

## Fuzzy logic-based load balancing for voltage symmetry in distribution networks

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### Article Info

#### Article history:

Received Sep 4, 2025

Revised Jan 15, 2026

Accepted Feb 26, 2026

#### Keywords:

Asymmetrical load

Distribution system

Fuzzy logic

Membership function

Power quality

Voltage imbalance

### ABSTRACT

This paper introduces a load balancing approach based on fuzzy logic to enhance the efficiency of power distribution networks. The unbalance of voltages and an unequal load of the phases continue to be the problematic situation of the low-voltage distribution networks, particularly as the percentage of photovoltaic (PV) systems is growing. The results of such conditions include a deviation of voltage, higher losses of power, faster equipment aging, and lower power quality. This paper proposes a fuzzy logic-based phase load balancing approach that explicitly integrates voltage symmetry requirements defined by the GOST 13109-97 power quality standard. Unlike optimization-based and heuristic methods, the proposed fuzzy logic controller (FLC) redistributes phase currents using linguistic rules derived from voltage unbalance coefficients and phase current conditions, without iterative optimization procedures. Simulation results obtained in MATLAB/Simulink demonstrate a reduction of the voltage unbalance factor (VUF) by approximately 25–30% and a decrease in active power losses by 12–15% compared to the initial unbalanced operating state. The proposed method offers low computational complexity, fast response, and high interpret-ability, making it suitable for real-time implementation in smart distribution networks with distributed PV generation.

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## 1. INTRODUCTION

Distribution networks constitute the final stage of electric power delivery and supply residential, commercial, and industrial consumers [1]. These networks commonly operate at low and medium voltage level and are typified by non-uniform loads and dynamically varying operating conditions [2]. The rise in the use of distributed energy resources, and specifically photovoltaic (PV) systems, further complicates the process of the low-voltage distribution network functioning and the threat of the phase imbalance of the loads.

One of the primary factors of voltage asymmetry in three-phase distribution systems is phase load imbalance, which is usually measured by the voltage unbalance factor (VUF) [3]. High VUF values cause voltage deviation, technical losses, overheating of electrical equipments and rapid aging of transformers and cables [4]. In addition, excessive voltage unbalance negatively affects power electronic converters, induction motors, and sensitive consumer loads, resulting in reduced power quality and decreased system reliability [5]. The requirement of maintaining good VUF levels is thus an essential of the contemporary distribution

networks. The phase load balancing helps in the improved regulation of voltage as well as minimized power losses, and operational reliability [6]. Intermittent generation combined with the integration of PV systems makes phase loading more stochastic and thus conventional methods of balancing available only in ideal conditions [7].

A number of techniques have been put forward to control voltage unbalance in low-voltage networks. Some of the conventional methods of minimizing VUF include feeder reconfiguration and phase swapping [8]. The use of optimization-based techniques, such as genetic algorithms and particle swarm optimization, has been well applicable in the solution of problems of phase load balancing and have been found to be very accurate in the minimization of VUF [9]. Nevertheless, such techniques are often highly iterative, need to be carefully parameterized and can be very expensive to compute, making them inconvenient in the real-time control of networks with fast-varying PV generation [10]. Another alternative that has been developed to control voltage unbalance during uncertainty and non linearity is through the use of fuzzy logic [11]. Fuzzy logic, in contrast to optimization-based techniques, does not need a clear mathematical model of the distribution network, and may use the expert information in the form of linguistic rules [12]. The past researches have demonstrated that FLCs have the potential to achieve a successful VUF minimization, better voltage profiles, and power quality in distribution systems [13]. In addition, the fuzzy inference systems provide high interpret-ability and rapid response that is critical in practical application in low-voltage networks [14].

Regardless of these benefits, the majority of current fuzzy logic-based solutions consider the reduction of voltage unbalances without incorporating control requirements in the control mechanism. In most situations, the adherence to the quality of power standards is checked after control measures have been implemented [15]. Conversely, the regulations of voltage quality like GOST 13109-97 establish strict boundaries on the acceptable VUF levels and these should be met during network operation. The major novelty of the given work is the straightforward inclusion of the GOST 13109-97 voltage symmetry requirements in a fuzzy logic phase load balancing controller. The suggested algorithm takes VUF and phase current measurements as the input variables and executes the redistribution of phase current using a Mamdani fuzzy inference system and makes sure that the standard is being adhered to. This method does not require computationally intensive optimization processes and allows real time operation with low computational overhead.

According to the research gap identified, the research question of the work is whether a fuzzy logic-based controller is effective in minimizing the VUF in low-voltage networks with a high PV concentration, whether the explicit consideration of GOST 13109-97 constraints can enhance performance compliance in dynamic working conditions, and whether the proposed approach provides a feasible trade-off between the performance and computational efficiency aspects and the simplicity of implementation in comparison with optimization-based techniques. To answer these questions, a FLC is developed and validated using simulation models implemented in MATLAB/Simulink. The obtained results demonstrate that the proposed approach effectively reduces VUF and power losses while maintaining transparency, robustness, and suitability for practical deployment in smart distribution networks.

