The methodology for reactive power control to ensure voltage quality using fuzzy logic

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Abstract. The article discusses the relevance of various models in addressing the challenges of solving electrical supply issues, particularly in the context of monitoring and optimizing power distribution networks. Researchers describe unique algorithms proposed for different aspects of power systems, including voltage regulation and enhancement, such as reactive compensation and optimal capacitor deployment. The benefits of utilizing fuzzy logic for controlling reactive power and improving regulation are highlighted, along with assessments of future developments in this field. Comparisons are made with conventional methods, emphasizing the advantages of fuzzy control. The article provides descriptions of results obtained in real-world conditions. It serves as an interesting resource for specialists in electrical engineering, automation, and researchers engaged in utilizing fuzzy models in engineering systems.

1 Introduction

The most important property of human intelligence is the ability to make the right decisions in an environment of incomplete and unclear information. The construction of models of approximate human reasoning and their use in computer systems of future generations is today one of the most important problems of science. The first publication on the theory of fuzzy sets is considered to be the work of a professor from the University of Berkeley (California, USA) Lotfi Zadeh, which dates back to 1965. The concept of a fuzzy set in the sense of L. Zadeh marked the beginning of a new impulse in the field of mathematical and applied research, within which fuzzy generalizations of all basic set-theoretic and formal logical concepts were proposed in a short time. A fuzzy evolutionary programming algorithm for optimizing the placement of compensating capacity in a radial distribution network, proposed by the authors in [1], opens up a new methodology with which it will be possible to solve compensation problems in conditions of uncertainty, fuzziness, often present in power supply systems of the type under consideration. Based on fuzzy wave representations, the method of identification of the CE violation, considered in [1], is an original way of determining the places and causes of the violation of the electromagnetic environment in the ES. Using the developed algorithm, the authors show the possibility of using fuzzy logic in solving the problem of electromagnetic compatibility. In [2], a justification for the principle

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of fuzzy voltage regulation using load regulation (OLTC) of a transformer is presented. In case of fuzzy regulation of the load voltage, the first control parameter may be its deviation from the required one (large deviation, small deviation, very large deviation). The second control parameter can be a reference voltage value, which is calculated as a function of current or reactive power. To regulate the voltage, it is necessary to maximize the area of intersection of these fuzzy quantities. Research has shown the prospects for the development of this area. The advantages of fuzzy control: switching is performed less frequently programming of automatic control is easier and more convenient. The problem of optimal connection of capacitors in distribution networks has been solved by many researchers using various developed algorithms. Thus, in [1], the optimal connection of a compensation capacitor in a radial-type power distribution system is investigated. The uncertainty in the network load prediction model is described using fuzzy sets. Details of the computational algorithms used in modeling are described. The method of sequential integer linear programming is used to solve the problem. Examples of specific calculations are given for a distribution network with 16 nodes, 16 lines and 6 capacitors in a 10 kV network. The calculation results illustrate the effectiveness of the proposed method. The examples given repeatedly confirm the prospects of using the mathematical apparatus of fuzzy sets in electrical systems. Control systems based on fuzzy logic have significant advantages over traditional ones, which is confirmed in a number of works, including the above ones [1].

2 Materials and methods

Fuzzy logical conclusion. According to the Fuzzy Approximation Theorem proved by B. Kosko, any mathematical system can be approximated by a system based on fuzzy logic. In other words, with the help of natural language statements-the "if-then" rules, with their subsequent formalization by means of fuzzy set theory, it is possible to reflect arbitrarily accurately the arbitrary "inputs-outputs" relationship without using the complex apparatus of differential and integral calculus, traditionally used in management and identification.

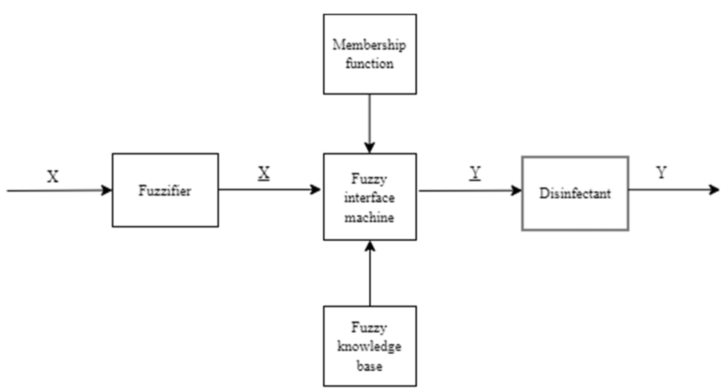


Fig. 1. Fuzzy logic output.

A fuzzy logical conclusion (Figure 1) is the approximation of the dependence Y=F(X) using a fuzzy knowledge base and operations on fuzzy sets. The membership function allows you to calculate the degree of membership of an arbitrary element of a universal set to a fuzzy set. Defazzification is a procedure for converting a fuzzy set into a clear number. A fuzzy knowledge base is a collection of logical statements. In the Figure 1 X is the input clear vector; X is the vector of fuzzy sets corresponding to the input vector X; Y is the result of logical inference in the form of a vector of fuzzy sets; Y is the output clear vector. Examples of systems based on fuzzy logical inference are given in [1]. The advantages of the method are visibility in the representation of clusters and high accuracy.

