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# FUZZY PROBABILISTIC MODEL FOR MANAGING THE MODES OF NETWORKS WITH RENEWABLE ENERGY SOURCES

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**Abstract**- This article proposes probabilistic fuzzy models that describe the variability of the state of the power system caused by the stochasticity of load and generation based on renewable energy sources, in which second degree uncertainties are determined. As expected in these situations, deterministic, probabilistic and fuzzy approaches in separation are not suitable. The proposed models are presented in the form of a fuzzy Gaussian description with a variable center and width for membership functions of mode parameters that determine the state of the system. It is shown that the proposed models make it possible to more accurately approximate the current and predicted values of its parameters based on the simultaneous consideration of the stochasticity and uncertainty of the variability of the state of the power system with distributed generation based on renewable energy sources. The paper formulates the problem of modeling the state of the power system, taking into account the stochasticity and uncertainty of its variability in the form of a probabilistic fuzzy set, proposes a procedure for identifying the model structure of a probabilistic fuzzy set in relation to the description of the random variability of the state of the system caused by the stochasticity of the load power, presents the results of modeling the functioning of intelligent protection of a complex load node with connected sources of renewable sources, represented by a fuzzy-probabilistic description of the vector, the ratio of the currents of the forward and reverse sequences. As an example of the implementation of the proposed fuzzy probability model in the control of power system modes, the solution results of the intellectualization of the protection of electrical equipment from asymmetric and incomplete phase modes are given.

**Keywords:** Power System, Renewable Energy Sources, Protection from Asymmetric Modes, Probabilistic Fuzzy Model, Probability Density Function, Membership Function.

## 1. INTRODUCTION

In the modern power grid, the requirements for the use of new approaches to control the generation, transmission and distribution of electric energy are increasing more and more, based on the consideration of the initial information variability corresponding to the real nature of its uncertainty and stochasticity. The uncertainty state, random variability of system mode parameters depends on many factors, as well as on the degree of their consideration in the problem models, such as load forecasting, power flow distribution, load distribution.

In many practical applications, stochastic and deterministic fuzzy modeling methods are used separately, independently of each other. At the same time, at present the traditional theory of fuzzy mathematics and probabilistic models are considered only as one of the types of uncertainty.

There are studies in references, in which an attempt is made to integrate methods of probability theories and fuzzy mathematics [1, 2]. In the list of these studies some approaches and methods were proposed, for example, in [3] methods of probabilistic measurements of fuzzy events, fuzzy random sets [4, 5], fuzzy random variables [6-9], non-stationary fuzzy sets (FS), fuzzy logic (FL) and fuzzy model with probabilistic weighted rules [10].

Two integration rules are used based on these methods. In one of them fuzzy description is given in statistical form, in the other stochastic uncertainty is given in fuzzy system. In this method, the probabilistic fuzzy logical set (PFLS) is described in the stochastic variable coordinates represented by the binary probability density function containing stochastic and non-stochastic uncertainties. The thesis presents the development of the proposed approach for solving the regulation of reactive power and voltage in the electrical system.

In the paper it is proposed to model a PFSL in the form of Gaussian-type FS with randomized chance variability of the center and width of the probability distribution. For the first time in power systems, the modeling of FS with random changes in the width of a Gaussian FS is considered. The methodology of combined use of probabilistic methods and FL methods in relation to the solution of problems of power grid is given. The fuzzy probability model considered on the basis of the Gaussian type function can be successfully applied in the reverse control of normal and fault modes in the power system and in solving other problems related to ensuring the stable operation of the power system. To visually confirm this, the results of the inclusion of the proposed model in the algorithm of intellectual protection from asymmetric modes and the modeling of its practical implementation in the Matlab environment are reflected.

## 2. THE ESSENCE OF FUZZY MODEL PROBABILISTIC REPRESENTATION PROBLEM

Currently, two forms of fuzzy system representation are theoretically developed and widely used. The first form is represented as a fuzzy mathematical model in which the uncertainty is specified by the state parameter clustering.

The second form of the fuzzy model is based on a sequence of fuzzy rules, the adoption of which makes it possible to support the fuzzy decisions.

Probabilistic fuzzy set is a set that has stochastic and fuzzy properties. These properties can be represented in the form of probabilistic model of fuzzy system, which can be represented in the form of the variability of the center and width of the fuzzy set Gaussian expansion. Thus, in the PFLS, for example, there is one value or many values of membership function (MF) for $x$ input variable. The MF and its parameters become a random variable that can be described by their randomness by a secondary probability density function (PDF). The MF of the load random variability by hours and its MF are represented in Figure 1.

