diagnostic system input variables, data from the SCADA system, along with transformer and line protection devices, are used to allow the proper formation of rules and ultimately to determine the diagnostic status of the CB. The proposed method is tested on an authentic test power system, and the outcome results are compared with a previously reported technique. The obtained test results and the comparison prove the efficiency, authenticity, and fast operation feature of the suggested strategy.

Keywords: circuit breaker (CB); CB diagnosis; fuzzy logic

1. Introduction

The electrical power system is expanding and getting more complex throughout all its sectors—power generation, transmission and distribution, and load systems. Faults in the system, such as short circuits, result in potential economic loss and a reduction in power system reliability. A power system fault is an unexpected condition caused by equipment breakdowns such as transformers and generators, human errors, and unwanted environmental circumstances. This paper presents a new method for determining the availability of a circuit breaker state in real-time with a solution to the problems that have not been solved so far, and thus provides a significant increase in the security of the power system. These faults cause electric flow disruption, equipment damage, bird and other animal deaths, and even possible human casualties. A substantial body of scientific work deals with the problem of determining faults in the power system and the characteristics of these faults concerning their impact on system availability [1–5]. Some papers describe the location function and methods for determining the state of circuit breakers in the power system [6–9]. Many researchers do not address the problem of diagnosing the breaker state and its availability to perform a function in the likelihood of an undesirable event [10–14]. Only few papers determine the breaker availability or fault section availability using fuzzy logic but not in real-time [15–19]. It is important to note here that there are various methods for measuring phasor voltages or currents, the implementation of which could have high accuracy in determining the available switch states. These data and methods were not available to the authors when designing the
application for the necessary determination of real-time CB availability, and thus only data from the SCADA system and protection devices should be used. Some researchers have engaged in power system fault detection [20–26], and some have engaged in fault modeling in the power system. Most of the fault detection techniques have exploited artificial intelligence (AI)-based techniques [20,23–25], and among them, some methods have performed fault diagnosis using fuzzy logic [27,28].

This paper tries to address the problems of determining the diagnostic state of high-voltage circuit breakers using fuzzy logic with the help of information from SCADA systems and protection devices in real-time network events, consequently increasing the safety and reliability of the whole power system. The authors provide a new fuzzy logic method and procedure overview for determining the availability of CBs, which can be applied and used in any transmission or distribution network.

Expert (authors) knowledge and experience in the field of CB availability examination are used in the entire fuzzy logic implementation process. The availability of each element of the grid, and thereby the system as a whole, could be improved with the CBs state availability assessment. The importance of the presented method is even more significant if implemented in a real-time environment. An adequate selection of faulty network elements, as well as increased security and reliability of the entire power system, is the expected contribution of the presented method.

Additionally, keeping a faulty CB in operation in the event of a fault on a network element, and due to the inability of the CB to operate, could lead to nonselective tripping of other network parts. This can significantly reduce the security and reliability of a network element, part of the network, and the power system as a whole. For the calculation of the safety and reliability of the power system to be adequate, it would have to cover countless possible and specified individual cases on a specific part of the network, and the same could not be carried out due to the content, topic, and interests of this paper. We exploit fuzzy MFs to handle the uncertainties of the information used in the diagnosis process and use the expert knowledge of an individual to determine the availability of a CB state to fulfill its function. The required data (including changes in current on the NECB, position and switch state, CB alarm status, and star or trip action of a protection relay on the NECB) are acquired from the SCADA system and system, along with transformer and line protection devices. We also propose a real-time strategy to determine the availability of the CB state and test it on an authentic test power system. Additionally, the suggested strategy is compared with a previously reported method to show its efficiency, authenticity, fast operation, and superiority over other techniques.

The rest of this paper is organized as follows: Section 2 presents the state estimation model of the grid concerning the CB status. Section 3 presents the possibility of determining the breaker state in various events in the transmission network. Furthermore, Section 3 provides a parameter view and a fuzzy regulator display for the determination of the circuit breaker availability in the Croatian transmission network. Section 4 presents the variable inputs of the decision-making and conclusion process for the fuzzy regulator and a test example of the real-time events in a real transmission network. Real-life practical test results are elaborated on in Section 5. Discussions are elaborated on in Section 6. Finally, conclusions are stated in Section 7.