3 Results and discussion

The total power of the distribution system is determined from the condition of the balance of reactive power (RM) between the power system and low voltage carriers during the passage of the maximum active load by the power system. The optimal placement of the total power is performed according to the criterion of minimum loss of active power in the network and allows for additional economic effect and voltage symmetry in the nodes. Taking into account the above, the task is formulated as follows: for a given power supply scheme, a section of the network is shown in Figure 2 taking into account the RM balance, determine the optimal compensation device power in the nodes of the network circuit with an asymmetric load [3].

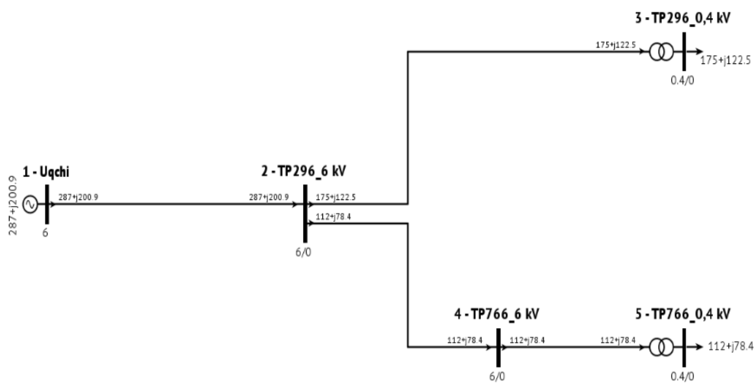


Fig. 2. Power supply system.

The estimated total power of the compensation device installed in the network is:

$$Q_\Sigma = Q_1 + Q_2 = 2000 \ kVAr \quad (1)$$

Table 1. Measuring and testing samples.

№	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Q_1	0	0	100	0	200	0	400	0	800	0	1600	0
Q2	0	100	0	200	0	400	0	800	0	1600	0	2000
ΔP	4378	3950	4372	3598	4367	3123	4358	3094	4343	6710	4332	1035
№	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Q_1	2000	1900	100	1000	1100	900	800	1200	600	1400	400	1600
Q2	0	100	1900	1000	900	1100	1200	800	1400	600	1600	400
ΔP	4336	3913	9332	3536	3273	3875	4291	3087	5350	2942	6714	3102

In the power supply system, it is necessary to carry out several measurements of the total losses of the active power of the reactive power at some predetermined values of the Q1 and Q2 compensation device capacities. When measuring, it is desirable to choose the values of compensation device in such a way that each of them has been both "small", "medium" and "large" values. Measurements should be carried out in two independent stages, the so-called training and testing samples. The measurements are shown in Tables 1 and 2.

Table 2. Testing sample.

№	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Q_1	0	300	0	500	0	700	0	900
Q_2	300	0	500	0	700	0	900	0
ΔP	3322	4362	3001	4358	2986	4346	3278	4340
№	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Q1	0	1100	0	1300	0	1500	0	1700
Q2	1100	0	1300	0	1500	0	1700	0
ΔP	3875	4336	4780	4334	5990	4332	7507	4333

The solution of the problem is divided into two stages: 1) finding out the dependence of the active power losses in the network on the power of the installed compensation device ΔP (Q1, Q2) based on the initial data with an asymmetric load; 2) finding the values of the compensation device capacities, i.e. their optimal arrangement in the network. All calculations are performed in the MATLAB system with the Fuzzy Logic Toolbox package.

A two-stage procedure for constructing fuzzy models of the Sugeno type is considered. At the first stage, fuzzy rules are synthesized from experimental data using subtractive clustering. In addition, this method can be considered as a kind of preprocessing for the ANFIS algorithm - the synthesized fuzzy model is the starting point for learning. An important advantage of using clustering to synthesize a fuzzy model is that the rules of the knowledge base are object-oriented [4, 5].

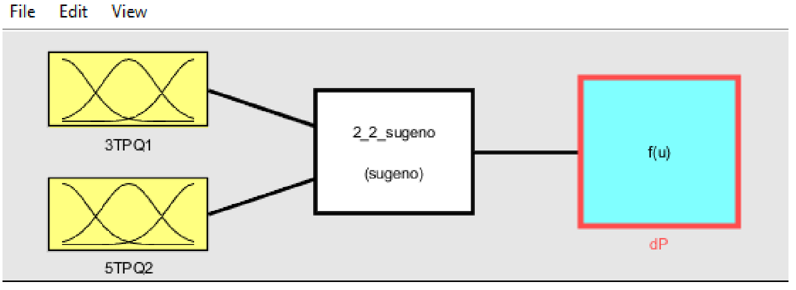


Fig. 3. Sugeno type system.

As a result, a fuzzy Sugeno model of the first order is synthesized (Figure 3) with 196 rules (Figure 4).