Essentially, the 3D MF, including a fuzzy measurement, introduced into PFLS as shown in Figure 2, makes it possible to control information that has the stochasticity and fuzziness properties.

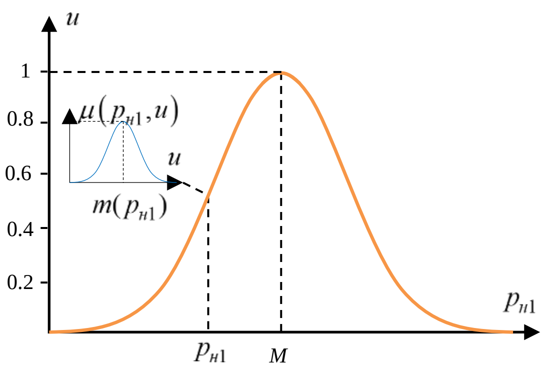


Figure 1. Graphical representation of probabilistic FS

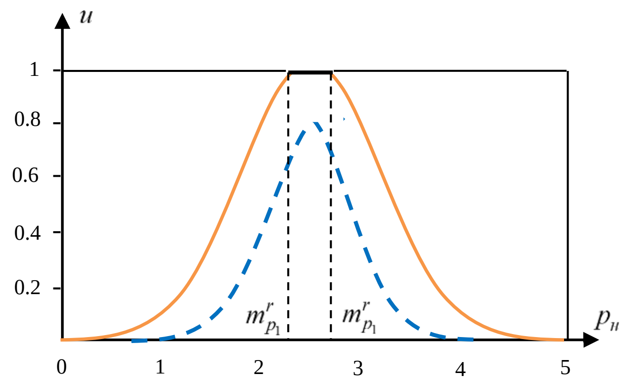


Figure 2. Graphical representation of a PFLS using the example of the expression of the primary MF in the form of a distribution of a FS of power systems load according to Gaussian with an undefined mean

Like the usual fuzzy logical system, the PFLS also has fuzzification operation and mechanism of logical inference and defuzzification. The difference also lies in the fact that when the parameter expression like PFLS, a probabilistic fuzzy set is used, in which it is modeled by a 3D MF.

In the process of fuzzification the real inputs are transformed into a PFLS composed based on probabilistic MF. Among the many situations in which MF in FS can be interpreted as a probabilistic distribution of linguistic fuzzy variables, and at the same time, real initial information is considered, and fuzzy control will provide a minimum error. Regarding power grid or its facilities, the fuzzy control methods are one of the successful practical implementations of fuzzy methodology in industrial conditions [11, 12].

Let's consider a generalized model of the power grid state, in which the vector of variables in the output $X = (x_1, \ldots\ldots, x_d)$ possesses the values within the range $x \subseteq \{R^{g,н}\}$, and the vector of variables in the output $Y$ possesses the values within the $Y \subseteq \{R^{u,p}\}$, where $x_{gj}, x_{нi}$ are current values of active and reactive powers of generation in nodes $j$ and load powers in nodes $i$ respectively; $x_{u_i}, x_{p_{ij}}$ are current values of voltage profile and power flows in electrical network, respectively.

Based on fuzzy rule supplemented by means of selection of "IF ..., THEN ..." we work out rules using natural language modeled by a fuzzy set in the form of $R_j$:

$$\text{IF } x_1 = A_{j1}, \ldots, x_d = A_{jd} \text{ THEN } y = B_j,\ j = 1, \ldots, n \quad (1)$$

where, $A_{ji}, B_j$ are fuzzy subsets of input $x_{gj}, x_{нi}$ and output $y_u, y_p$ variables, respectively.

The purpose of fuzzy control is to derive the control rule $y = f(x)$ from $R$. Now considering

$$A_j = \prod_{i=1}^{d} A_{ji} \quad (2)$$

$$A_j(x_1, \ldots, x_d) = t\left(A_{ji}(x_1), \ldots, A_{jd}(x_d)\right) \quad (3)$$

where, $t$ is a some norm, that $R$ means data sets from a pair of $(A_j, B_j)$ *type*, $j = 1, \ldots, k$ fuzzy numbers. If couple $(A_j, B_j)$, generalizing the numerical data, represents a relationship between $x$ and $y$ it is more preferable than specified by causal relation. In the context of control, $B_j$ is the representation for the implementation, when the input parameter subset $A_j$ is more preferable than just $A_j$, determined by the causal relation with $B_j$. Reasoning differently, it should be noted that the appearance of each $R_j$ representation of fuzzy relation on $X \times Y$ is more natural than the interpretation of "IF …, THEN …" as an implied operator.