A complex analytical approach for the solution of the given problem is given in the next section.

2. State Estimation Model

2.1. Conventional Model

In conventional state estimation, the topology processor determines the bus/branch network model based on topological measurements (statuses of switching devices). Afterwards, analog measurements are processed to estimate the bus voltages [29].
The conventional state estimation model is built by merging bus sections with closed circuit breakers. For an $N$-bus system and an $m$ measurement set, the model is given as [29,30],

$$z = h(\mathbf{x}) + \mathbf{v}$$

$$E(\mathbf{v}) = 0; \text{and } E(\mathbf{v}\mathbf{v}^T) = \mathbf{R}$$

(1)

(2)

where $\mathbf{x}$ is a $n \times 1$ nodal state vector or the set of state variables with $n$ variables. In power system representations, it generally consists of node voltage magnitudes and phase angles. The function $h(\mathbf{x})$ is a nonlinear function relating measured quantities and states, and $\mathbf{v}$ is a random vector representing normally distributed measurement errors. Each error is supposed to have zero mean, represented in (2). The set $z$ represents $m$ measured variables that generally consist of node active and reactive power flows in nodes and branches and node voltage magnitudes and phase angles (the set $\mathbf{x}$). $E$ represents the expectation operator and $\mathbf{R}$ diagonal covariance matrix ($m \times m$) of the measurement errors. The diagonal terms of $\mathbf{R}$ represent the square of the standard deviation of the measurements. The exponent $^T$ represents the transpose of the given sent.

$Z$ consists of bus voltages, branch power flows, and injections. The estimate of the error measure $\hat{x}$ is obtained by

$$J(\mathbf{x}) = [z - h(\mathbf{x})]^T \mathbf{R}^{-1} [z - h(\mathbf{x})]$$

$$\frac{\partial J(\hat{\mathbf{x}})}{\partial \mathbf{x}} = 0$$

(3)

(4)

where $\mathbf{R}$ minimizes the weighted least-square function $J$. The minimization of the scalar $J$ represents the optimum of $\hat{\mathbf{x}}$.

The estimate $\hat{\mathbf{x}}$ is computed by solving

$$G(x^k) \Delta x^k = H^T(x^k) R^{-1} \Delta z^k, \ k = 0, 1, 2, \ldots$$

$$\Delta x^k = x^{k+1} - x^k$$

$$\Delta z^k = z - h(x^k)$$

$$H = \frac{\partial h}{\partial \mathbf{x}}$$

(5)

(6)

(7)

(8)

where $H$ is the $m \times n$ Jacobian matrix of $h(x)$.

The $n \times n$ gain matrix is given by

$$G(x^k) = H^T(x^k) R^{-1} H(k^x)$$

(9)

where $n$ is the number of state variables $n = 2N - 1$. The state estimator outputs a database from which any number of other devices and functions can be fed.

2.2. Probabilistic Model

The probabilistic model defines the state of CBs. Let $X_{nm}$ be a discrete random variable that defines the state of circuit breakers n-m with the relation $X_{nm} = 1$—breaker closed and $X_{nm} = 0$—breaker opened.

The probability function of $X_{nm}$ is

$$P(X_{nm} = 1) = s_{nm}$$

$$P(X_{nm} = 0) = 1 - s_{nm}$$

(10)

(11)

where $P$ represents probability, and $S_{nm}$ is a continuous variable ranging from 0 to 1.
The expected variance of $X_{nm}$ is given by

$$\text{Var}(X_{nm}) = s_{nm}(1 - s_{nm})$$  \hspace{1cm} (12)

If the circuit breakers status can be correctly assumed ($S_{nm} = 1$ or $S_{nm} = 0$ for closed and opened breakers, respectively), the following equation can be derived:

$$(1 - s_{nm})P_{nm} = 0$$  \hspace{1cm} (13)

$$(1 - s_{nm})Q_{nm} = 0$$  \hspace{1cm} (14)

$$s_{nm}\delta_{nm} = 0$$  \hspace{1cm} (15)

$$s_{nm}V_{nm} = 0$$  \hspace{1cm} (16)

where $P_{nm}$ and $Q_{nm}$ represent active and reactive power flow and $\delta_{nm}$ the n-m angle difference. If (13)–(16) are not true, the status of the breakers is not certain.