Starting from the 98th iteration, the effect of retraining manifests itself, consisting in the loss of generalizing properties of the model. The retrained model reflects reality very well, represented by a training sample. Outside the learning points, the adequacy of such a model is low - the simulation results are very different from the experimental data. To prevent over-training, the tactic of "early stop" is usually used - stopping training when the error increases in the testing sample. The learning curves are represented by the dependence of the mean square deviation between the results of fuzzy inference and the values of the output variable, respectively, from the training and testing samples in relative units and the number of training [6, 7].

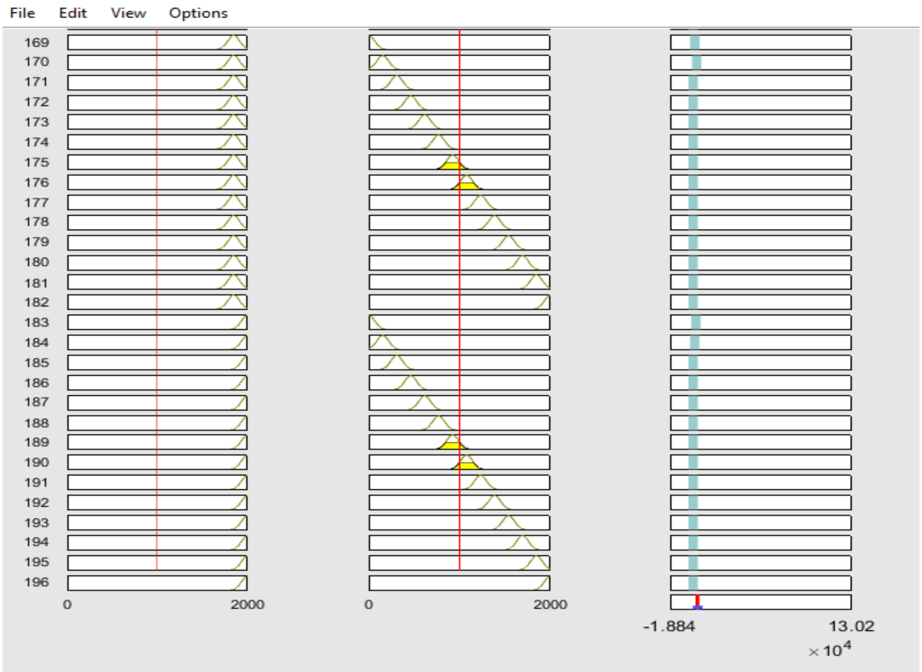
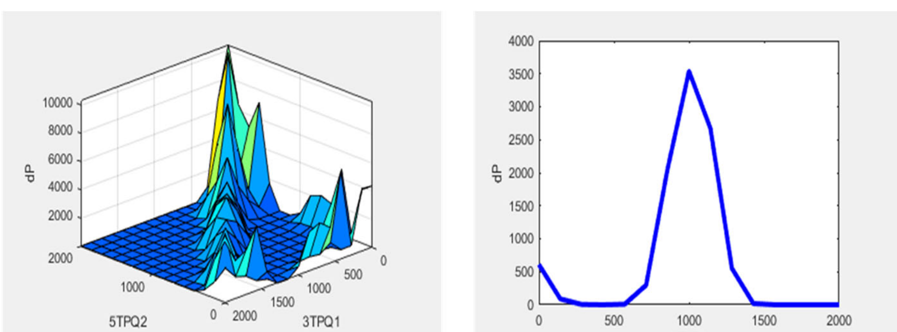


Fig. 4. Visualization of Sugeno's fuzzy inference.

The visualization of fuzzy inference is shown in Figure 5 (illustrates the course of inference for each rule).



a) b)

Fig. 5. The given pictures show two-dimensional and three-dimensional graphs of the dependence of ΔP (Q1, Q2), constructed using the resulting system.

The presented graphs illustrate two- and three-dimensional representations of the dependence of ΔP on variables Q1 and Q2 in a power distribution system. These models were developed using a fuzzy logic-based approach to analyze and optimize system performance. The three-dimensional graph provides insights into system interdependencies, while the two-dimensional graph highlights critical trends for ΔP variation. This study contributes to improving voltage regulation and power system stability through intelligent modeling techniques [8].

4 Conclusion

The solution of the problem by fuzzy logic methods has significant advantages over the dynamic programming method in terms of the speed of finding the optimal placement of CB capacities. For dynamic programming, it is necessary to draw up a network replacement circuit, obtain additional data (active resistances of transformers, specific active power losses in high-voltage and low-voltage circuits, etc.); In the calculation process, it is necessary to obtain an analytical dependence of the losses of active power in the network on the reactive power of the CB (which is not always possible) and repeatedly determine the flow distribution in the network. Creating a fuzzy model is much easier and more natural, and to obtain the initial data, you need to make only a few measurements directly related to the essence of the problem. The effectiveness of the fuzzy logic algorithm in optimal control problems is proved by the shorter time it takes to find the optimal values of the power. The algorithm is suitable not only for systematic asymmetric mode (at the design stage), but also for managing short-term asymmetry of modes of electric power systems.

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