## 2. MATHEMATICAL MODELS

In this study, the method of balancing a three-phase ES was improved, assuming that the currents are symmetrically distributed among the phases when the supply phase of a certain number of consumers is converted into a rational phase. Load balancing can be achieved in many ways, but this section refines the method of current balancing using fuzzy logic theory. The phase currents of the three-phase distribution network are denoted as  $I_A$ ,  $I_B$ , and  $I_C$ . The voltage unbalance factor is denoted as VUF. The fuzzy logic-based corrective phase current is represented by  $\Delta I$ , while the final corrected phase current after error compensation is denoted as  $\Delta I_{final}$ .

Fuzzy logic-based control approach provides several important benefits that strengthen its applicability in low-voltage networks with distributed PV systems. It does not require a precise mathematical model of the electrical network and remains under conditions of substantial parameter variability, uncertainty, and intermittent solar generation. The approach is highly resistant to measurement noise and incomplete input information, and provides control actions that are smooth and continuous which will alleviate rapid switching and improve the overall power quality. Moreover, fuzzy controllers are described as having transparency and interpretability in architecture, as operation is clearly stipulated about sets of linguistic rules. It is also fundamentally flexible and scalable and does not require a redesign of the entire control system to incorporate new inputs, altered rule bases, or other operating constraints. These characteristics make fuzzy logic highly suitable for real-time operation in renewable-rich distribution grids [15]-[17]. The electrical network can be improved by changing the on/off position of the voltage quality assurance device in Figure 1 to make it asymmetrical.

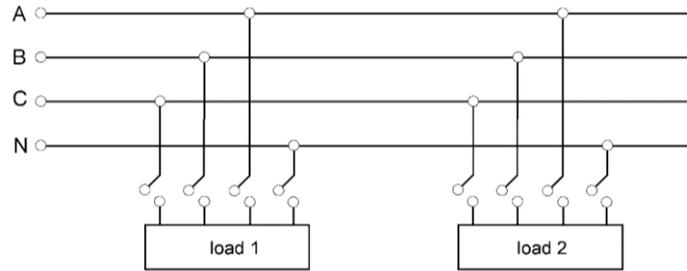


Figure 1. General view of a switchgear in a low voltage electrical network

The load currents can be transferred from phase to phase, that is, from a phase with a large load to a phase with a smaller load. However, this only helps if it is possible. This facilitates the painstaking work that is currently performed manually by installing phase shift devices. To implement the decision to change currents in the distribution PS, along with the system, current balancing based on fuzzy logic was considered. The block diagram of the proposed current balancing algorithm is shown in Figure 2.

The algorithm works in the following order:

- The coefficients of the negative  $K_{2U}$  and zero sequences of voltage asymmetry  $K_{0U}$  and data on phase currents are formed on the basis of daily measurement results.
- The voltage symmetry with the permissible and limit intervals is checked based on the conditions given in GOST 13109-97. If this condition is met, the electrical network is considered symmetrical and the calculations are completed. Otherwise, it goes to load balancing stage using fuzzy logic.
- According to the rules created on the basis of fuzzy logic from the input and output data, modified fuzzy logic currents are obtained at the output. The negative value of these currents means that the phase in consideration is overloaded and it is necessary to distribute these loads, while the current in another phase with a positive sign means that this phase is less loaded and receives these currents.
- The sum of positive and negative phase loads must be equal to zero. Otherwise, the average error is calculated, that is, it is given in the form of a matrix.
- The value of the average error current expressed in the form of a matrix is subtracted from the value of the modified fuzzy logic current at the output, and the final value of the fuzzy logic current is obtained.
- The condition that the mutual sum of the phase currents of the final fuzzy logic is equal to zero is checked. If this condition is not met, the calculation of the average error will be repeated.
- The resulting fuzzy logic ensures that the value of the phase loads in the network meets the requirements of GOST.

The algorithm works as follows. After receiving daily measurements of the asymmetry coefficients and phase currents  $I_A, I_B, I_C$ , the input current is determined as in (1).

$$I_{out} = \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{1}$$

In (1) defines the initial output current based on the measured phase currents. This value represents the current imbalance level used as an input for evaluating the degree of phase asymmetry in the distribution network. Here,  $I_{out}$  is output current;  $I_A, I_B, I_C$  are phase currents. The average current per phase, determined using as in (2), undergoes scrutiny to verify whether the asymmetry coefficient falls within permissible bounds. This check ensures that the calculated asymmetry aligns with predefined acceptable limits, thereby evaluating the electrical system's adherence to specified standards or requirements as in (2).

$$I_{a.load} = \frac{I_A + I_B + I_C}{3} \tag{2}$$

In (2) calculates the average phase current, which serves as a reference value for assessing load symmetry among the three phases. This parameter is used to determine whether the measured VUF exceeds the permissible limits defined by GOST 13109-97. Here,  $I_{a.load}$  is average current;  $I_A, I_B, I_C$  are phase currents. If the asymmetry coefficient is within acceptable limits, then the system is asymmetrical. Otherwise, we will move on to balancing currents based on fuzzy logic.

