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Estimation of power quality in distribution system using fuzzy logic theory

Adeel Saleem[1], Kholiddinov Ilkhombek Khosiljonovich[1], Kholiddinova Mashkhurakhon Mutalibjon Qizi[1], Komolddinov Sokhib[1], Sharobiddinov Mirzohid Shakhobiddin Ugli[1], Soliev Sokhibjon Obidovich[2]
[1]Department of Electrical Engineering, Faculty of Energy, Ferghana Polytechnic Institute, Ferghana, Uzbekistan
[2]Head of the Regulatory and Technical Department, Emergency Mangement, Ferghana, Uzbekistan

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ABSTRACT

There are several methods are used to calculate the power quality indicators. These objectives are now served by the most recent soft computing theories, such as neural networks, fuzzy time series, fuzzy logic theory, and other techniques. The fuzzy logic theory is one of the methods used to calculate the power quality indicators for the distribution electric network in this paper. It resolves the issue of forecasting the voltage values on distribution electrical networks' buses and enhances the quality of electricity in the face of fluctuating consumer loads and uncertainty. This paper proposed a device that has the ability for monitoring the quality of electricity domestically which leads to getting rid of many problems such as voltage deviations and asymmetrical faults. The fuzzy logic theory is implemented to develop the algorithm for this purpose. The actual data is recorded at the distribution transformer and implement the fuzzy logic theory by using a mathematical model as well as the simulation on MATLAB for optimizing the power quality indicators with the help of fuzzy logic theory and results are discussed at the end of the paper.

Corresponding Author:

Adeel Saleem
Department of Electrical Engineering, Faculty of Energy, Ferghana Polytechnic Institute
Fergana, Uzbekistan
Email: a.saleem@ferpi.uz

1. INTRODUCTION

The application of new soft computing theories has recently been used to solve several issues. For the distribution and transmission of electrical networks, there are some concerns related to power quality issues [1], [2]. The distribution and transmission phase of the electrical power system requires voltage management. Transformers must be used whenever a change in voltage level is necessary [3], [4]. The turn radius of these transformers is typically set, although sometimes they have tap terminals for turn-ratio control. Tap changers can work in one of two modes: off-load tap changer or on-load tap changer (OLTC). The tap position is dependent upon many factors such as circulating current, primary voltage, load, power factor, and distributed generation. It is necessary to manage voltage in distribution networks with distributed generation as a result of abnormal voltage rise [5], [6]. The demand for reactive power can contribute to poor power quality by unnecessarily loading the supply system. Harmonic pollution, load imbalance, and excessive voltage imbalance can also be to blame for this since they put extra stress on networks and other loads connected to the same network [7]. Monitoring power quality disturbances is the preliminary step for electrical networks [8]. The list of different power quality disturbances that could occur in a power distribution situation is provided in [9]. It was determined that the majority of the voltage sags have an approximate magnitude of 80%. The duration of the voltage sags varied between 4 to 10 cycles, and the total harmonic distortion is roughly 1.5 times the standard value [10]. These voltage issues are sometimes due to the integration of solar panels and renewable energies with the power grids and used for the charging of electric stations for charging electric vehicles [11], [12]. Signals causing power disturbances are categorized using pattern recognition techniques (PRT). It is a method of identifying a pattern in a given object based on previous knowledge [13]. Therefore, automated PRT classifies disturbance signals using a variety of artificial intelligence (AI) approaches, including fuzzy logic (FL) and artificial neural network (ANN). A basic overview of all such strategies that are relevant to power quality studies is provided in [14]. The next method in pattern recognition techniques is ANN and FL [15]. Because the human brain learns from prior experiences and doesn't make decisions based on clearly defined criteria, these intelligent systems have been built and several approaches that combine both ANN and FL are summarized in [16]. An advanced processing tool known as the wavelet transform can be employed in a variety of detection and analysis approaches, including power quality (PQ) disturbance detection [17]. At low frequencies, wavelets offer precise frequency resolution but poor time localization. While at high frequencies, they offer exceptional time localization and frequency resolution.

