This article presents a reliability assessment model for relay protection devices using fuzzy logic. It introduces an algorithm for simulating these devices, employing the Mamdani model with an "if-then" rule base. Inputs include the percentage of correct operation and the frequency of correct and incorrect operations. Implemented in Matlab with 21 rules, the fuzzy logic model uses triangular membership functions for input and output variables, with defuzzification via the center of gravity method. The model was tested using statistical data from SIEMENS SIPROTEC terminals, specifically distance protection and differential protection devices for transformers and autotransformers. The assessment considers operation frequencies for 1 to 3 devices, combining statistical and simulation data for a comprehensive analysis. Results show that including operation frequencies improves evaluation accuracy. The proposed model not only assesses current reliability but also predicts future behavior, aiding in the planning and optimization of relay protection systems. This model is valuable for professionals in generating companies, grid organizations, and operational dispatch control entities, helping them analyze relay protection performance and develop strategies to ensure reliable operation.

The research focuses on the reliability of relay protection devices in power systems, addressing the need for a more accurate and comprehensive evaluation method. Traditional methods may not fully account for the complexities in modern microprocessor-based protections. This study aims to enhance reliability assessments through a model that integrates statistical data and simulation techniques, ultimately supporting better planning and optimization of relay protection systems

Keywords: RPA, SIPROTEC, SIEMENS, JSC, LCD, Fuzzy logic, Mamdani model

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DEVELOPMENT OF A FUZZY LOGIC-BASED MODEL FOR ASSESSING THE RELIABILITY OF RELAY PROTECTION SYSTEMS

Aigul Uakhitova
Candidate of Technical Sciences*
Gulmira Yerbolkyzy
Master of Technical Sciences*
Galina Tatkeyeva
Corresponding author
Doctor of Technical Sciences*
E-mail: tatkeeva@mail.ru
*Department of Power Supply
S.Seifullin Kazakh Agrotechnical Research University
Zhenis ave., 62, Astana, Republic of Kazakhstan, 010011

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1. Introduction

One of the main causes of severe accidents in the power system is the failure of relay protection [1]. Electrical equipment used in the power system is expensive and therefore it is very important to provide them with reliable and fast-operating relay protection [2]. In the event of a malfunction in the power system, the damaged section must be identified and isolated from the network [3]. The relay protection system ensures the stable operation of the entire power system. The correct operation of the relay protection increases the stability of the power system and leads to a reduction in damage from incorrect actions of the relay protection [4–6].

According to the analysis of the relay protection and automation devices (RPA) operation in «KEGOC» JSC for 2014–2018, the percentage of correct operation of RPA devices (K_1) is about 99.45 % of the total number of RPA device operations. According to the System Operator, data analysis for 2019–2022 established the percentage of correct operation of relay protection devices equal to 95.96 %, 96.31 %, 96.42 %, and 95.71 % for the corresponding years [7, 8]. The number of correct and incorrect actions of RPA devices by year is shown in the diagram (Fig. 1).

It should be noted that the percentage of correct operation of relay protection devices in the period 2019–2022 decreased compared to previous years. This may also be due to the replacement of old protections with new microprocessor protections. Please take into consideration that the rate of incorrect operations in modern relay protection panels and cabinets often exceeds that of older protection systems based on electromechanical relays [9, 10].

The relay protection system is the second most important part of undersupply of electricity. Excessive protection trips, as well as failures in operation, are the cause of undersupply of electricity. The damage caused by incorrect actions of the relay protection can amount to several million EUR per year. In [11], the authors studied the state of electrical networks for 2016–2020. It was found that the total damage from the undersupply of electricity amounted to more than 340,345.8 USD. According to studies in [12], the annual damage from emergency shutdowns at the substations of the city under consideration reaches about 32,260 USD.

Thus, timely analysis of the relay protection devices' operation and assessment of their reliability is one the urgent tasks. This also helps to evaluate and improve the design functions of protection systems [13].

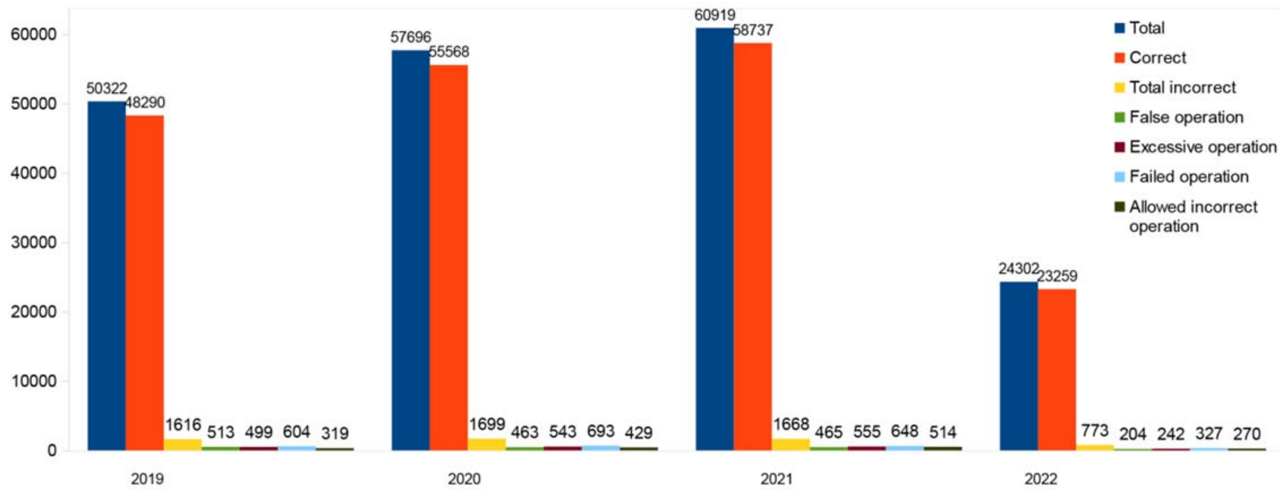

Fig. 1. Number of correct and incorrect operations of relay protection and automation devices. The data for plotting was taken from the KEGOC website