However, sometimes the fuzzy logic system may not be able to handle the exact amount of change in currents specified by the step. This is because the actual current points for any phase may not result in a rational combination corresponding to the exact change value specified in the fuzzy logic step. Thus, we

make the best possible changes to the implementation system and keep checking the balance of the system until we achieve the asymmetry coefficient within acceptable limits.

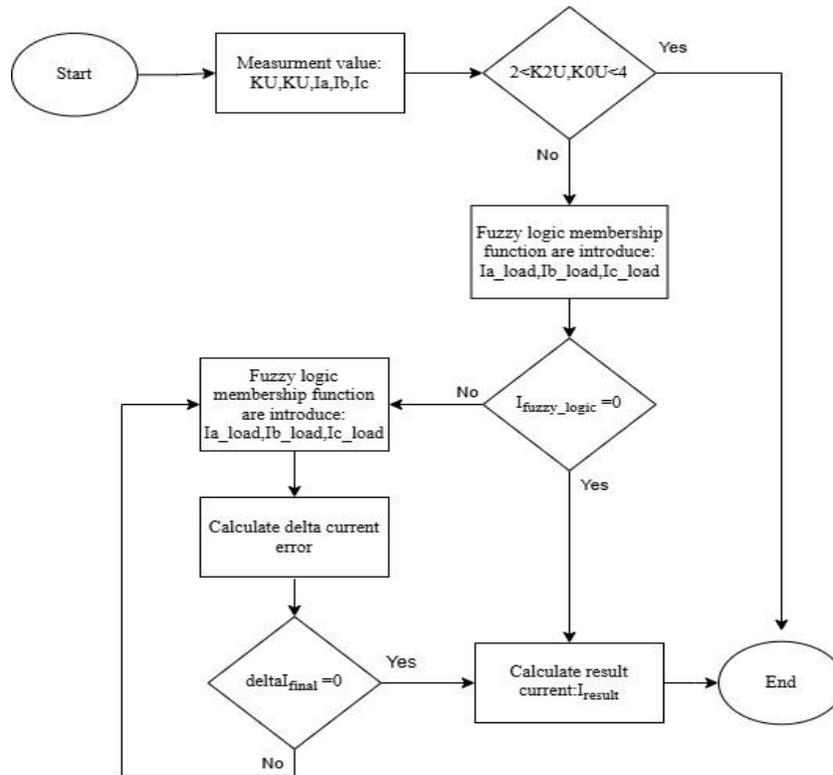


Figure 2. Block diagram of the proposed current balancing algorithm

The configuration of the fuzzy logic transformation of the output current is determined as in (3).

$$I_{fuzzy\ logic} = \begin{bmatrix} I_A\ fuzzy\ logic \\ I_B\ fuzzy\ logic \\ I_C\ fuzzy\ logic \end{bmatrix} \tag{3}$$

In (3) represents the fuzzy logic transformation of the output current. This value corresponds to the corrective current suggested by the fuzzy inference system before applying any physical constraints related to current conservation. Here,  $I_{fuzzy\ logic}$  is fuzzy logic transformation of the output current. However, we encounter an error with this current change configuration. Because the sum of a positive and a negative value is not equal, that is,  $\sum \Delta I_{fuzzy\ logic} \neq 0$ . This is impossible, because with symmetrical current we can switch the consumer current points only between three phases, without increasing or decreasing the total current equally, that is, the total current. Thus, changing the current configuration will result in a decrease in the total current. It is necessary to correct the error; for this, the average error is determined as in (4):

$$\sigma = round\left(\frac{\sum \Delta I_{fuzzy\ logic}}{3}\right) \tag{4}$$

In (4) defines the average error arising from the imbalance between positive and negative fuzzy logic output currents. This error reflects the mismatch that occurs because phase current redistribution must conserve the total current in the system. Here,  $\sigma$  is average error,  $\sum \Delta I_{fuzzy\ logic}$  is sum of a positive and a negative value of fuzzy logic current. In summary, the sentence describes a process where an error matrix is created  $I_{error}$  using the average error. The average error is then evenly distributed over three phases, and the calculation involves the current value of the load as in (5). The specific details of the phases and load are likely explained in more depth elsewhere in the context or document as in (5).

$$\Delta I_{error} = \left[ \begin{array}{c} \sigma \\ \sigma \\ \sum \Delta I_{fuzzy logic} - 2 \cdot \sigma \end{array} \right] \tag{5}$$