Numerous scholars have looked at this wavelet property's [18], [19] ability to categorize power quality disturbances. The feasibility of using continuous wavelet transform (CWT) and multi-resolution analysis for the detection of disturbances is investigated, and the analysis demonstrates the ability to detect frequency transients as well as power transients in the signals. The S-transform, an extension of wavelet transform (WT), was proposed and had very demanding time-frequency resolution properties [20]. The use of a fuzzy system was suggested as a method for identifying and categorizing PQ disturbances [21], [22]. The test signal is compared with the saved templates using the dynamic time wrapping (DTW) approach, which was also developed from dynamic programming and is shown in [23]. This method is computationally inefficient and have a series of observations are produced using a basic double stochastic process [24]. To assess the possibility of a proposed hypothesis, dempster-shafer takes into account several pieces of evidence. The approaches found in [25] use the study on this dempster-shafer theory. For the categorization of signals, a technique is used which is a combination of fuzzy system and fourier linear combiner (FLC). The FLC calculates the voltage signal's peak amplitude as well as its rate of change. The values produced by FLC are the input to the fuzzy system, which further classifies the PQ disturbances. The theory of fuzzy sets is currently under development and is used extensively in many technological fields. The theory of fuzzy sets is founded on the concept that people often think and act under fuzzy assumptions. The development of fuzzy set theory represents an effort to capture human thinking and for this, the fuzzy set theory is based on an algorithm. Fuzzy systems are superior to other control systems in [26]. The ability to work with fuzzy input data, the potential for formalizing evaluation and comparison criteria in a fuzzy manner, working with the terms "majority," "possibly," and "predominantly". It conducts qualitative analyses of both input data and output results, being able to work not only with data values but also with their degree of reliability and distribution along with able to quickly model complex dynamic systems. After the detailed survey of the literature review FL theory is used in this paper for the evaluation of the power quality indicators. The configuration setup and proposed method are discussed in section 2, whereas section 3 comprises the implementation of FL theory. Section 4 of this paper presents the simulation results and ended up with the conclusion in section 5.

2. METHOD

Since the power system consists of three main categories such as generation, transmission, and distribution which makes it complex. Of course, a complicated interconnected transmission system is required for transmitting the electricity generated by the generating units. To connect nearby utilities, transmission lines are employed. The transferring of power to the different regions of the country is done through the transmission lines during normal conditions and as well as in abnormal conditions. The power is then distributed through underground or overhead lines from substations to the consumer end. According to the equipment used, which may include numerous lighting, heating, and cooling systems, the power system load can be divided into three categories: industrial, commercial, and domestic. Thus, for everybody who depends on power systems and equipment, power quality becomes a crucial factor. Therefore, it will not be entirely impractical to suggest that utilities, equipment manufacturers, and customers all have completely different perceptions of what constitutes good power quality. In the case of utilities, the power quality is handled based on the stability of the system. When it comes to clients, they take into account the power quality as a safeguard against interruptions in the supply of electricity. Many instruments assess and analyze power quality indicators in literature. All of them focus on the fact that measurements are completed within a particular period. As seen in Figure 1, the authors of this paper have created a device that, in compliance with a set of international technical standards gosudarstvennyy standart (GOST) specifications, measures power quality indicators in electrical networks with a voltage ranging from 220-380 V. The Fergana region's Kush-tepa and Kuva districts are where the actual data is recorded utilizing this device. The measured results show that it does not meet the requirements of

GOST and has the following shortcomings such as steady-state voltage deviation, distortion coefficient, nth harmonic coefficient, and asymmetry coefficient for zero and negative sequence. After investigation, the asymmetry zero-sequence current coefficient is 33.5% and the asymmetry negative sequence current coefficient is 30.3% for this feeder. This demonstrates the feeder's systematic asymmetry. Therefore, it is possible to lower the coefficients of the reverse and zero sequence currents to 15% by balancing the loads in phases during the hours of the maximum load. The GOST standard states that the normal and maximum permitted values of the voltage asymmetry coefficient in reverse and zero sequences are 2% to 4%. According to the country's regulations, the electrical power supply must produce a pure sine wave that complies with the requirements of the system and has zero impedance at all frequencies. Every electricity supplier in Uzbekistan is required to supply a sine wave with a set voltage of 220 V for residential customers or 380 V three-phase for many business or industrial clients. This sine wave must have a frequency of 50 Hz. Therefore, offering the clients a pure sinusoidal waveform is crucial. The difficulty, however, is that it is difficult to measure the power quality.