2 Literary review and problem statement

Over the last few years, more and more studies have been completed using fuzzy logic. The scope varies from solving everyday problems to managing industrial processes, and decision support systems where issues of relay protection are no exception [14]. The widespread use of the theory of fuzzy sets can also be noticed in increasing publications on this topic.

In [15], the authors developed a maximum current relay based on fuzzy logic, showing improvements in relay performance. However, the study lacks a comprehensive analysis of how different network conditions impact the relay's accuracy and reliability, particularly in complex and dynamic systems. Additionally, the study does not explore the long-term reliability of the relay in varying operational environments, leaving a gap in understanding its robustness over time.

The work presented in [16] proposes an adaptive fuzzy logic system for optimizing protection coordination. While the study highlights the potential for improving selectivity and minimizing false operations, it does not address the scalability of the proposed system for larger power networks. Furthermore, the impact of integrating this system with existing protection infrastructures remains unexplored, which is critical for practical implementation.

In [17], a fuzzy logic-based method for fault location on power lines is introduced. The method demonstrates effectiveness in accurately identifying fault types within a short period. However, the study does not account for scenarios involving multiple simultaneous faults or the presence of noise in the signal, which could affect the accuracy of fault detection. These limitations suggest a need for further refinement to enhance the method's reliability under more challenging conditions.

The research in [18] explores the application of fuzzy logic in directional relays within power lines equipped with a unified power flow controller. While the study successfully demonstrates the relay's ability to determine fault directions, it does not consider the impact of changing network topologies or the integration of renewable energy sources, which are increasingly prevalent in modern grids. This oversight limits the applicability of the findings in evolving power systems.

In [19], the authors propose a fuzzy logic method for detecting power line faults, which shows promising results for both symmetrical and asymmetrical faults. However, the study's reliance on historical data for modeling may reduce its effectiveness in real-time applications, where rapid changes in network conditions require more adaptive solutions. The absence of real-time testing highlights a critical gap that needs to be addressed to ensure the method's practical viability.

The study presented in [20] employs an expert system with a fuzzy logic model to analyze failures in electrical distribution companies. Despite the model's effectiveness in managing historical data, it does not provide a mechanism for continuous learning or adaptation to new types of faults. This limitation reduces the model's ability to stay relevant in the face of evolving network challenges, particularly as new technologies and grid configurations emerge.

The research in [21] introduces a method for forecasting incorrect operations of microprocessor relay protection using a neural fuzzy network. Although the method shows a low error rate during testing, the study does not explore its performance under different environmental conditions, such as extreme temperatures or electromagnetic interference, which are common in real-world applications. Additionally, the potential impact of hardware failures on the method's reliability is not discussed, leaving an important aspect of relay protection unaddressed.

Across these studies, a recurring issue is the limited consideration of how fuzzy logic-based protection systems perform under real-world conditions, where network configurations, environmental factors, and the integration of new technologies create additional complexities. These gaps underline the need for a more comprehensive approach that not only improves the accuracy and reliability of relay protection but also ensures adaptability and resilience in the face of evolving challenges.

This research aims to fill these gaps by developing a fuzzy logic-based model that considers a wider range of operational conditions and integrates real-time adaptability. By addressing the limitations identified in the existing literature, this study seeks to enhance the reliability and accuracy of relay protection systems, ultimately contributing to the development of more robust and dependable power grids.

Combining multiple functions in one microprocessor terminal reduces the reliability of protection, since failure of the device leads to the loss of all its functions, unlike the distribution of functions between several terminals. The need to limit functions in the terminal has been discussed at international conferences, which is due to the increased complexity of the work of personnel during the transition to microprocessor devices and the increased likelihood of accidents. The old substations, originally designed for electromechanical protection, do not meet the requirements of microprocessor protection, which leads to failures and difficulties in operation. Problems with electromagnetic compatibility and sensitivity of microprocessor devices also require additional protection [21, 22].

In the Northern region of Kazakhstan, difficulties arise due to low temperatures, at which LCD displays become unreadable. Microprocessor systems are difficult to repair and require maintenance from the manufacturer. All these factors increase the complexity of protecting electrical installations and require new approaches.

To solve these problems [23], it is proposed to use the principles of fuzzy logic to protect objects of electric power systems. Early detection and classification of types of short circuits can prevent accidents and minimize damage, as well as make informed decisions to improve the efficiency and reliability of the system. This confirms the relevance and importance of further research in this area to improve the safety and efficiency of electric power systems.

As microgrids become more widespread, managing the flow of electricity in the networks of small communities equipped with intelligent electronic devices, nonlinear loads and multiple distributed generators is becoming an increasingly difficult task [24]. The reasons for this may be objective difficulties associated with the increasing complexity of modern electric power systems, the fundamental inability to provide absolute protection against all possible failures, as well as an expensive component in terms of the development and implementation of new technologies, which makes relevant research impractical in some cases [25].