In (5) determines the average error current that is evenly distributed among the three phases. This step ensures that the corrective current adjustments do not artificially increase or decrease the total network load. Here,  $\Delta I_{error}$  is average error current;  $\sum \Delta I_{fuzzy logic}$  is sum of a positive and a negative value of fuzzy logic current. This part of the sentence describes a subtraction operation. The symbol  $\Delta I_{error}$  represents the error in some variable (probably current, based on the context), and  $\Delta I_{fuzzy logic}$  represents the uncorrected output from a fuzzy logic system. So, you are subtracting the error from the uncorrected fuzzy logic output  $\Delta I_{final}$  as in (6).

$$\Delta I_{final} = \Delta I_{fuzzy logic} - \Delta I_{error} \tag{6}$$

In (6) calculates the final fuzzy logic-based corrective current  $\Delta I_{final}$ . In practical terms,  $\Delta I_{final}$  represents the actual current correction applied to each phase after compensating for conservation errors, ensuring physically feasible load redistribution. Here,  $\Delta I_{final}$  is fuzzy logic output current;  $\Delta I_{fuzzy logic}$  is fuzzy logic current;  $\Delta I_{error}$  is average error current. The final value of the fuzzy logical current is required to meet condition as in (7). If it fails to comply with this condition, a process is triggered where the values undergo re-determination. This ensures that the specified condition as in (7) is satisfied in the final configuration.

$$\sum \Delta I_{final} = 0 \tag{7}$$

In (7) enforces the current conservation constraint by ensuring that the sum of the final corrective currents across all phases equals zero. This condition guarantees that load balancing is achieved solely through phase redistribution. Here,  $\sum \Delta I_{final}$  is final value of the fuzzy logical current. The resulting output is determined as in (8).

$$I_{res.} = I_{out} + \Delta I_{conf.} \tag{8}$$

In (8) determines the resulting phase current after applying the final corrective current. This value represents the updated phase current configuration used to reassess the VUF. Here,  $I_{res.}$  is result current;  $I_{out}$  is output current,  $\Delta I_{conf.}$  is current configuration. Applying (1) and (8) in (2) the values of the initial absolute average symmetry and the resulting absolute average symmetry are determined. This makes it possible to reduce voltage asymmetry according to requirements.

The current points are then determined to be allocated for the current reduction steps. Repeat for all three phases to check for negative (diminutive) phases. For each of the output phases, the average load value of this phase is first calculated. Then, by dividing the current change value by the average value and rounding the result, the number of current points that will be changed from this phase is determined as in (9).

$$N_i = round \left( \frac{\Delta I_{fuzzy logic}}{\sum_{j=1}^n \text{phase } I_j^i / n} \right), \quad i \in \{1,2,3\} \tag{9}$$

Here,  $n$  is the number of connected consumers,  $\Delta I_{fuzzy logic}$  is fuzzy logic current. Using the given method, a specific load point  $N_i$  is determined, which must move from phase  $i$  to another phase. Here  $i$  shows the distributed phases. After this, special current points are taken that must go to another phase, and the sequence is repeated for the next distribution phase. Algorithm for selecting a current point based on the algorithm is briefly explained below. The task is to find a set of current points of 32 current points (for phase  $i$  distribution), the sum of the set is equal to the load change value based on fuzzy logic as in (10) and (11).

$$i \text{ phase} = \{I_j^i, \quad j = 1, \dots, n\} \tag{10}$$

$$N_i = \{I_k^i, \quad k = 1, \dots, N_i\}, \quad I_k^i \in i \text{ phase} \tag{11}$$

Here,  $N_i$  is specific load point,  $i$  is for phase distribution. The difference between the sum of the elements of the distributed set of load points and the change value based on fuzzy logic for this phase should be minimal, ideally 0. Thus, the optimal set  $N_i$  should be found by performing the following task as in (12).

$$\text{argmin} |N_i - I_{fuzzy\ logic}| \tag{12}$$

This statement indicates the presentation of the current change value specific to the *i*-th fuzzy logic phase using fuzzy logic methodology. The displayed information likely represents the variation in current within a phase, reflecting the application of fuzzy logic principles to capture nuanced changes in the current associated with the *i*-th phase of a system or process. Compliance with GOST 13109-97 is verified by evaluating the resulting VUF after each iteration of the fuzzy logic-based correction. The control process is terminated when the calculated VUF falls within the permissible limits specified by the standard.

### 3. SIMULATION MODELS

Figures 2–8 are presented using consistent graphical notation and labeling to improve readability. Standardized symbols are employed to represent measurement, decision-making, and control processes, while unified terminology is used across all block diagrams to clearly illustrate the fuzzy logic-based phase load balancing workflow. To build a fuzzy control algorithm, the fuzzy logic toolbox software package was used in the MATLAB environment [18]. In the considered fuzzy interval system there are two input linguistic variables - the coefficient of voltage and phase current asymmetry, and one output linguistic variable - the configuration of the fuzzy logical transformation of the output current [19].