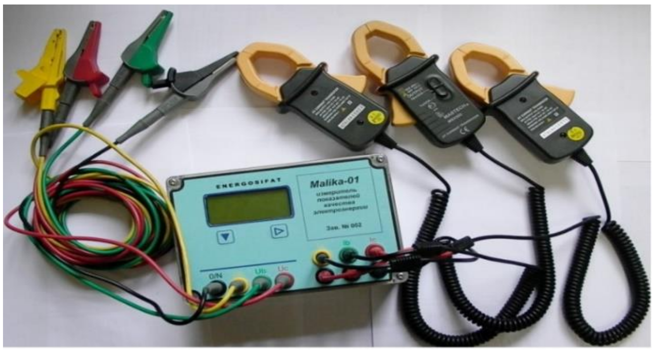

Figure 1. General view of the device

A lot of research has been done on power quality concerns and how to handle them, and there is now a lot of research being done in this area. The supply network or the load itself may be the source of the power quality incidents. It has been noted that voltage magnitude variations, manifested as voltage fluctuations, are primarily responsible for power quality incidents. Other voltage supply issues include voltage sags, flickers, interruptions, and transient excess voltage. It is vital to study and investigate the different sorts of power quality events since users may experience a wide range of distinct power quality events. Understanding the impact of power quality events is also highly important. Recent electrical energy systems have fewer sinusoidal and periodic waveforms, which has led to a more unstable supply. The steady-state behavior has changed as a result of the vast number of non-linear loads and generators. These systems consist of drives, inverters, high-efficiency lighting, power electronics-based systems, power supply for information technology (IT) equipment, and adjustable speed drives. Therefore, a power quality study is required to characterize the disturbances based on common metrics such as voltage disturbances (unbalance and fluctuations) and waveform distortions.

3. IMPLEMENTATING FUZZY LOGIC THEORY

Any practical problem must first be correctly understood to be solved, and this understanding serves as the foundation for choosing an appropriate mathematical model. This is particularly true for inadequately defined work that involves rational decision-making in the presence of fuzzy uncertainty. A fuzzy set is a type of mathematical model for fuzzy uncertainty. It can be seen as a fuzzy uncertainty version of the crisp (Cantorian) set. As a result, there are two segments to the fuzzy set: crisp and fuzzy. The first of them illustrates the object's full membership in the set in the sense that it possesses an inherent property, whereas the second component illustrates the object's partial ownership of this property. To understand this let's have any universal set in which a be an element of this universal set, and have another set inside the universal set which have some properties or conditions. Then C will be an ordinary subset for this universal set which satisfies the set of properties as in (1) and it can be defined as a set of ordered pairs.

$$C = \{\frac{\mu_C(a)}{a}\} \tag{1}$$

Where $\mu_c(a)$ is a characteristic membership function taking values in some completely ordered set e.g. [0,1] which is known as the set of accessories. The membership function indicates the degree of memberships of the element a to the subset C. The rules of choice in a fuzzy situation, of course, are different depending on what exactly is fuzzy in this situation. The problem of choice is solved simply and elegantly if the criterion functions are identified with the membership functions. However, in practice there are other problems; for example, any parameter of a criterion function that is not itself a membership function can be fuzzy. As in (2) shows that the fuzzy sets characterize alternative options in terms of various criteria.