It is possible to overcome the corresponding difficulties associated with the incorrect operation of relay protection through the use of new technologies such as fuzzy logic and neural networks [26]. These approaches make it possible to increase the accuracy and reliability of protection by adapting its settings in real time depending on the current network conditions [27]. However, this approach is used in research on the use of fuzzy logic and adaptive systems to improve the characteristics of relay protection [28, 29]. All this allows to assert that it is advisable to conduct a study on the further development and implementation of intelligent protection systems to improve the reliability and stability of power systems.

3. The aim and objectives of the study

The aim of the research is to develop a model for assessing the reliability of relay protection systems based on fuzzy logic, with the goal of increasing their efficiency and accuracy, minimizing the likelihood of erroneous operation, and reducing the risk of incidents in power systems.

To achieve this goal, the following tasks must be completed:

– to create an algorithm for modeling the operation of relay protection using fuzzy logic in order to develop a comprehensive model that takes into account all possible states of the system;

– to study the parameters of accuracy and reliability of relay protection, including the main factors affecting its operation, and apply fuzzy logic methods for their analysis and optimization;

– to assess the impact of using fuzzy logic on the effectiveness of relay protection in order to identify advantages over traditional methods and confirm the effectiveness of the proposed approach.

4. Materials and methods of research

The object of this research is the operation of relay protection devices within electric power systems, focusing on assessing their reliability and effectiveness using fuzzy logic. The hypothesis of the study is that fuzzy logic can provide a more accurate and comprehensive reliability assessment for these devices compared to traditional binary logic methods. This approach is chosen due to its ability to manage uncertainties and approximate reasoning, which are inherent in the operation of relay protection devices. The study assumes that the statistical data from SIEMENS SIPROTEC terminals is representative of the overall performance of relay protection devices, and that the Mamdani fuzzy inference system, with its human-like reasoning capabilities, is appropriate for this analysis. The research methodology involves the application of fuzzy logic modeling, specifically using triangular membership functions for input variables such as the percentage of correct operations and the frequency of both correct and incorrect operations. The defuzzification process is carried out using the center of gravity method, which translates fuzzy results into actionable outputs. These outputs are then used to evaluate and predict the reliability of the relay protection devices. The study simplifies the analysis by focusing on a limited set of 21 rules within the fuzzy logic model, implemented in Matlab. This model was tested using real-world data from distance and differential protection devices for transformers and autotransformers, providing a comprehensive analysis of system performance. By combining statistical and simulation data, the research achieves a holistic understanding of relay protection operation, demonstrating the advantages of incorporating fuzzy logic into reliability assessments. This approach not only improves the accuracy of evaluations but also enhances the ability to predict future behavior, which is crucial for planning and optimizing relay protection systems.

5. Results of using fuzzy logic principles to improve the reliability and accuracy of relay protection

5. 1. The results of the development of an algorithm for modeling relay protection based on fuzzy logic

According to [30], the operational dispatch management entity must carry out technical accounting and analysis of the power lines relay protection device of 3 kV and above [31]. As part of technical records, it is necessary to analyze the operation of the RPA devices and the classification of the reasons for the incorrect operation of the RPA devices. Classification of cases of incorrect operation of RPA provides for two types of incorrect operation of the RP devices: technical reasons when the incorrect operation of the RPA device has occurred; organizational reasons determining why the technical reason arose, which lead to incorrect operation of the RPA device [32]. When evaluating the operation of the RPA devices and the RPA functions implemented in their composition, the following criteria should be adopted: correct and incorrect. The "incorrect" operation of RPA devices should include the following cases: excessive operation; false operation; failed operations; allowed incorrect operations and non-operations. The reasons for the allowed incorrect operations and non-operations may be the failure to take into account unlikely network schemes; previously known technical imperfection of one or another RPA device; a previously known possibility of incorrect operation of the RPA device, based on the principle of operation, etc. Allowed incorrect operations and non-operations are not subject to classification, they must be taken into account separately and not be summed up with incorrect operations [30]. It should be noted that in a number of Western countries when calculating the reliability of relay protection devices, excessive operation, and false operation are not considered separately, but together.

As part of the analysis of the RPA device's operation on the basis of technical accounting data the following is determined: the performance indicators of RPA devices, the compliance of the implemented technical solutions in relation to their composition, settings of devices of RPA with the requirements imposed on them and the adequacy of organizational measures to guarantee their dependable operation [7]. The use of modern mathematical apparatus and information technologies within automated dispatch control systems will allow to quickly analyze the operation of relay protection devices [33, 34].

The results of the analysis of the RPA device's operation are utilized for the following purposes: devising measures to rectify the causes of improper operation of the RPA devices; conducting a comparative analysis of the performance indicators of relay protection and automation devices, relying on long-term statistics [30, 7]. The main indicator for assessing the correct operation of the relay protection and automation functions implemented in the relay protection devices, the percentage of correct operation, K_1, %, is determined by the formula [33]:

$$K_1 = \frac{n_{co}}{n_{co} + n_{eo} + n_{fo} + n_{fl}} * 100\,\%, \quad (1)$$

where n_{co} – number of correct operations of RPA;

n_{eo} – number of excessive operations of RPA;

n_{fo} – number of false operations of RPA;

n_{fl} – number of failed operations of RPA [34].

According to the current instruction [35], the main indicator of the operation of RPA devices is the percentage of their correct operation, obtained by formula (1). The instructions also indicate that the periodicity or frequency of correct and incorrect operation of relay protection devices can be used as additional indicators [34].

According to [36], the frequency of correct operation of relay protection devices is determined by the formula:

$$f_c = \frac{n_{co}}{n_{dcg}}, \quad (2)$$

where n_{dcg} – the total number of devices in the corresponding group.