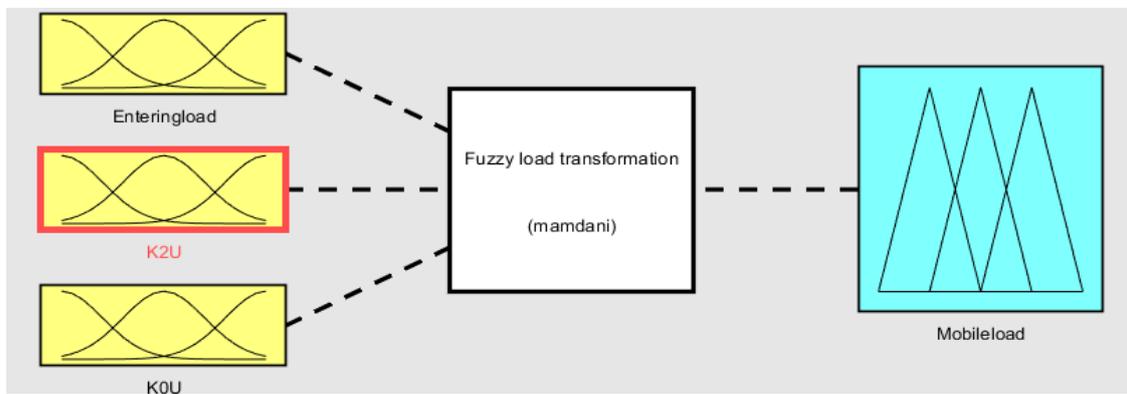


Figure 3. Block diagram of fuzzy load transformation

To make logical decisions, the considered fuzzy expert system is shown in Figure 4. According to the above linguistic variables for the system proposed in Figure 4 contains 136 fuzzy logical rules. Thus, for the linguistic variable “voltage asymmetry coefficient” there are five terms (Figure 5): low– low voltage; NA–normal allowed voltage; LA – low allowed voltage; High– high voltage as given in Table 1.

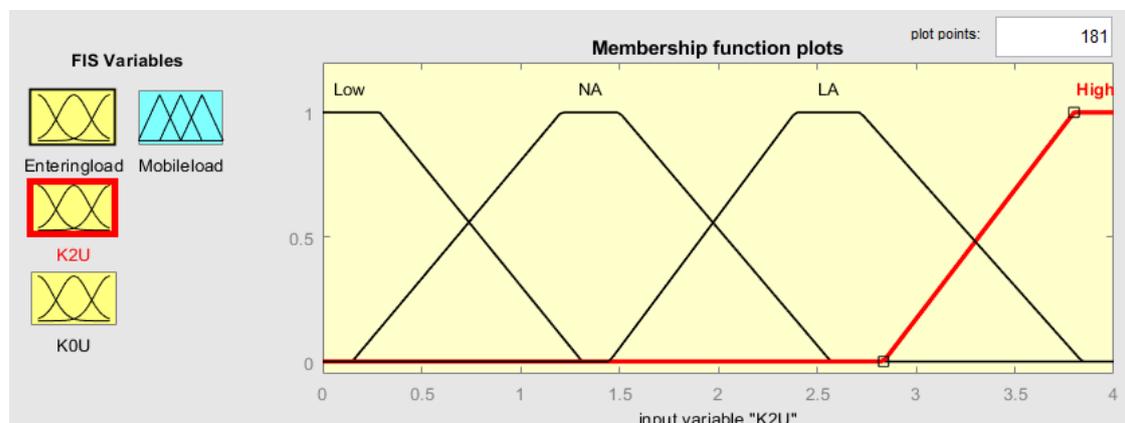


Figure 4. Linguistic variable “voltage asymmetry coefficient”

For the linguistic variable “phase current” there are eight terms (Figure 6): FL – few loaded; MFL - moderately few loaded; ELL – extremely low load; LL – low load; NL – normal load; OL – over load; NOL – normal over load; EOL – extremely over load.

For the linguistic variable “configuration of the fuzzy logical transformation of the output current” – eight terms (Figure 7): HM– high mobility; M - mobility; AM– average mobility; LM– low mobility; NA– normal addition; MA– middle addition; HA – high addition; EHA – extremely high addition.

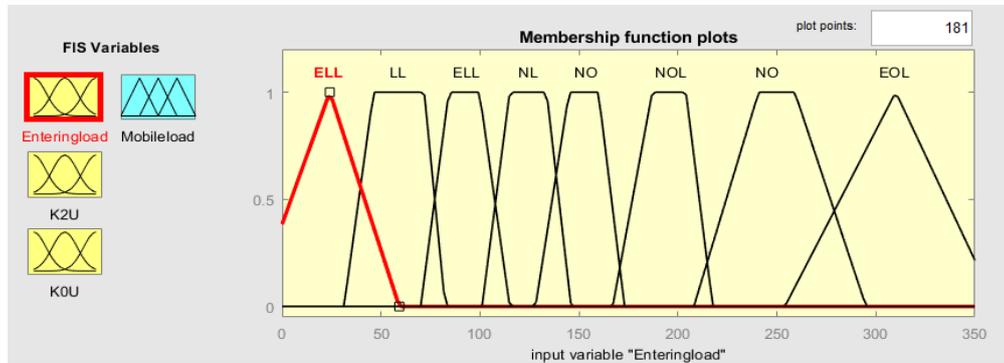


Figure 5. Linguistic variable “phase current”