2.3. Generalized Model

In the generalized state estimation model, parts of the grid are modeled at the bus CB level. The conventional measurement model (1) is extended with the addition of the CBs status. Additionally, modeling of the switch facilitates the analysis when incorrect switch states occur. For each CB, voltage angles and magnitudes ($\delta_{nm}$, $V_{nm}$), active and reactive power flow ($P_{nm}$, $Q_{nm}$), and probability ($s_{nm}$) to be closed are taken into account as additional state variables [29,30].

For every CB, we add:

- measurement equations based on CB status
  - CB closed:
    $$0 = \delta_{nm} + v_{\delta}$$  \hspace{1cm} (17)
    $$0 = V + v_{V}$$  \hspace{1cm} (18)
  - CB opened:
    $$0 = P_{nm} + v_{P}$$  \hspace{1cm} (19)
    $$0 = Q_{nm} + v_{Q}$$  \hspace{1cm} (20)

- Equations based on the probabilistic model (21)–(24)
  $$0 = s_{nm}\delta_{nm} + v_{\delta}$$  \hspace{1cm} (21)
  $$0 = s_{nm}V_{nm} + v_{V}$$  \hspace{1cm} (22)
  $$0 = (1 - s_{nm})P_{nm} + v_{\delta P}$$  \hspace{1cm} (23)
  $$0 = (1 - s_{nm})Q_{nm} + v_{\delta Q}$$  \hspace{1cm} (24)

- CB status equations
  $$s_{nm}^m = s_{nm} + v_{s}$$  \hspace{1cm} (25)

where $s_{nm}^m$ is the measured status of CBs n-m. Therefore, flow through the breakers can be written by:

$$P_{nm}^m = P_{nm} + v_{P}$$  \hspace{1cm} (26)

$$Q_{nm}^m = Q_{nm} + v_{Q}$$  \hspace{1cm} (27)
3. Determining CB State, Variable Definition and the Display of a Fuzzy Regulator

The general assumption this method uses is that the substation communicates via the SCADA system and that the information from both the SCADA system and the protection devices can be used for exploitation. The Supervisory Control and Data Acquisition (SCADA) system is used for control, communication efficiency to send/receive data, and overall smarter decision making. It monitors the system based on information from event listings, chronology, alarms, changes in circuit breaker states, starts and trips of protection devices, and changes in voltages and currents. The information processing draws on the necessary expertise to analyze it. These properties will be used to determine the relationship between the state determination and the occurrence of a fault on the CB in the transmission network based on fuzzy logic.

Modern SCADA systems are very complex. Figure 1 shows a schematic diagram where information is provided to make decisions about the condition and availability of equipment and thus the circuit breaker when operating the power system.

![Schematic diagram of the decision-making process of the breaker diagnostic state.](image)

Figure 1. Schematic diagram of the decision-making process of the breaker diagnostic state.

For complex faults, due to the large number of different errors that can occur in network events, determining the correct state of the breaker or its network fault status is a great challenge.

Determining the diagnostic state of a breaker and its availability at a power system event is a very complex and demanding task. In a power network event, almost all of the breakers’ faults can be described by changes in some of the key variables:

- Change in the CB state in a branch;
- Change in the flow or value of the current on some elements of the network;
- Start or trip of a protection device;
- Switch alarm status.

In real-life situations and practical applications, with the use of a fuzzy regulator, these four parameters associated with information represent the necessary and sufficient information for the proper allocation of the breaker state at network events.