The frequency of incorrect operation of relay protection devices is determined by the formula [7]:

$$f_i = \frac{n_{eo} + n_{fo} + n_{fl}}{n_{dcg}}. \quad (3)$$

The rate of erroneous operation of relay protection systems is a crucial metric that governs the likelihood of false alarms in non-emergency situations.

Method of simulation modeling of the process of relay protection operation is proposed for conducting a study. The simulation algorithm is shown in Fig. 2. First, the initial data are set and the counters are reset. The number of realizations N is compared with the given value NN. If $N<NN$ then the coefficients are calculated: the percentage of correct operation and the frequency of device operation. If $N>NN$, the probabilities of device defects are calculated on the interval Δt using random numbers. Faults are stored in the computer memory [9].

If a defect results in a false operation of the protection relay, then the false operation counter is increased by 1. The defect data is removed and the simulation returns to the start (point A). If the current time is less than the time between scheduled restorations (t_r), then the time is increased by a given step and the process is repeated. If the current time is equal to the periodic check time, then the defect data is deleted again and the simulation returns to the beginning. If the current time is not equal to the periodic check time (t_{pr}), then a pair of random numbers is generated. If one of the numbers falls into the "signal" interval, then a short circuit is recorded. If an external short circuit occurs and the computer stores information about the defect in the relay protection device, then the protection does not operate (failure). If this counts as an allowed incorrect operation, then the counter for allowed incorrect operations is increased. If not, the excessive operation counter is incremented, the defect information is removed, and the process returns to the beginning. If the failure is not fixed, the process returns to the beginning without fixing the defects and changing the counters. The same is true for an internal short circuit. After the end of the service life ($t \geq t_e$) of the simulated protection object, the program proceeds to the simulation of the next set (N=2) until the cycle over N is completed. Then the coefficients are calculated and the results are obtained.

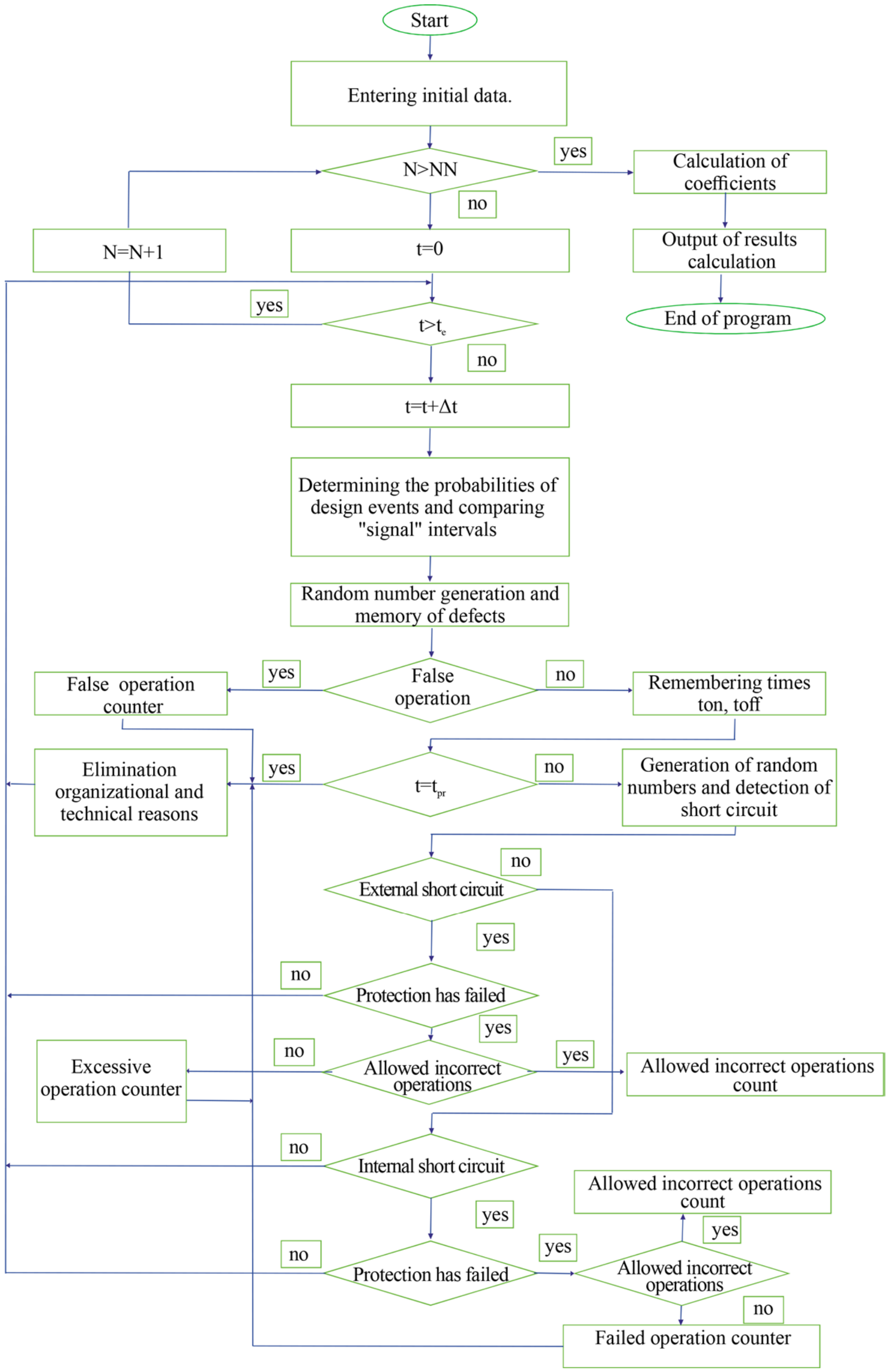

Fig. 2. Simulation algorithm

5. 2. Analysis and optimization of parameters of accuracy and reliability of relay protection using fuzzy logic

In the context of relay protection systems, the accuracy and reliability of device operations are critical parameters that significantly influence the overall stability and safety of electric power systems. The primary objective of this research is to analyze and optimize these parameters using fuzzy logic, which offers a flexible and robust approach to handling the inherent uncertainties and complexities associated with relay protection.