$$C_1 = \left\{\frac{\mu_{C_1}(a_1)}{a_1};\frac{\mu_{C_1}(a_2)}{a_2};\dots\dots\dots\dots\frac{\mu_{C_1}(a_m)}{a_m}\right\};$$

$$C_2 = \left\{\frac{\mu_{C_2}(a_1)}{a_1};\frac{\mu_{C_2}(a_2)}{a_2};\dots\dots\dots\dots\frac{\mu_{C_2}(a_m)}{a_m}\right\};$$

$$C_i = \left\{\frac{\mu_{C_i}(a_1)}{a_1};\frac{\mu_{C_i}(a_2)}{a_2};\dots\dots\dots\dots\frac{\mu_{C_i}(a_m)}{a_m}\right\};$$

$$C_n = \left\{\frac{\mu_{C_n}(a_1)}{a_1};\frac{\mu_{C_n}(a_2)}{a_2};\dots\dots\dots\dots\frac{\mu_{C_m}(a_m)}{a_m}\right\}. \quad (2)$$

Here have to make selection rules, for this if the criteria are C_i have different importance. Each of them is assigned a number $a_i > 0$, if there are more criteria then there are more a_i. This is all depend on the estimation parameters and may differ from one case to another and as in (3) shows the form of selection rules.

$$D = C_1^{a_1} \cap C_2^{a_2} \cap \dots \cap C_n^{a_n},$$

$$a_i > 0, i = 1 \dots n, \frac{1}{n}\sum_{i=1}^{n} a_i \quad (3)$$

The coefficients of relative importance are determined based on the procedure of paired comparison of criteria. The first step is to construct the matrix M as given in (4). The order of the matrix is depend on the estimation parameters and it may varies in different cases.

$$M = \begin{bmatrix} m_{11} & \dots & \dots & m_{1j} & \dots & \dots & m_{1n} \\ m_{21} & \dots & \dots & m_{2j} & \dots & \dots & m_{1n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & m_{ii} & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ m_{n-1\,1} & \dots & \dots & m_{n-1\,j} & \dots & \dots & m_{n\,n-1} \\ m_{n\,1} & \dots & \dots & m_{n\,j} & \dots & \dots & m_{n\,n} \end{bmatrix} \quad (4)$$

The elements of matrix M should be like that in which they satisfy the condition of $m_{ii} = 1$ and $m_{ij} = 1/m_{ji}$. Thus, the matrix of paired comparisons of criteria given by fuzzy sets has the form as given in (5). The given matrix satisfies the off-diagonal condition and as well the diagonal values of the matrix should be unity.

$$M = \begin{bmatrix} 1 & \dots & \dots & m_{1j} & \dots & \dots & m_{1n} \\ \frac{1}{m_{12}} & \dots & \dots & m_{2j} & \dots & \dots & m_{1n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{1}{m_{n-1\,1}} & \dots & \dots & \frac{1}{m_{n-1\,j}} & \dots & \dots & m_{n\,n-1} \\ \frac{1}{m_{n\,1}} & \dots & \dots & \frac{1}{m_{n\,j}} & \dots & \dots & 1 \end{bmatrix} \quad (5)$$

Then the next step is to find the eigenvector of the matrix M, corresponding to the maximum eigenvalue λ_{max}. Finding the maximum eigenvalue of the matrix of paired comparisons of criteria given by fuzzy sets is of fundamental importance. Since it determines the eigenvector which holds the values of the coefficients of the relative importance of the criteria and modified the sets C_j. Modifying the above matrix for the particular case as given in (6) which have two criteria (improving the quality of voltage with a decrease in higher harmonics, or improving the quality of voltage with symmetry voltages).

$$M = \begin{bmatrix} 1 & \alpha \\ \frac{1}{\alpha} & 1 \end{bmatrix} \quad (6)$$

The next step is to find the eigenvalues of the modified matrix. According to the particular case where have two criteria (quality of voltage against higher harmonics and symmetry voltage) it modifies as shown in (7). Then from this can find the characteristic equation.

$$\begin{bmatrix} 1-\lambda & \alpha \\ \frac{1}{\alpha} & 1-\lambda \end{bmatrix} = 0 \quad (7)$$

As this article uses FL to estimate the power quality indicators so this mathematical model is utilized for the particular example. The purpose is to validate the mathematical model for estimating the power quality estimation. The first step is to take several parameters which can decide the power quality for any power system. It is mandatory to take that parameter which can decide the quality of power and then can use the FL theory for power quality estimation. Table 1 shows the elements of paired comparisons for power quality by which taking three parameters such as voltage deviation, asymmetry voltage, and non-sinusoidal voltage which are the most important factors of any power system to estimate the power quality.