Since the output value of fuzzy inference systems, obtained using the knowledge base, is a fuzzy set, and a clear signal must be supplied to its input so that the control system can receive the corresponding command.

Restoration of crispness (defuzzyfication) is carried out by calculating the mathematical expectation of the center of output parameter. Traditionally, the values of the output parameter $y_c$ according to the values of MF:

$$y_c = \frac{\sum_{j=1}^{\bar{j}} y_j \mu_R\left(x, y_j\right)}{\sum_{j=1}^{\bar{j}} \mu_R\left(x, y_j\right)} \tag{4}$$

$$\mu_R = \max\left(\mu_{\bar{R}_1}, ..., \mu_{\bar{R}_j}, ..., \mu_{\bar{R}_{\bar{1}}}\right) \tag{5}$$

where, $y_j$ is sequence of crisp inputs and $y_c$, $\mu_{\bar{R}_j}$ are random variables. The clear output parameter PFLS is the mathematical expectation carried out during the traditional defuzzification procedure [13]:

$$y = M\left[x\left(y_c\right)\right] \tag{6}$$

## 3. PROBABILISTIC MODELING OF POWER GRID FUZZY STATE: STOCHASTIC VARIABILITY CASE OF GAUSSIAN DISTRIBUTION WIDTH OF MFOF INPUT VECTOR VARIABLES

The use of probabilistic methods in the solutions of PG problems makes it possible to increase the resolving possibility of the system state assessment by detail consideration of the initial information. This is a new field in the theory of artificial intelligence. One of the forms of development of this theory is a combination of the field of knowledge with the data obtained by means of measuring.

At fuzzy control or use of expert systems in this case, we need to create linguistic (fuzzy) rules and have numerical measurements of input and output ($x_i, y_i$) parameters that determine the power grid state. To combine linguistic and numeric variables that have different data types, it is necessary to have a mechanism of transformation of one of them into another. Given that linguistic data are more informative than measurements $(x_i, y_i)$, these obtained paired data are converted into linguistic, in which it is easy to simulate for control. The above fact can be illustrated by performing a transformation procedure, which in fuzzy control is known as formation of fuzzy rules based on machine learning.

Let us consider the example of integration of the field of knowledge with statistical data base don the use of Bayesian statistics.

The generated database and on its basis the knowledge base are presented in the form of generalized fuzzy linguistic terms, which are necessary for fuzzy modeling. To create a fuzzy control for the power system objects, the field of knowledge relative to their states is formed based on studying of the system behavior. The object state under study covers the fuzzy rule set.

Let us consider the system state simulation to predict the value of consumption based on random changes in the input variable observation data, defined in the form of power value of the total load in the power grid. In general, the value of the consumption forecast ($\Sigma P$) can be determined from the following parametric model:

$$\left\{ f(X, \Sigma P) : \Sigma P \in \Omega \right\} \tag{7}$$

It is necessary to obtain the estimates of parameter $\Sigma P_0$ based on the following data:

- random sampling for $X\left(x_1, ..., x_n\right)$;
- field of knowledge: some additional information regarding $\Sigma P_0$.

If its distribution is known for additional information, the Bayesian model will be the most realistic. Now we'll consider one of the cases when the information obtained relative to $\Sigma P_0$ is linguistic variable "$\Sigma P$ is small", at which the model with the linguistics "small" corresponds to subset $A$ that is expressed with a MF $\mu_{\Sigma P}$. It should be noted that if several experts have a different opinion regarding $\Sigma P_0$, then you can use one more logical connection "and" to combine them and represent them in a simple set of fuzzy statements.