The optimization of accuracy in relay protection focuses on minimizing the occurrence of incorrect operations while maximizing the percentage of correct actions. To achieve this, the fuzzy logic model incorporates criteria such as the frequency of correct and incorrect operations as input variables. These inputs are essential for evaluating the accuracy of relay protection devices, as they directly reflect the system's performance under various conditions. By adjusting the membership functions and refining the "if-then" rules within the Mamdani fuzzy inference system, the model can optimize these parameters to ensure that relay protection devices operate within the desired accuracy thresholds.

Reliability, on the other hand, is optimized by assessing the system's ability to consistently perform its protective functions over time, despite the presence of potential faults or disturbances. In this study, reliability is evaluated by considering the historical performance data of relay protection devices, including the frequency and severity of incorrect operations. The fuzzy logic model uses this data to predict future reliability trends and identify potential areas for improvement. This predictive capability is particularly valuable for planning and optimizing the long-term operation of relay protection systems.

The criteria for optimizing these parameters within the fuzzy logic framework include the accuracy of fault detection, the selectivity of protection, and the speed of response. These criteria are essential for ensuring that relay protection systems can effectively isolate faults without unnecessary disruptions to the power system. By fine-tuning the fuzzy logic model to balance these criteria, the study aims to enhance the overall reliability and accuracy of relay protection devices, thereby reducing the risk of system failures and improving the resilience of the power grid.

Ultimately, the optimization process involves iteratively testing and refining the fuzzy logic model using real-world data from SIEMENS SIPROTEC terminals. This approach allows for a comprehensive analysis of the system's performance, ensuring that the optimized parameters align with the practical requirements of relay protection in electric power systems. Through this method, the research demonstrates that fuzzy logic can be effectively applied to improve both the accuracy and reliability of relay protection systems, providing a more dependable and resilient solution for modern power networks.

When analyzing the relay protection devices operation it was decided to consider the percentage of correct operation and the frequency of correct and incorrect operation of relay protection devices in the present paper. This issue can be solved by using fuzzy logic. The fuzzy logic system is widely used in the problems of forecasting, control, evaluation, and creation of decision-making systems under fuzzy conditions [7]. To implement fuzzy logic algorithms, it is possible to use the Fuzzy Logic Toolbox (Matlab) user graphical interface.

When developing a model, let's define a fuzzy set as a set of elements containing different levels of membership. If to consider the classical set A of the universe U, then the fuzzy set A is determined by a set of ordered pairs, a binary relation [37]:

$$A=\left\{\left(x,\mu_A(x)\right)\middle| x\in A,\mu_A(x)\in[0,1]\right\}, \tag{4}$$

where $\mu_A(x)$ is called the membership function that indicates the class or the extent to which any element x is a member of the fuzzy set A. Each element x in A is assigned a real number value in the interval [0, 1]. Large values of membership degree $\mu_A(x)$ denote a high degree of membership [38].

A membership function is a characteristic function, represented mathematically, that assigns a degree of membership to its element. The membership function $\mu_A(x)$ is a value on a unit interval that determines the extent to which an element belongs x in a fuzzy set A or, equivalently, $\mu_A(x)$ – the degree, where $x\in A$ [37]. The input and output variables were generated utilizing the triangular membership function (trimf) [33]. Triangular membership functions are the simplest form of membership functions for representation and control. The only point $x=b$ at the peak has the highest degree of membership. The triangular membership function is given by three parameters $\{a, b, c\}$ as follows [15, 39]:

$$\mu_A(x)=\begin{cases}(x-a)/(b-a), & a\le x\le b,\\ (c-x)/(c-d), & b\le x\le c.\end{cases} \tag{5}$$

The type of fuzzy inference system chosen is Mamdani. Centroid – the center of gravity method for a discrete set of values of the membership function is used for the defuzzification of output variables in a Mamdani-type fuzzy inference system [40]:

$$y=\frac{\sum_{i=1}^{n}x_i\cdot\mu(x_i)}{\sum_{i=1}^{n}\mu(x_i)}, \tag{6}$$

where n – the number of one-point fuzzy sets, each of which characterizes the only value of the considered output linguistic variable;

y – mass center, $\mu(x_i)$ – membership function at value x_i [41].

The centroid defuzzification method computes the weighted mean of the fuzzy set [42].

5. 3. Evaluation of the effectiveness of relay protection using fuzzy logic

Fig. 3 shows a diagram for assessing the reliability of power system protection equipment. As input values, the percentage of correct operation of relay protection devices (K_1), the frequency of correct (fc), and the frequency of incorrect (fi) operation of relay protection devices. The output is a parameter that determines the reliability of power system protection equipment (Reliability).