The use of MFs, the development of conclusion rules, and ultimately the decision making and concluding in conduction of the complex process of determining the diagnostic state of a breaker are based on the operator’s knowledge and experience. Figure 2 shows a decision system that uses FL to determine the specified state. Both Figures 1 and 2 show the decision-making process. Figure 2 shows the specific SCADA data in detail, while Figure 1 shows the process from a higher level and with all of the needed information obtained.
This decision-making process is based on four input variables of fuzzy systems. Each of the input variables is divided into several ranges of values and together they represent the input variables of the fuzzy regulator [31,32].

For binary relations, a binary fuzzy variable \( R \) with the value \( R(X,Y) = 1 \) implies that the truth of \( X \) suggests the truth of \( Y \). On the contrary, \( R(X,Y) = 0 \) implies that there is no inference between \( X \) and \( Y \). The union of two fuzzy sets is stated generally by a function as follows:

\[
\mu : [0,1] \times [0,1] \rightarrow [0,1] \tag{28}
\]

The function uses a combination consisting of the element’s membership grades in the set as its argument and generates the membership grade of the element in the combination forming the union of \( A \) and \( B \) for each element in the universal set. Thus, we can write:

\[
\mu_{\tilde{A} \cup \tilde{B}}(x) = \mu[A(x), B(x)] = \max[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] \tag{29}
\]

The function specifies the general fuzzy intersection of two fuzzy sets \( A \) and \( B \) as:

\[
[0,1] \times [0,1] = [0,1].
\]

The argument of this function is a combination consisting of the membership grade of some component in set \( A \) and the membership grade of that same component in set \( B \). The function generates the membership grade of the element in set \( A \cap B \). Thus, we can write:

\[
\mu_{\tilde{A} \cap \tilde{B}}(x) = \mu[A(x), B(x)] = \min[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] \tag{30}
\]

In this paper, two fuzzy implication functions are used to derive that the section is faulty. For coordinative fuzzy relation, it uses the fuzzy implication, as the following shows:

\[
\tau(x_i \rightarrow y_i) = \max\left[\left(\mu_{\tilde{A}}(x_i) \cap \mu_{\tilde{B}}(y_i)\right), \left(1 - \mu_{\tilde{A}}(x_i)\right)\right] \tag{31}
\]

For binary fuzzy relation, it uses the standard sequence fuzzy implication, as (32)

\[
\tau(\tilde{x} \rightarrow \tilde{y}) = \begin{cases} 
1, & \mu_{\tilde{A}}(x_i) \leq \mu_{\tilde{B}}(y_i) \\
0, & \mu_{\tilde{A}}(x_i) > \mu_{\tilde{B}}(y_i) 
\end{cases} \tag{32}
\]

where \( A \) and \( B \) are fuzzy sets in the universes of discourse \( X \) and \( Y \). Let the MFs for \( A \) and \( B \) be \( a(x) \) and \( b(y) \), respectively.

4. Input Variables of Decision Making and Conclusion Process Based on Fuzzy Regulator

For a complete representation of the fuzzy regulator and its formation, it is paramount to conclude and describe its corresponding MF for each variable. The variables and equivalent MFs are shown below. These appropriate MFs are important for defining conclusion rules in making decisions.
4.1. Start or Trip of a Protection Relay on an NECB

The second input variable of the fuzzy regulator and its conclusion process is the value defined by the state of the start or trip of a protection relay on the NECB. Two conditions can occur:

- Unchanged state: no start or trip of a protection action in the network element;
- Changed state: start or trip of a protection action on the NECB.

Index N indicates no start or trip of a protection action, while D indicates a start or trip of a relay on the NECB.

For the unchanged state, the equivalent MF has a value of 0, and in the case of a changed state, the corresponding MF has a value of 1.

4.2. Change in NECB State

The first input variable of the system stands for the value defined by the breaker switch state shift on a network element. Two conditions can occur:

- Unchanged state: no change in the switch state on a network element;
- Changed state: there is an alteration in the switching state of a breaker on a network unit.

Figure 3 shows the MF for the variable of a switch state in the network unit. Unchanged state is represented in blue while the changed state is represented in red.

Index N indicates no change in the switch state, while D indicates a switch state change in CB.