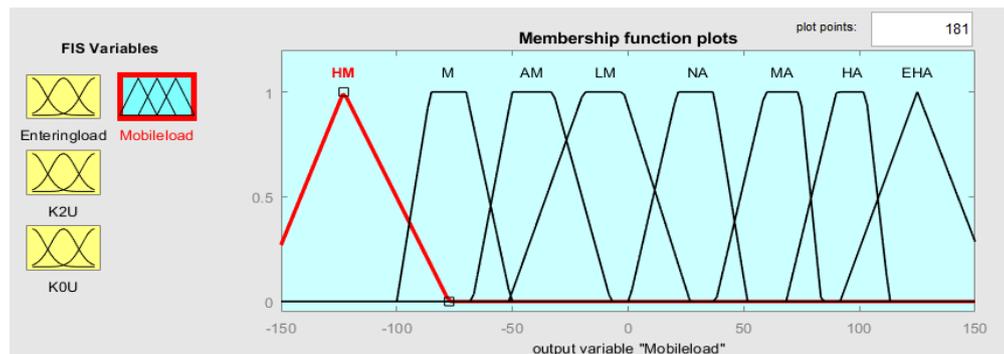


Figure 6. Fuzzy logic membership function for output current conversion

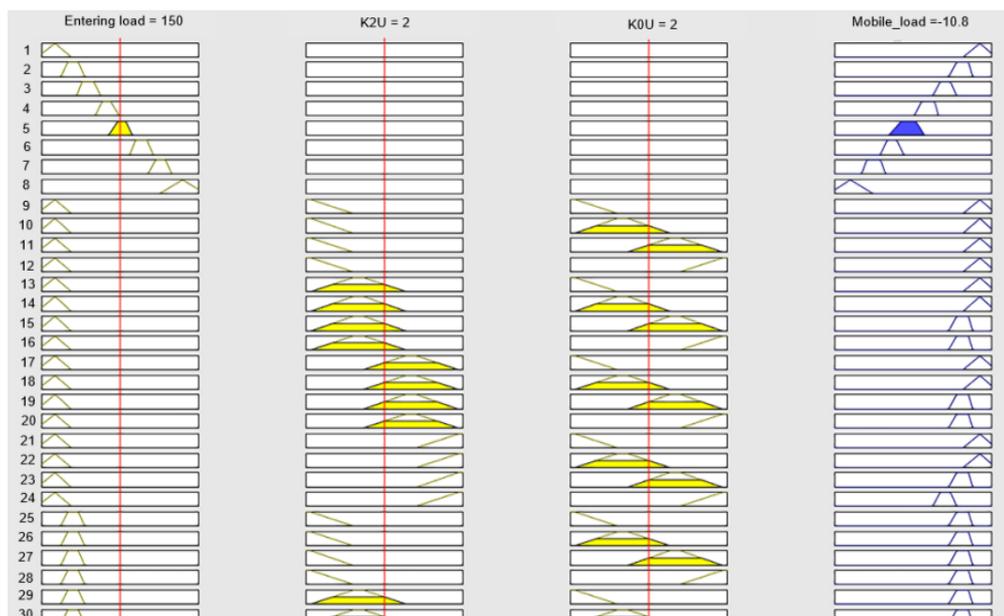


Figure 7. Decision making procedure

Table 1. Name of abbreviated words

Abbreviation	Extension
Low	low voltage
NA	normal allowed voltage
LA	low allowed voltage
High	high voltage
FL	few loaded
MFL	moderately few loaded
ELL	extremely low load
LL	low load
NL	normal load
OL	over load
NOL	normal over load
EOL	extremely over load
HM	high mobility
M	mobility
AM	average mobility
LM	low mobility
NA	normal addition
MA	middle addition
HA	high addition
EHA	extremely high addition

In this process, a set of logical rules is established using the IF-then structure. These rules govern the relationship between input and output variables and are documented as in Table 2. Essentially, the rules provide a framework for decision-making, specifying how changes in input conditions correspond to changes in output variables within the defined system.

VUF is explained by using five lingo words to achieve a trade-off between the accuracy of the models and the ease of computation. The chosen quantity of terms enables the controller to know the difference between normal operating conditions, permissible deviations, and critical unbalance levels established by GOST 13109-97. The size of the vocabulary should be minimal to define slow variations in VUF, whereas employment of more terms would raise the complexity of the rule base without any improvement in performance. Phase current is modeled by eight words of language to describe a broader spectrum of variation of loads between phases. Contrary to VUF, phase current directly indicates the extent of loading and must be finer to distinguish lightly loaded, normally loaded and overloaded phases. This is achieved by using eight linguistic terms that allow a fine distinction of the load conditions that enhances redistribution of the phase current, especially when there are fluctuation in load and PV generation.