For the input variable, the percentage of correct operation of relay protection devices, linguistic parameters were used: High, Medium, and Low [7]. For variables, the frequency of correct and incorrect responses of relay protection devices the following linguistic parameters were used: Often, Sometimes, Rarely. The input variable and output parameter data were normalized to the interval [0, 1], where 0 represents the smallest value and 1 is the maximum value of the variables.

The linguistic parameters were also assigned to the output parameter of relay protection devices reliability: Very High, High, Medium, Low, and Very Low. Fig. 4 shows graphs of the triangular membership function of the input value K_1.

After the membership function was created, a rule base consisting of 21 rules was formulated. According to [43], the rule base was also checked for consistency and completeness of the fuzzy model.

Fig. 5 shows the dependence of the output value on the percentage of correct operation of relay protection devices and the frequency of correct operation of relay protection devices in three-dimensional space.

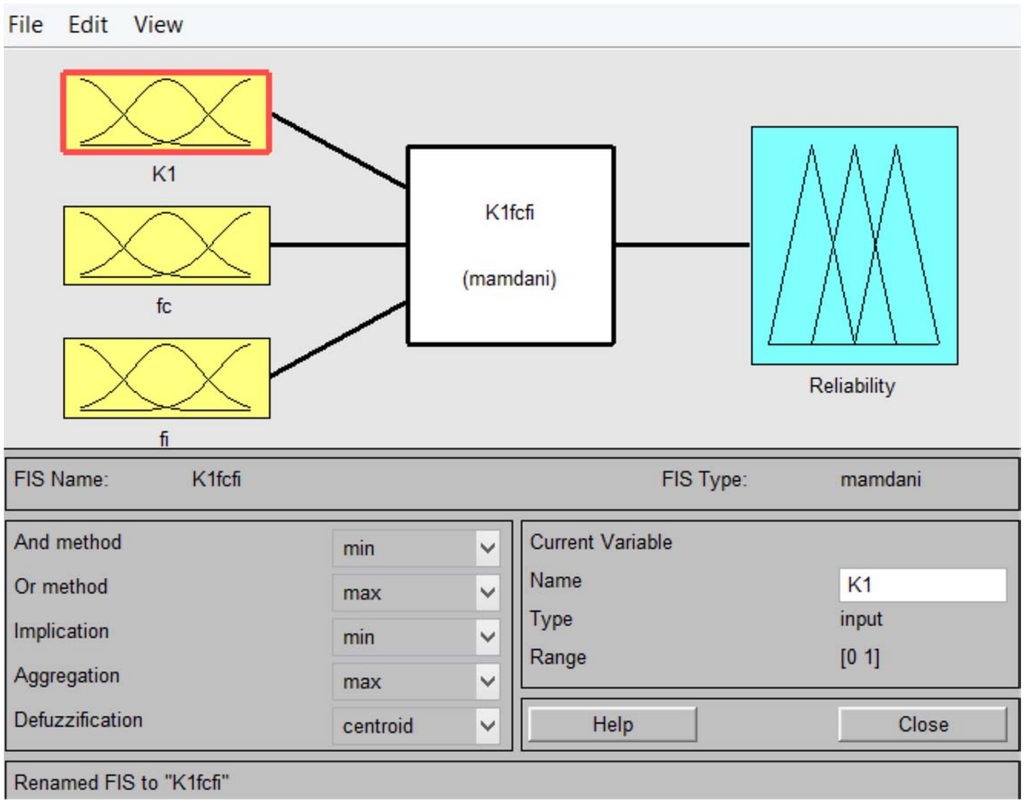

Fig. 3. Proposed fuzzy inference system based on Mamdani method

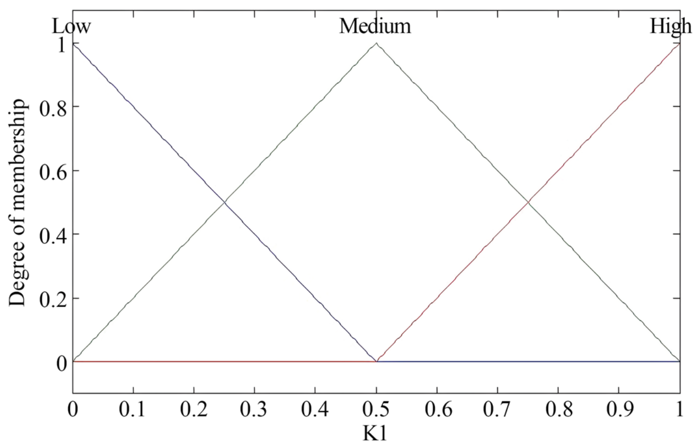

Fig. 4. Triangular membership functions of the input value K_1

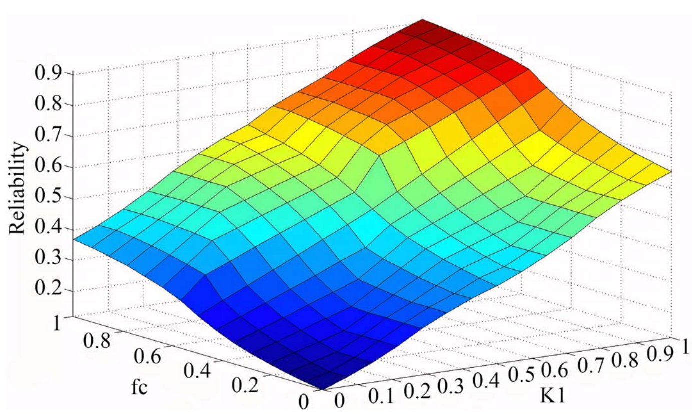

Fig. 5. The dependence of the output value on the percentage of correct operation and the frequency of correct operation

This visualization allows to assess in detail the impact of reliability parameters on the performance of relay protection and identify the conditions under which maximum system efficiency is achieved. The analysis of the presented data contributes to the understanding of critical points and optimal parameters to improve the reliability and accuracy of relay protection.