For the unchanged state, the equivalent MF has a value of 0, and in the case of a changed state, the corresponding MF has a value of 1.

Figure 4 shows the MF for and input variable for the start or trip of a protection relay and the CB switch state.

4.3. Current Change on a Network Element

The sensitivity of the current change can be expressed by:

\[ \Delta I \]

where \( \Delta I \) denotes the current after an event or change and \( I_{\text{before}} \) denotes the current before an event or change on a given network trip of a relay on the NECB.

The sensitivity indexes of the current change.

4.4. Circuit Breaker Alarm State

The fourth input variable of the system is the state of a breaker alarm. To determine the alarm status indexes. The first input variable of the system constitutes the availability of a breaker or the existence of an alarm state on the breaker, it is important to determine conclusion rules in making decisions.

Figure 5 shows the MF for the breaker input state on a network element. In the case of an unchanged state, the corresponding MF has a value of 0. The intermediate position has a value between 0 and 1, representing the indefinite state of the breaker availability.

The MF has a value of 1. Figure 5 determines the corresponding MF.

Figure 3. MF of the start or trip of a protection relay and the CB switch state.

Index N indicates no start or trip of a protection action, while D indicates a start or trip of a relay on the NECB.

For the unchanged state, the equivalent MF has a value of 0, and in the case of a changed state, the corresponding MF has a value of 1.

Figure 4 shows the MF for and input variable for the start or trip of a protection relay and the CB switch state.

Figure 4. Membership functions of the absolute sensitivity of current change through a network element.
4.3. Current Change on a Network Element

The third input variable of the system is the change in the amount of current through the breaker or network element. To determine this change, it is important to determine the sensitivity indexes of the current change.

If \( |\Delta I| \) denotes the absolute value of the sensitivity of the breaker current change and the same is defined by the amount change and current flow in the network element to its relative state before that change and the current before that change on a given network element, then the absolute sensitivity of the current change can be expressed by [18]:

\[
|\Delta I| = \left| \frac{I_f - I_s}{I_s} \right|
\]

(33)

where \( I_f \) denotes the current after an event or change and \( I_s \) current before an event or before a value change.

The corresponding MF is shown in Figure 4, where NH stands for high negative sensitivity, L stands for low sensitivity, and PH stands for high positive sensitivity.

Then the MFs are determined by:

- If \( \Delta I >> 1 \), then the change in fault current is positively large;
- If \( \Delta I << 1 \), then the change in fault current is negatively large;
- If \( \Delta I = 1 \), then the current has small and slow changes

Where a significant, fast or slow-paced current change, with the above preconditions satisfied, determines the CB state availability, which is accepted in the fuzzy system conclusion rules.

4.4. Circuit Breaker Alarm State

The fourth input variable of the system is the state of a breaker alarm. To determine the availability of a breaker or the existence of an alarm state on the breaker, it is important to determine the alarm status indexes. The first input variable of the system constitutes the value defined by shifts in the breaker state in the network unit. Three states can appear:

- Unchanged switch state: no alarm indicating the breaker is not ready;
- Intermediate position: changes in switching the state of a breaker requiring verification;
- Unavailability of the switch to operate: the alarm state indicates unavailability.

Figure 5 shows the MF for the breaker input state on a network element. In the case of an unchanged state, the corresponding MF has a value of 0. The intermediate position has a value between 0 and 1, representing the indefinite state of the breaker availability. For an alarm state indicating unavailability for the breaker to operate, the corresponding MF has a value of 1. Figure 5 determines the corresponding MF:

![Figure 5. Membership functions of the NECB alarm state.](image)

Index NA is marked with no alarm, IP indicates intermediate switch position, and PA indicates permanent alarm with high sensitivity.
The existence of the CB alarm does not necessarily correspond to its unavailability but rather marks a condition that, with the other three, determines the CB availability. The same will be applied in the rules of conclusion elaborated on in the following chapters.