Time-domain simulations were performed in order to give some quantitative understanding of the system behavior to determine the dynamic performance of the VUF. The results obtained prove the rapid value of VUF reduction after the FLC activation, which confirms the fast conditions of its operation and PV production. The input and output membership functions displayed in graphical form in the FLC are presented in Figures from 4 to 7. Figure 4 shows the membership functions of the VUF, Figure 5 shows the membership functions of phase current and Figures 6 and 7 show the output membership functions of the FLC corrective current. Such graphical dependencies are what determines how physical measurements relate to linguistic variables that are employed in the fuzzy inference process.

Table 2. Fuzzy logic rules for input and output variables

K2U	K0U	ELL	LL	ELL	NL	NO	NOL	OL	EOL
N	N	EHA	HA	MA	NA	LM	AV	M	M
	ND	EHA	HA	MA	NA	LM	AV	M	M
	OL	EHA	HA	MA	NA	LM	AV	M	HM
NA	M	EHA	HA	NA	NA	LM	AV	M	HM
	H	EHA	HA	MA	NA	LM	AV	M	M
	NA	EHA	HA	MA	NA	LM	AV	M	M
LA	LA	HA	HA	MA	NA	LM	AV	M	HM
	M	HA	MA	NA	LM	AV	M	HM	HM
	H	EHA	HA	MA	NA	LM	AV	M	HM
H	NA	EHA	HA	MA	NA	LM	AV	M	HM
	LA	EHA	HA	MA	NA	LM	AV	M	HM
	LA	HA	MA	NA	NA	LM	M	HM	HM
H	M	HA	MA	NA	LM	AV	M	HM	HM
	H	EHA	HA	MA	NA	LM	AV	M	HM
	NA	EHA	MA	NA	NA	LM	M	HM	HM
H	LA	HA	MA	NA	LM	AV	M	HM	HM
	M	MA	NA	NA	LM	AV	M	HM	HM

#### 4. RESULTS AND DISCUSSION

In the case of VUF, Mamdani algorithm, which is a fuzzy logic technique, was chosen. The reason behind the choice of the Mamdani fuzzy inference method is that it offers high interpretability of the control decisions, it allows the fuzzy output to be completely utilized and it is easy to visualize the impact of the input parameters on the resulting control action which is very fundamental when analyzing VUF processes in low-voltage networks with distributed PV generation.

In addition, Mamdani is more appropriate in systems that are nonlinear and have uncertainty in its operation. The Sugeno approach was not used since it results in a crisp mathematical result and is biased towards the use of an explicit analytical control function which is not well suited in highly varying load conditions and unsteady PV generation. Therefore, the preference of Mamdani can be explained by the flexibility, clarity and qualitative consideration of control actions in the offered methodology. Figure 7 illustrates the results of this choice, which probably represents the results or performance of the Mamdani algorithm in the scenario of present balancing [20], [21].

The complexity of the computational procedure of the proposed fuzzy logic-based approach depends on the quantity of the rules in the knowledge base, the quantity of variables as the inputs, and the form of the membership functions [22]. As it is shown in the given model, the FLC utilizes a limited number of membership functions together with two input variables which leads to a small rule base. This makes the computation load to be moderate and appropriate to run in real-time.

The fuzzification, rule evaluation and defuzzification are linearly proportional to the number of rules in the system and so the entire algorithm is computationally efficient and can easily be modified to more complex network structures should this be necessary. In contrast to an optimization-based approach, e.g., GA, PSO or neural networks, fuzzy logic does not make use of an iterative process or a training process, which minimizes the computational burden. Hence, the FLC controller proposed has low computational complexity and can be effectively used in embedded systems, distributed PV controllers, and decentralized control architecture of the low-voltage distribution networks.

Phase symmetrization of low-voltage networks which are distributed PV generation systems used the 2-FLC controller. The FLC design involves the specification of input and output variables, building of fuzzy sets and IF-THEN rules, choice of a defuzzification method as well as visualizing the control surfaces. To put it into practice, one may apply microcontrollers, DSP processors, digital voltage and current sensors to measure the values properly, and adaptive DC-DC converters. Implementation software implementation may be done in MATLAB/Simulink using the fuzzy logic toolbox or embedded libraries.

As shown in Table 3, the proposed FLC approach achieves a reasonable balance between accuracy, response speed, and practical implementability compared with other optimization-based methods. The proposed FLC has been tested using a comparative analysis of the modern techniques, such as the genetic algorithm (GA), particle swarm optimization (PSO), and heuristic techniques. The major criteria were the reduction of phase unbalance (VUF), response time, computational complexity, and interpret-ability. Although intelligent adaptive solutions such as fuzzy logic or AI-solutions are more flexible, they are more costly to calculate, need initial training using a set of past values, and can cause decision delays. Therefore, FLC is more practical since it offers high interpret-ability, low computational load and fast response to low-voltage networks with PV generation.