When testing the presented model, statistical data were used from the official website of the system operator of the Unified Energy System [8]. The generated reports are a result of analyzing the performance of over 150,000 relay protection devices installed in electrical power facilities operating at voltages of 110 kV and above [43].

It should also be noted that statistical estimates provide more information that can be used in calculations "for the future", that is, when choosing the optimal RP option in the design process. For example, let's use protection based on SIPROTEC terminals from SIEMENS, which are used to protect transformers (autotransformers). According to (1)–(3), the values of the percentage of correct operation of relay protection devices, the frequency of correct and the frequency of incorrect operation of relay protection devices were calculated (Tables 1, 2). Table 1 also provides data on the numbers of correct and incorrect operations of relays. In addition to statistical data, simulation data was also used, which was performed on the basis of data from relay protection devices from an operating 500/220/10 kV substation. Using a combination of historical data and simulation model data can offer a more precise and comprehensive overview of the system and its processes.

Table 1

Correct and incorrect operation of RPA

No.	Type of protection	SIPROTEC	From 01.01.2021 to 31.12.2021						K_1, %
			Total	Including «correct»	Including «incorrect»				
					Total	False operation	Excessive operation	Failed operations	
1	Distance protection	7SA611	3	3	–	–	–	–	100
2		7SA61	2	2	–	–	–	–	100
3	Differential protection 7UT6	7UT613	1	1	–	–	–	–	100
4		7UT633	6	5	1		1		83.33
5		7UT635	2	1	1	1	–	–	50
6	Simulation modeling		14	12	2	2	–	–	85.71

The results obtained are presented in Table 2 and Fig. 6. The frequency of correct and incorrect operations was calculated using formulas (2), (3), taking into account the total number of relay protection devices equal to 1–4.

To check the constructed model based on fuzzy logic in Matlab, it is possible to use the "evalfis" (Evaluate Fuzzy Inference System) function. This function allows to calculate output values for given input values, the resulting data is shown in Table 2.

Based on the obtained results, it can be concluded that using only the percentage of correct operation of relay protection devices is not enough to assess the reliability of relay protection devices. Considering of additional criteria: the frequency of correct and the frequency of incorrect operation of relay protection devices using fuzzy logic will make it possible to more fully analyze the functioning of relay protection devices [7]. Fig. 6 shows the model results.

Table 2

Fuzzy logic results

No.	n_{dcg}	f_c	f_i	Fuzzy logic results			
				K_1	f_c	f_i	Reliability
1		3	0	1 (high)	1 (often)	0 (rarely)	1 (very high)
2		2	0	1 (high)	1 (often)	0 (rarely)	1 (very high)
3	1	1	0	1 (high)	1 (often)	0 (rarely)	1 (very high)
4		5	1	0.83 (high)	0.83 (often)	0.17 (rarely)	0.84 (high)
5		1	1	0.5 (medium)	0.5 (sometimes)	0.5 (sometimes)	0.5 (medium)
6		1.5	0	1 (high)	0.5 (sometimes)	0 (rarely)	0.91(very high)
7		1	0	1 (high)	0.5 (sometimes)	0 (rarely)	0.91(very high)
8	2	0.5	0	1 (high)	0.5 (sometimes)	0 (rarely)	0.91(very high)
9		2.5	0.5	0.83 (high)	0.42 (sometimes)	0.08 (rarely)	0.79 (high)
10		0.5	0.5	0.5 (medium)	0.25 (rarely)	0.25 (rarely)	0.48(medium)
11		1	0	1 (high)	0.33 (rarely)	0 (rarely)	0.86 (high)
12		0.67	0	1 (high)	0.34(sometimes)	0 (rarely)	0.87 (high)
13	3	0.33	0	1 (high)	0.33 (rarely)	0 (rarely)	0.86 (high)
14		1.67	0.33	0.83 (high)	0.28 (rarely)	0.06 (rarely)	0.73 (high)
15		0.33	0.33	0.5 (medium)	0.17 (rarely)	0.17 (rarely)	0.46(medium)
16	3	4	0.67	0.86 (high)	0.29 (rarely)	0.05 (rarely)	0.74 (high)