The problem is to integrate the non-statistical model of the membership function with statistical information. To solve this problem within the Bayesian approach by normalizing $A$ to get the PDF:

$$\sigma(\Sigma P) = A(\Sigma P) / \int_{R^+} A(\lambda) d\lambda \tag{8}$$

Let us consider the case when fuzzy information combined with statistical data is represented by a normal PDF:

$$f(x, \Sigma P) = \frac{1}{\sqrt{2\pi} \cdot \Sigma P_h} \exp\left(-\frac{\left(x - \Sigma P_c\right)^2}{2\sigma_h^2}\right) \tag{9}$$

The probability that the observed statistical data $x$ with dimension $h$ and the function $A(\Sigma P)$ established by experts, in which the $\Sigma P$ value is joint with

$$L(x, \Sigma P) = \frac{1}{\sqrt{2\pi} \cdot \Sigma P_h} \exp\left(-\frac{\left(x - \Sigma P_c\right)^2}{2\sigma_h^2}\right) A(\Sigma P) \tag{10}$$

where, $\Sigma P_0$, $\Sigma P_h$ are the center and width of primary MF $\Sigma P$ respectively, changing according to normal law (Figure 3); and $x$ is measured statistics of input value.

In the control (9), the value of width $\Sigma P_h$ of the normal probability density of the MF $\mu_{\Sigma P}$ is considered as a random variable, also changing in accordance with the normal distribution [14, 15]:

$$\Sigma P_h \cong N\left(\omega, \lambda^2\right) \tag{11}$$

and $\omega$ is average value of $\Sigma P_h$ and $\lambda$ is deviation of $\Sigma P_h$.

Accordingly, the fuzzy rank estimation for the MF $\mu_{\Sigma P}$ becomes a random variable:

$$\mu_{\Sigma P} = \exp\left(\frac{-\left(x-\Sigma P_c\right)^2}{2\Sigma P_h^2}\right) \quad (12)$$

The probability distribution for $\mu_{\Sigma P}$ can be defined using expression [16, 17]:

$$F(\mu_{\Sigma P}) = \begin{cases} \int\limits_0 \frac{|x-\Sigma P_c|}{\sqrt{-2\ln \mu_{\Sigma P}}} \times \\ \times \frac{1}{\sqrt{2\pi}} \exp\left(\frac{\left(\Sigma P_h - \omega\right)^2}{2\lambda^2}\right) d\Sigma P_h & 0<\mu_{\Sigma P}<1 \\ 0 & \text{in other cases} \end{cases} \quad (13)$$

Finally, the secondary distribution density function of the value of the MF $\mu_{\Sigma P}$ caused by the stochastic change in the width of the distribution $\Sigma P_h$ is:

$$\text{Prob}_{A(\Sigma P)}(\mu_{\Sigma P}) = \begin{cases} \frac{|x-\Sigma P_c|\left(-2\ln \mu_{\Sigma P}\right)^{\frac{3}{2}}}{\sqrt{2\pi}\lambda \mu_{\Sigma P}} \times \\ \times \exp\left(\frac{\left(\frac{|x-\Sigma P_c|}{\sqrt{-2\ln \mu_{\Sigma P}}} - \omega\right)^2}{2\lambda^2}\right) & 0<\mu_{\Sigma P}<1 \\ 0 & \text{in other cases} \end{cases} \quad (14)$$

The distribution functions of the MF value for the total load power in the power grid are shown in Figure 3.

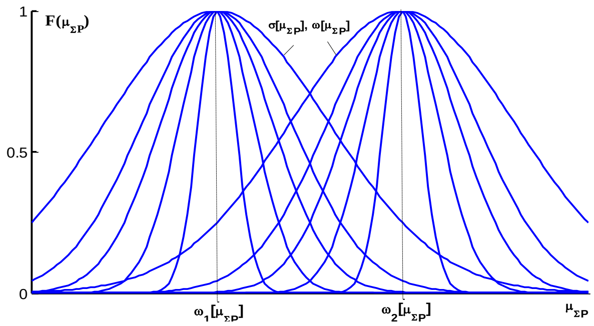


Figure 3. The distribution functions of the MF value for the total load power in the power grid