Table 3. Comparison of phase control methods in LV networks with PV

Method	VUF reduction (%)	Loss reduction (%)	Response time	Computational complexity	Interpretability
Fuzzy logic	25–30	12–15	Fast	Low	High
Genetic algorithm	28–32	14–16	Medium	High	Low
Particle swarm optimization	27–31	13–15	Medium	High	Low
Heuristic method	15–20	8–10	Fast	Low	Medium

A comparison shows that the proposed FLC has attained a reasonable balance between accuracy, speed, and practical implementability whereas more complicated optimization-based approaches need computational resources as well as more complicated realizations. In this research, the sensitivity analysis of the developed FLC on the most important parameters, such as the type and form of membership functions, the number of linguistic terms, the arrangement and weighting of the rules, and the defuzzification method was carried out. In order to measure the impact of these parameters on phase symmetry performance, scenario simulations were undertaken by changing each of the parameters by up to 10-20% and monitoring phase change in the VUF, among other power quality indicators. The findings revealed that the shape and the range of the membership functions is the one that exerts the most important influence whereas the slight alteration of the rules or defuzzification techniques does not introduce severe deviations in the output.

This discussion provides evidence of the strength of the proposed FLC and guidance of the next optimization and adjustment of the network conditions.

Figure 8 is three-dimensional graph, which shows changes in the voltage asymmetry coefficient and phase load. This presentation is used as an example of a fuzzy algorithm, presenting the connection of these parameters visually and in a holistic way. The input value is chosen as VUF and phase currents i.e., total phase load (A) on each of the three phases and the output value is chosen as fuzzy logic transformation configuration output currents i.e., change [23]-[25].

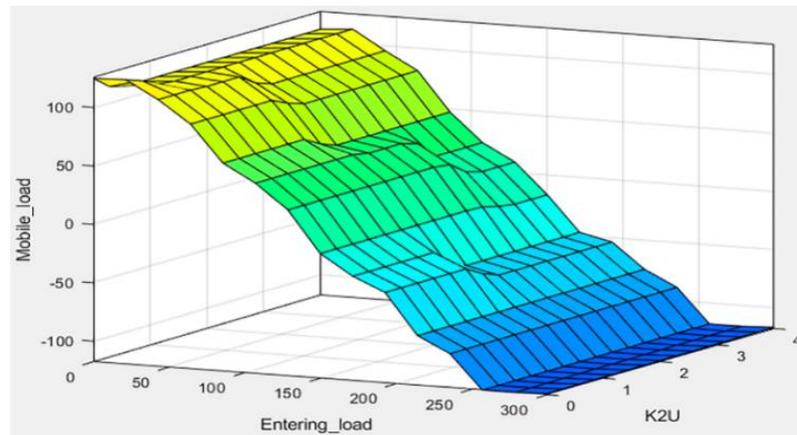


Figure 8. Temperature graph of the formation of the resulting output current

## 5. CONCLUSIONS

This paper outlined a phase load balancing technique using fuzzy logic that would help in minimizing VUF and enhancing quality of power in low-voltage distribution networks with PV integration. The proposed approach guarantees regulatory compliance without increasing computational complexity or high interpret-ability since the voltage symmetry constraints given by the GOST 13109-97 standard are explicitly implemented in the fuzzy inference process.

The simulation findings in MATLAB Simulink proved that the obtained FLC may be successfully used to decrease VUF by about 25-30% and decrease active power losses by 12-15% under asymmetric loading conditions. This is helping to cause improvement in voltage regulation, less thermal stress on the electric equipment and more stability of the distribution networks in operation. The proposed solution is also quite suitable to practice in the smart grid setting because of its rule based design and low calculation needs, such as decentralized controllers, micro controller based systems, and distributed PV inverters.

In practical terms, the fuzzy logic-based controller may be implemented into the intelligent distribution automation systems to facilitate real time phase load balancing in networks with large penetration of renewable energy sources. It can be adjusted to varying load patterns and intermittent PV generation, which is why it is a potential solution to the future smart grids and active distribution networks.

In spite of these strengths, the current study has some shortcomings. The proposed method has only been validated through simulation analysis and experimental validation by hardware-in-the-loop or field-deployed equipment is yet to be conducted. Also, the present model presupposes the precise measurements of phase currents and VUF, without specifically taking into account communication delays or sensor errors that can be encountered in practice.

Future studies will be on the extension of the proposed framework by incorporation of hybrid fuzzy-artificial intelligence algorithms like neuro-fuzzy and adaptive fuzzy controllers in order to increase the learning ability and flexibility. The integration of real time communication infrastructures and distributed control architectures and experimental validation using hardware implementation and field experiments in operational low-voltage distribution networks will also be undertaken further.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the facilities provided by Zhengzhou Research Institute, Beijing Institute of Technology and Department of Energy Engineering, Fergana State Technical University for the accomplishment of this work and the Uzbekistan Government for their financial support.

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