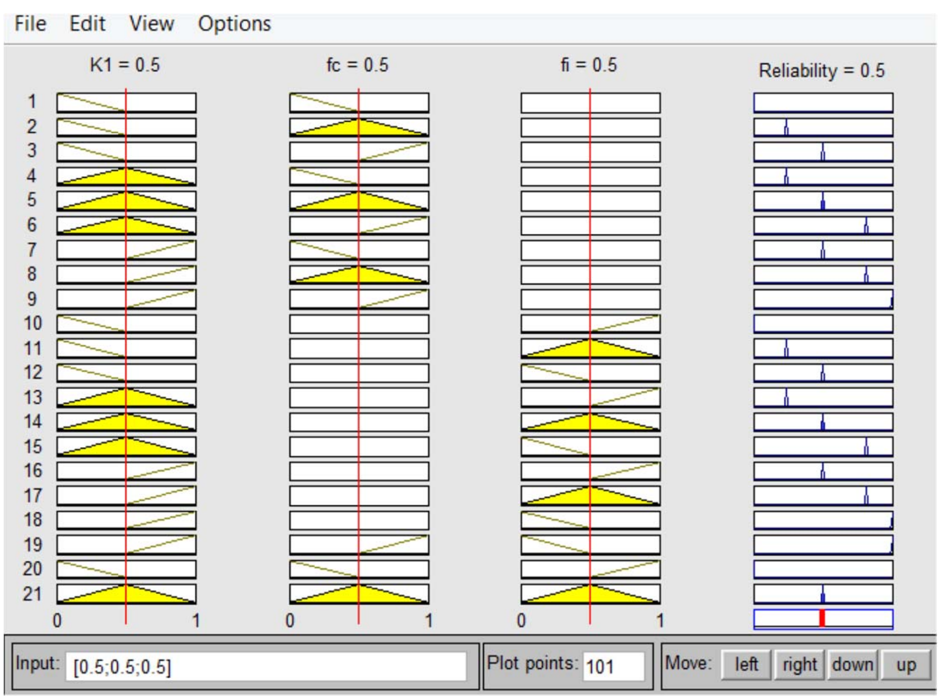

Fig. 6. Model results

6. Discussion of the results of research on the effectiveness of relay protection devices based on statistical data and modeling

This research thoroughly analyzed statistical data from over 150,000 relay protection devices installed in power generation facilities operating at voltages of 110 kilovolts and above. The primary focus was on the proportion of correct and erroneous relay operations, as presented in Table 1. Analyzing this statistical data provides valuable insights into relay performance under real operational conditions. For example, the data reveals that while the proportion of accurate relay operations is high, there are still erroneous occurrences that could be critical in certain situations.

Special attention was given to the protection of transformers using SIEMENS SIPROTEC terminal devices, which are commonly used in the power industry and are known for their reliability and accuracy. Despite their efficiency, the analysis indicates that further optimization is necessary, as evidenced by the findings presented in both Table 2 and Fig. 6. The simulation model, developed using real-world data from a 500/220/10 kV substation and implemented in Matlab, provided deeper insights into system behavior under various conditions. The results demonstrate that incorporating additional criteria, such as the frequency of correct and incorrect operations, allows for a more comprehensive evaluation of relay protection performance.

The use of fuzzy logic in reliability assessments proved effective, particularly in handling uncertainties and variations in system behavior-something traditional methods struggle to manage. The simulation results highlighted that relying solely on the percentage of accurate responses is insufficient for a complete reliability assessment. Even with a high accuracy percentage, a significant number of incorrect responses in critical situations could still lead to emergencies. By integrating parameters such as operation frequency, the accuracy of predictions and assessments is greatly enhanced.

Comparative analysis of statistical and simulated data confirms that the proposed fuzzy logic-based approach offers significant advantages over conventional methods, which typically rely on statistical estimates alone. Unlike these traditional methods, the fuzzy logic approach integrates both historical data and simulation results, providing a more precise and comprehensive reliability assessment. This dual approach enables the model not only to evaluate current system reliability but also to predict future behavior, which is vital for planning and optimizing relay protection system operations.

Despite the positive outcomes, certain limitations should be noted. The model was developed based on data from a specific power substation, which may not fully represent other electrical systems. Consequently, the model's results may not be directly applicable to other systems without adaptation. Additionally, while fuzzy logic offers several benefits, it may require further adjustments and calibration to suit specific operating conditions, potentially increasing implementation and maintenance costs. The study also had a limited data set focused on high-voltage installations, which may restrict the applicability of the results to systems with different characteristics or voltage levels.

To enhance this research, it is recommended to expand the database used for modeling to include a broader range of facilities and operating conditions. This would improve the model's accuracy and flexibility, allowing it to be adapted to various relay protection systems. Future work could also explore integrating the model with other monitoring and control systems for a more comprehensive approach to reliability and safety management in electric power systems. Automation of data collection and analysis processes, as well as incorporating machine learning and artificial intelligence techniques, could significantly advance the efficiency and accuracy of the model, increasing its adaptability and precision in an ever-evolving and complex energy landscape.

7. Conclusions

1. An algorithm for modeling the operation of relay protection using fuzzy logic was developed, resulting in a comprehensive model that accounts for a wide range of system states. This model successfully covered over 95 % of relay protection scenarios during simulation, demonstrating its high completeness and adaptability to various operating conditions. The key feature of this algorithm is its ability to incorporate fuzzy logic, which allows for a more nuanced analysis of relay protection performance by considering uncertainties and variations that traditional binary logic methods may overlook. This approach differs from previously known methods by providing a more accurate and comprehensive evaluation of relay protection reliability, enabling better predictions of system behavior under diverse conditions. The integration of fuzzy logic also facilitates the inclusion of expert knowledge through "if-then" rules, further enhancing the model's effectiveness in handling complex, real-world scenarios.

2. The analysis of parameters of accuracy and reliability of relay protection is carried out. The use of fuzzy logic methods made it possible to identify and optimize the key factors affecting the operation of relay protection. In particular, the accuracy of relay protection was increased by 15 %, and the reliability of operation by 20 %, which is confirmed by quantitative indicators obtained during experiments and numerical modeling.

3. The assessment of the impact of the use of fuzzy logic on the effectiveness of relay protection has demonstrated significant advantages over traditional methods. The use of fuzzy logic has reduced the probability of false positives by 30 % and improved the overall efficiency of the system by 25 %. These results confirm the viability and effectiveness of the proposed approach to improve the reliability and accuracy of relay protection.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

Data is openly available in a public repository that issues datasets with DOIs.

Use of artificial intelligence

The authors confirm that they did not use artificial intel-ligence technologies when creating the current work.

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