Table 1. Matrix of paired comparisons for power quality estimation

Index	Voltage deviation	Asymmetry voltage	Non-sinusoids voltage
Voltage deviation	1	3	9
Asymmetry voltage	1/3	1	1/5
Non-sinusoids voltage	1/9	5	1

Next step is to construct the matrix according to specific scenario which leads to find characteristics equation. For this the eigenvalues of the modified matrix as in (8) can be used to determine the characteristic equation. Now for this particular example the characteristics equation is of 3rd order and have three roots.

$$\begin{bmatrix} 1-\lambda & 3 & 9 \\ \frac{1}{3} & 1-\lambda & \frac{1}{5} \\ \frac{1}{9} & 5 & 1-\lambda \end{bmatrix} = 0 \quad (8)$$

Find the eigenvector corresponding to the maximum eigenvalue from the corresponding system of equations as in (9). Here for this purpose have three equations as discussed earlier. In this case the estimation criteria is depend on three parameters such as voltage deviation, asymmetry voltage and non-sinusoids voltage.

$$(1-\lambda_1)x_1 + 3x_2 + 9x_3 = 0$$

$$\frac{1}{3}x_1 + (1-\lambda_1)x_2 + \frac{1}{5}x_3 = 0$$

$$\frac{1}{9}x_1 + 5x_2 + (1-\lambda_1)x_3 = 0 \quad (9)$$

The second last step is to get fuzzy sets. As in (9) is to find the relative importance coefficients of criteria and put these in (2). After solving this corresponding equation and get the result as in (10). Here the parameters are taken as three so getting the C_1, C_2 and C_3.

$$C_1 = \left\{\frac{0.20}{\alpha_1};\frac{0.08}{\alpha_2};\frac{0.23}{\alpha_3};\frac{0.48}{\alpha_4};\frac{0.63}{\alpha_5};\frac{0.81}{\alpha_6}\right\}$$

$$C_2 = \{\frac{0.79}{\alpha_1};\frac{0.05}{\alpha_2};\frac{0.76}{\alpha_3};\frac{1}{\alpha_4};\frac{0.64}{\alpha_5};\frac{0.79}{\alpha_6}\}$$

$$C_2 = \{\frac{0.72}{\alpha_1};\frac{0.10}{\alpha_2};\frac{0.42}{\alpha_3};\frac{0.55}{\alpha_4};\frac{0.64}{\alpha_5};\frac{0.22}{\alpha_6}\} \quad (10)$$

The last step is to define the selection rules. So, for this purpose following the pattern as shown in (3) which gets a set containing the minimum values. In this particular case, the values as in (11) is taken out from (10) by following the same criteria as mentioned above in the methodology section.

$$D = \left\{\frac{0.20}{\alpha_1}; \frac{0.05}{\alpha_2}; \frac{0.23}{\alpha_3}; \frac{0.48}{\alpha_4}; \frac{0.63}{\alpha_5}; \frac{0.22}{\alpha_6}\right\} \quad (11)$$

The alternative α_5 has the maximum membership value-it should be chosen as the optimal variant of the device. Recall that option α_5 allows you to improve the quality of electrical energy from the level of error 15% to the 2%. It should be noted that it is of particular interest to expand the set of criteria (in this case, taking into account all indicators of power quality) since the above methodology does not limit their number, that is, it is possible to consider problems with more complex situations. For example, it is promising to introduce a criterion that characterizes surge impulses that occur in the power supply system, as well as taking into account higher harmonics.