4.5. Determining the Availability of a Breaker Status in Network Events Using Fuzzy Logic

The fuzzy system conclusion rule base was determined based on expert knowledge, and it was determined and stored in the form of rules to determine the availability of a state and a possible fault condition of a switch. Defining the rules and reaching conclusions minimizes the possibility of errors that may occur when operating the power system. Based on the mentioned expert rules for determining the possible faults of a circuit breaker of a network element, a database of rules for the conclusion based on a fuzzy system for determining the fault of a switch was derived, as it is symbolic and shown in Table 1. The database has a total of 36 rules ($2 \times 2 \times 3 \times 3$ states).

Table 1. Rules base for concluding the breaker’s availability state based on fuzzy logic.

| Nr | PROT | CB | SEN | A   | $X_i^{r}$ |
|----|------|----|-----|-----|-----------|
| 1  | D    | D  | PH  | PA  | IF        |
| 2  | N    | D  | PH  | PA  | IF        |
| 2  | D    | D  | PH  | NA  | NF        |
| 3  | N    | N  | NH  | NA  | NF        |
| 4  | N    | N  | NH  | NA  | NF        |
| ... | ...  | ...| ... | ...  | ...       |
| 36 | ...  | ...| ... | ...  | NF        |

Where PROT represents the protection start or trip (D start or trip, N no start or trip), CB represents the circuit breaker state change (D change, N no change), SEN represents the current sensitivity change (NH negative sensitivity, L low sensitivity, PH positive sensitivity), A represents the alarm (NA no alarm, IP intermediate position, PA permanent alarm), and $X_i^{r}$ represents the fault (NF no fault, IF fault).

The creation of a list of breaker states from the SCADA systems and protection devices with network elements is done automatically based on the already established priority and order, as shown in Figure 6.

![Figure 6](image)

Figure 6. Schematic representation of information processing and breaker fault detection.

The method itself is used within the application, where data from SCADA and protection devices are displayed in the EXCEL table, transferred from the EXCEL table, and used in FIS within MATLAB, as shown in the schematic in Figure 7.

![Figure 7](image)

Figure 7. Schematic representation of the used applications.
From Table 1, it can be noted that the output variable $X_{rli}$ can have two states: IF (there is a fault) and NF (there is no fault or no fault). The numerical values of the output quantities corresponding to the language variables states are one and zero (Table 2).

Table 2. Output value conversion to numeric values.

| $X_i$ | IF | NF |
|------|----|----|
| Numeric value | 1  | 0  |

Each diagnosed switch or network element can receive only one state or one value and have binary states 1 or 0, respectively, a fault state or a fault-free state. Finally, from Table 2, a list, to which a numeric value of one is assigned, is created. This is a list of elements with faulty breaker states.

5. Real-Life Practical Test Results

To determine the advantages of the mechanism for verifying the breaker state, network element in the possible fault occurrence, and breaker unavailability, it is important to analyze a simple system model example in the operating events in the transmission network. In doing so, a very large number of events and data from the system are analyzed.

Then, in the short term, due to insufficient knowledge and information, it is not possible to reliably determine the breaker availability. In addition, the state of ability to operate and the causes of that condition should be determined, and ultimately, steps should be taken to restore normal system status.

Table 3 shows the list of events from the system with the associated screen display, which can determine the availability of the breaker state and thus the availability status of the network element. This list shows events that happened in one minute. It consists of information in chronological order from the SCADA system and the relay protection device and represents the most important data for determining the availability of the breaker state in the system. Because of the obtained data and measurements, stats, and trips of protection devices, as well as indications of the alarm condition, we have the necessary data for the following variables [5]:

- Protection trip on the breaker in transformer bay 110 kV;
- A breaker state change in transformer bay 110 kV—OFF;
- Currents on network element: $I_x > 3$ kA;
- Existing transformer bay circuit breaker alarm.

Based on the rules of the conclusion, presented in Table 3, using the data on the starts and trips of protection devices, changes in the breaker state, and current flow through the network elements and breaker alarm, we can determine the breaker unavailability to perform its function and consequently the unavailability of the network element.

Based on the rules of conclusion, from 1 to 36, it was determined that this was an event—in this case, the unavailability of a switch in the Virovitica junction at 110/35 kV TB. No analyzed events in the system meet the defined conditions for breaker failures. In this way, a list of breaker unavailabilities in the power system can be generated from the events at different intervals.