## 4. MODELING RESULTS

Let's consider the application of the developed fuzzy probability algorithm to the solution of a specific electric problem. For the case under consideration, modeling of intellectual protection of equipment from asymmetric modes in a complex load node with renewable sources is considered. It is known that for fuzzy controllers of such protection, the input parameters are the coefficient of asymmetry for the reverse sequence of current - $K_I = I_2/I_1$ and its rate of change - $\dot{K}_I = d\left(I_2/I_1\right)$, the output quantities can be considered as the tolerance time - *L* and the direction of operation of the protection RM1 - *I* [18]. For the input quantity, we can write the expressions of the affiliation function and its probable distribution, similar to formulas (12) and (13), as follows:

$$\mu_{K_I} = \exp\left(\frac{-\left(K_I - K_{or,I}\right)^2}{2\sigma_{K_I}^2}\right) \quad (15)$$

$$\mu_{\dot{K}_I} = \exp\left(\frac{-\left(\dot{K}_I - \dot{K}_{or,I}\right)^2}{2\sigma_{\dot{K}_I}^2}\right) \quad (16)$$

where, $\sigma$ is standard deviation of the quantity. Similar to expression (13) $0<\mu_{K_I}<1$ and $0<\mu_{\dot{K}_I}<1$ we can assign appropriate distribution functions for the cases:

$$F\left(K_I\right) = \int \frac{|K_I - K_{or,I}|}{\sqrt{-2\ln \mu_K}} \cdot \frac{1}{2\pi} \exp\left(\frac{\left(K_I-\omega\right)^2}{2\lambda^2}\right) dK_I \quad (17)$$

$$F\left(\dot{K}_I\right) = \int \frac{|\dot{K}_I - \dot{K}_{or,I}|}{\sqrt{-2\ln \mu_K}} \cdot \frac{1}{2\pi} \exp\left(\frac{\left(\dot{K}_I-\omega\right)^2}{2\lambda^2}\right) d\dot{K}_I \quad (18)$$

According to the obtained (15)-(18) fuzzy probability models, the algorithm of operation of electrical equipment depending on the degree of asymmetry of intellectual protection from asymmetric modes is modeled in Matlab environment and the obtained diagrams are illustrated in Figure 4. As can be seen from Figure 4, the asymmetry with the input parameters $I_2/I_1$ and its rate of change $d\left(I_2/I_1\right)$ the step-by-step models and the corresponding variation diagrams of the protection RM1 output parameters (*L*, *I*) were also obtained in stages. The operation diagram of the protection *I* = *f*(*t*) was generated according to the changing nature of the asymmetry for the period of time (0-20) s. As can be seen from the diagram, the algorithmic protection based on the fuzzy probability model works more intelligently, in other words, it provides reliable protection of electrical equipment by influencing the signal in the range (0-0.5) and opening with the appropriate tolerance in the range (0.5-1).

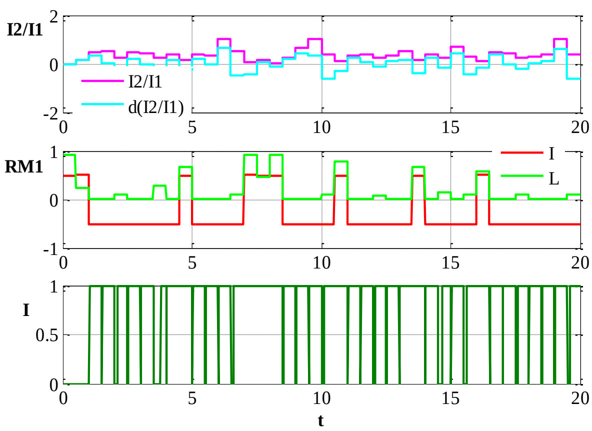


Figure 4. Operational diagrams based on fuzzy probability model of intellectual protection from asymmetric modes

## 5. CONCLUSION

1. Probabilistic fuzzy models, describing the variability of the power grid state caused by the load and generation stochasticity, are proposed. The proposed models are presented in the form of fuzzy description of the Gauss with a changing center and width for the membership functions of the mode parameters that determine the system state. It is shown that the proposed models make it possible to approximate the current and forecasting values of the power grid parameters with higher accuracy on basis of simultaneous consideration of stochasticity and uncertainty in power grid state variability.

2. Fuzzy probability models of mode and operating quantities can be effectively applied in solving the problems of its operational control, control of normal and emergency mode parameters in the conditions of the power system covering all possible circuit-mode changes.

3. Based on the proposed fuzzy probability model, the modeling results of the intelligent relay protection algorithm were obtained from asymmetric modes. The results showed that, depending on the values of the input quantity and its rate of change, more selective operation of the protection and reliable protection of electrical equipment from the considered modes are provided.

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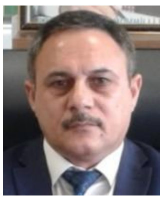

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