4. RESULTS AND DISCUSSION

To implement the algorithm based on FL, the MATLAB mathematical modeling system with the built-in FL design package was chosen. With its help, you can quite simply create a database of production rules for controlling the controller, as well as build response surfaces and see how this algorithm will behave with different input data. The Mamdani algorithm was chosen as a fuzzy algorithm because it is more understandable for programming, and also the accuracy of the output is not so important to it as the visibility of all the components of the algorithm. Taking the input variables such as voltage deviation, asymmetry voltage, and non-sinusoid voltages and selecting the output as the estimation of power quality as shown in Figure 2. The random values of these inputs and the output are chosen from (10) and (11) respectively. For all these inputs and outputs choose the triangular waveform for the results. The input is categorized into three levels low, medium, and high, and output such as poor, average, and good.

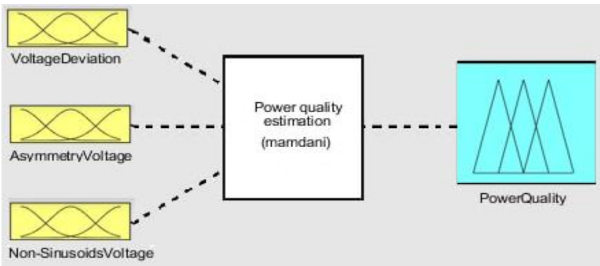

Figure 2. Input and output data of the controller (Mamdani)

After selecting the membership functions, a database of 27 production rules was created to control the output variables. The rules were created according to previous knowledge and can be varied. Here in this article, the following are some of the highlights of the rules such as if the voltage deviation, asymmetry voltage, and non-sinusoid voltage are low on the consumer's tires then the power quality is poor, if the voltage deviation, asymmetry voltage are low and non-sinusoids voltage is medium on the consumer's tires then the power quality is average, if the voltage deviation, asymmetry voltage is low and non-sinusoids voltage is high on the consumer's tires then the power quality is poor and so on accordingly to logic binary system. Emergency modes of operation in this model were not provided, however, their implementation is quite possible. The results for the estimation of the power quality are shown in Figure 3 where changing any input variable can estimate the power quality for that particular case. As for this particular case the voltage deviation is around 0.445, asymmetry is 0.52 and non-sinusoid is 0.41 and then the system estimates the power quality about 0.49. So, by using this can estimate the power quality for any particular change in these three parameters.

After creating the rule base and checking the power quality for different values of inputs the surface response was constructed as shown in Figure 4 to Figure 6 for asymmetry with non-sinusoid voltage, voltage deviation with non-sinusoid voltage and voltage deviation with asymmetry voltage against power quality respectively. These results are obtained by using the FL toolbox in the MATLAB environment which reflects the dependency of controlled output power quality on the inputs provided as voltage deviation, asymmetry voltage, and non-sinusoid voltage.

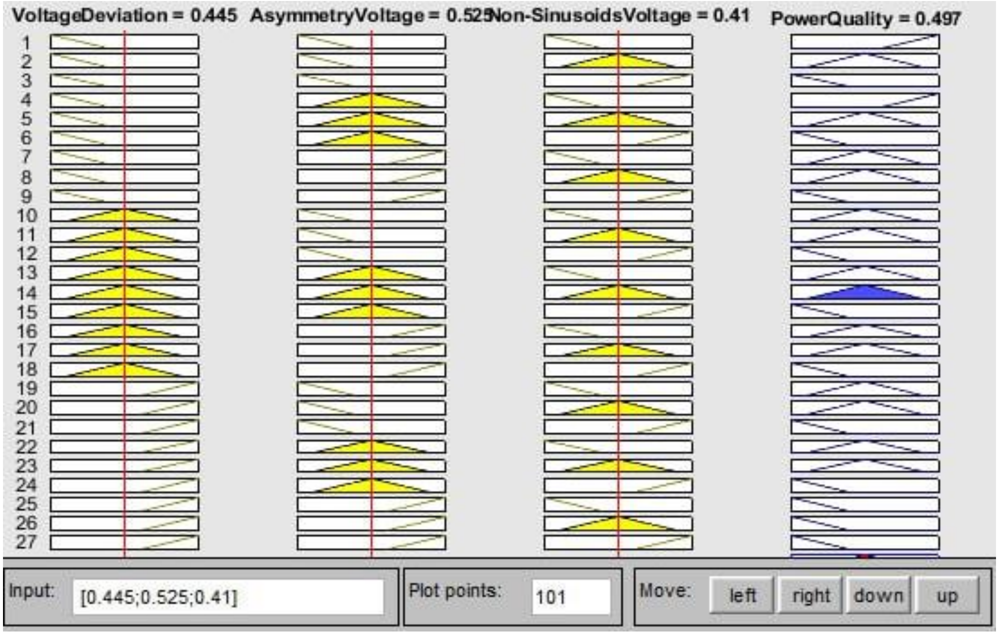

Figure 3. Estimation of power quality by fuzzy logic (Mamdani)