The four parameters used in the decision phase, presented in Table 3, consist of descriptions of the characteristic state that determines the state of the breaker unavailability. Table 3 provides an overview of individual MF and information on PROT, CB, SEN, and A. In this test case, using FL, based on data from the SCADA systems and real-time protection devices, a very simple conclusion about the breaker unavailability was reached.
Table 3. Example of the conclusion rules of fuzzy systems for breaker state determination based on SCADA and protection devices.

| Ev. No. | Date/Time    | Location | Object       | State Event       | PROT | CB | SEN | A |
|--------|--------------|----------|--------------|-------------------|------|----|-----|---|
| 1      | 8 January 2018 13:48:57 | VIROVIT 110 TP1 | PROT DIFF      | ACTIVATION        | D    | -  | -   | - |
| 2      | 8 January 2018 13:48:59 | VIROVIT 110 TP1 | BREAKER Q0     | OFF               | -    | D  | -   | - |
| 3      | 8 January 2018 13:48:59 | VIROVIT 110 TP1 | REG. PARAL OPER | TR2 LEADING       | -    | -  | -   | - |
| 4      | 8 January 2018 13:49:00 | VIROVIT 110 TR1 | REG SEPARATE   | ACTIVATION        | -    | -  | -   | - |
| 5      | 8 January 2018 13:49:00 | VIROVIT 110 TR2 | REG. PARAL     | TR2 LEADING       | -    | -  | -   | - |
| 6      | 8 January 2018 13:49:05 | VIROVIT 110 TR2 | REG SEPARATE   | ACTIVATION        | -    | -  | -   | - |
| 7      | 8 January 2018 13:49:07 | VIROVIT 110 TP1 | BREAKER Q0     | OFF-COMM          | -    | -  | -   | - |
| 8      | 8 January 2018 13:49:08 | VIROVIT 110 TP1 | BREAKER Q0     | OFF               | -    | -  | -   | - |
| 9      | 8 January 2018 13:49:09 | VIROVIT 35 TP1 | CURRENT        | 3.2 kA            | -    | -  | PH  | - |
| 10     | 8 January 2018 13:49:09 | VIROVIT 110 TP1 | SWITCH OFF     | ACTIVATION        | -    | -  | -   | - |
| 11     | 8 January 2018 13:49:10 | VIROVIT 110 TP1 | BREAKER Q0     | ACTIVATION        | -    | -  | -   | - |
| 12     | 8 January 2018 13:49:11 | VIROVIT 110 TP1 | SWITCH OFF     | DISCONTINUATION   | -    | -  | -   | - |
| 13     | 8 January 2018 13:49:11 | VIROVIT 110 TP1 | BREAKER Q0     | UNKNOWN POSITION  | -    | -  | -   | PA|
| 14     | 8 January 2018 13:49:40 | VIROVIT 35 TP1 | VOLTAGE        | LIMIT ZONE 0      | -    | -  | -   | - |
| 15     | 8 January 2018 13:50:15 | SLATINA       | REG. PARAL     | ACTIVATION        | -    | -  | -   | - |
| 16     | 8 January 2018 13:50:19 | SLATINA110 TP1 | REG SEPARATE   | NORM              | -    | -  | -   | - |
| 17     | 8 January 2018 13:50:20 | DARUVAR VP    | CURRENT        | 2.1 kA            | -    | -  | -   | - |
| 18     | 8 January 2018 13:50:21 | DARUVAR VP    | VOLTAGE        | LIMIT ZONE 0      | -    | -  | -   | - |
| 19     | 8 January 2018 13:50:22 | SLATINA VP    | CURRENT        | 1.1 kA            | -    | -  | -   | - |
| 20     | 8 January 2018 13:52:24 | SLATINA VP    | VOLTAGE        | LIMIT ZONE 0      | -    | -  | -   | - |

6. Discussion

The authors were unable to compare their method, i.e., studying the real-time breakers availability in the power network with other methods, because this has not been done before. Some methods determine the availability of network elements or the breaker state, but they do not use FL in the decision-making process.

Tables 4 and 5 show the characteristics and comparison of this method with the method labeled FLDCB proposed in [17]. FLDCB uses data from monitoring systems and probability calculations based on past data and has been studied regarding this issue. The methods [18–21] do not have quantitative performance indicators evaluated, which is the reason why it was not possible to compare them with the above method.

Table 4. Basic characteristics and method differences of the rules.

| Methods          | Max Alarm Delay | Correlation of Trips | Missed Alarm Rate | False Alarm Rate (FAR) | Detection Accuracy Average (DAA) |
|------------------|-----------------|----------------------|-------------------|------------------------|----------------------------------|
| CBFL             | 5 min           | 0.98                 | 0.05              | 0.03                   | 0.99                             |
| FLDCB [17]       | 1 h             | 0.99                 | 0.07              | 0.01                   | 0.99                             |

Table 5. Overview of the basic features, differences and objectives of each method characteristics.

| Methods          | Target Methods | Source of Data | Input Data | Time Inter. |
|------------------|----------------|----------------|------------|-------------|
| CBFL             | Real-time breaker state detection | SCADA Protect | Protection Breaker change | Current Alarm | 5 min |
| FLDCB [17]       | Breaker state detection after an event | Monitoring device | Current through Profile area Velocity contacts Operative voltage | 1 h |
The data source, collected from HOPS Internal Documents, are events in the Croatian regional transmission system in the period 2014–2018.

The shown characteristics define:

- Max alarm delay: longest time for the alarm detection;
- Correlation of trips: correlation of trips to 100 cases;
- Missed alarm rate: a ratio of missed alarms over the total number of alarms;
- False alarm rate: a ratio of false alarms over the total number of alarms detected;
- Detection accuracy average: average accuracy of the method determined by the above factors.

Table 5 shows that the CBFL method has 12 times shorter maximal alarm delay than the FLDCB method, which is expected because the CBFL method uses real-time breaker state detection.

When comparing all other data, especially the accuracy of the above methods, it can be seen that the accuracy of the method for detecting and determining the availability of the breaker state is the same as the method from the POST event monitoring data. The same is due to the actions themselves. It is clear that any procedure for determining an event or condition, in real time or prediction, is much more complex than detecting an event or condition.

Therefore, this method can be used in real-time system management for complex outages and network faults to eliminate a faulty element. Upon multiple nonselectively processed events, which are very complex and undocumented, using a fuzzy regulator based on the rules of event conclusions, a list of switch failures is established, and thus, a definite conclusion can be drawn about the occurrence of a fault.

This process is only possible with substations that communicate via the SCADA system with the operating center and where protection device data can be taken and processed. In case of other communication methods and/or protocols, those substations with their CBs cannot be taken into account, and possible wider protection and security might not be fully utilized.

7. Conclusions

Determining the availability of a circuit breaker as a network element in operation at complex real-time transmission events or fully performing its proper function is challenging. Very often, it is extremely difficult to determine the circuit breaker fault using standard methods and procedures.

When analyzing and determining availability using standard methods, which detect faults rather slowly and uncertainly, the procedure success depends on the knowledge and experience of each observer. In this paper, a fuzzy-logic-based regulator was made, and with its certain rules of the conclusion, it was possible to determine the breaker availability in a new way, as shown in the examples and discussion. This has never been done using the aforementioned methodology.

Information based the SCADA systems and protection devices is exploited. Essential information is obtained from the position and breaker state, change in current through the switching element, start or trip of a protection relay, and state of the breaker alarm. FL-based analysis provides real-time, unambiguous, and timely information regarding the state of the switch and the operation of the associated network element that the breaker switches on or off.

This demonstrates that the above method can successfully detect the state of breakers in real time while also having many advantages over similar methods for determining the availability of breakers or other network elements.

This significantly contributes to the faster determination of the breaker state, elimination of faults, and the increase in reliability and safety of the assigned as well as provides a list of elements with faulty breaker states.
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