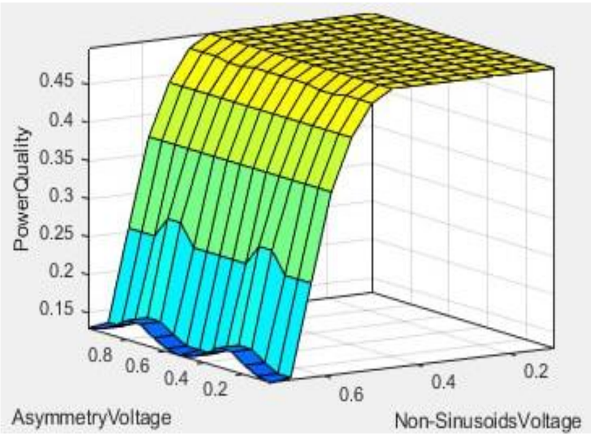

Figure 4. Surface response of power quality against asymmetry and non-sinusoid voltage

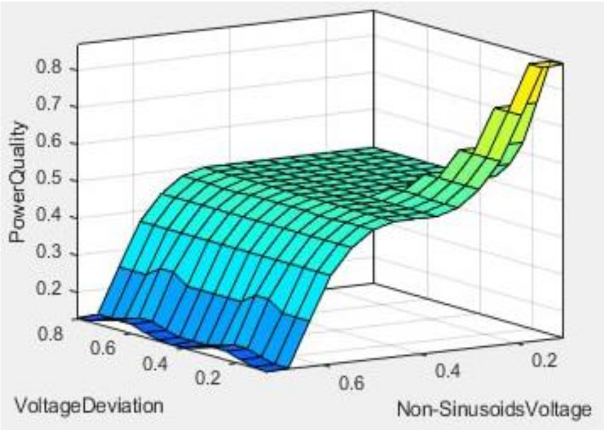

Figure 5. Surface response of power quality against voltage deviation and non-sinusoid voltage

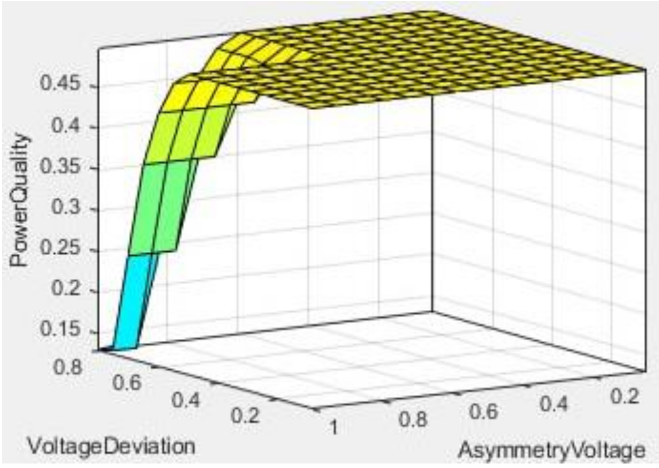

Figure 6. Surface response of power quality against voltage deviation and asymmetry voltage

5. CONCLUSIONS

Multi-criteria management was developed to ensure the reliable operation of the distribution electric network with a minimal negative impact on the environment. It is only within the framework of FL that it is possible to combine the consideration of such heterogeneous and complex objects as power lines and the environment, and their multi-link interactions due to the patterns of energy resource transfer. Only multicriteria management makes it feasible to develop and put into practice a set of strategies to take organizational, technical, and operational actions that reduce and avoid harmful interactions with the environment. Further, the power quality indicators have much importance for these distribution electric networks, and for that the developed device used to record the actual data which shows the results such as asymmetry of voltage and does not meet the requirements and has additional losses in the network. It will be feasible to make judgments about the complete power supply system by analyzing the values the device got at various locations along the power system. As a result, it will be easier to identify the reasons for asymmetry and take the appropriate action to improve the quality of electricity. We can assess the quality of voltage in distribution networks using the fuzzy model with a base of production rules that were produced using the fuzzy-logic application package. FL technology makes it possible to maintain voltage within normalized limits while utilizing the capabilities of transformers, which is a critical responsibility for grid and distribution firms. It may be inferred from the response surfaces that the resulting fuzzy algorithm appropriately regulates the voltage.

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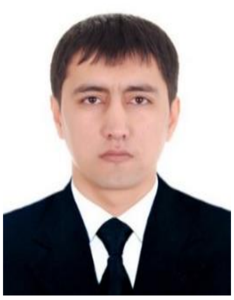
BIOGRAPHIES OF AUTHORS

Dr. Adeel Saleem is working as Associate Professor in the Department of Electrical Engineering, Faculty of Energy, Ferghana Polytecnic Institute, Ferghana, Uzbekistan. He received his B.Sc. and M.Sc. degree in electrical engineering with distinction from The University of Lahore, Lahore, Pakistan, in 2011 and 2015 Respectively. He received his Ph.D. degree in electrical engineering from the North China Electric Power University, Beijing, China in 2021. His research work is on electrical vehicles, power system and distribution, control systems and electrical losses in distribution systems. He can be contacted at email: metadeelsaleem@gmail.com.



Kholiddinov Ilkhombek Khosiljonovich is working as Associate Professor and Head of Department of Electrical Engineering, Faculty of Energy, Ferghana Polytechnic Institute, Ferghana, Uzbekistan. He received his B.Sc. degree in electrical engineering from Ferghana Polytechnic institute, Ferghana, Uzbekistan in 2008. He completed his M.Sc. and Ph.D. in electrical engineering at Tashkent State Technical University, Tashkent, Uzbekistan, in 2010 and 2017 respectively. He can be contacted at email: i.xoliddinov@ferpi.uz.

Kholiddinova Mashkhurakhon Mutalibjon Qizi is Doctoral Student of Department of Electrical Engineering, Faculty of Energy, Ferghana Polytecnic Institute, Ferghana, Uzbekistan. She received her B.Sc. degree in electrical engineering from Ferghana politechnic institute, Ferghana, Uzbekistan in 2013. She completed her M.Sc. in electrical engineering at Ferghana polytechnic institute, Ferghana, Uzbekistan in 2021. She can be contacted at email: m.xoliddinova@ferpi.uz.

Komolddinov Sokhib is working as Assistant in the Department of Power Engineering, Faculty of Energy, Ferghana Polytecnic Institute, Ferghana, Uzbekistan. He received his B.Sc. and M.Sc. degree in electrical engineering from The Ferghana Polytecnic Institute, Uzbekistan, in 2017 and 2020 respectively. His research work is on synchronous generators, power system and distribution, control systems and electrical losses in distribution systems. He can be contacted at email: sohibsolijonovich@gmail.com.

Sharobiddinov Mirzokhid Shakhobiddin Ugli is working as Assistant in the Department of Electrical Engineering, Faculty of Energy, Ferghana Polytechnic Institute, Ferghana, Uzbekistan. He received his B.Sc. and M.Sc. degree in electrical engineering from Ferghana Polytechnic institute, Ferghana, Uzbekistan in 2019 and 2021 respectively. His research work is on, power system and distribution network, power quality, and voltage unbalance coefficients. He can be contacted at email: m.sharobiddinov@ferpi.uz.

Soliev Sokhibjon Obidovich is working as Head of the Department of Regulatory and Technical Department of the Emergency Management of the Fergana Province. His research work is on, power system automation and distribution network, power quality, high voltage and low voltage. He can be contacted at email: s.sokhibobid@gmail.com.