METHOD OF FUZZY PROTECTION AGAINST ASYMMETRIC MODES OF ELECTRIC NETWORKS OF ENERGY SYSTEMS WITH RENEWABLE SOURCES

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ABSTRACT
The paper considers the creation of an intelligent protection system based on fuzzy controllers, which provides detection and effective protection against asymmetric modes, in particular, from open-phase modes in the electrical network of a power system with a complex load. An intelligent system that includes a positive and negative sequence current filter, an analog-to-digital converter, a switch, a calculation unit for the ratio of negative and positive sequence currents, an executive body that turns off the input switch and turns on the sectional switch.
Keywords: power system, electrical network, complex load, intelligent protection, asymmetric mode, open-phase mode, fuzzy controller.

The three-phase voltage applied to the stator windings of the motors applied in the nodes of the industrial and agricultural power supply systems, where short-circuited rotor asynchronous motors prevail, is in some cases asymmetric. These modes arise when multiple single-phase loads are unevenly distributed between the phases of the electric network or in the conditions of emergency modes. The boundary condition of asymmetry, for example, the breaking of one phase of the feeder line, the burning of the fuse in one phase of the network, etc. is the incomplete phase regime that occurs in cases. In complex load nodes, the probability of incomplete phase modes arising due to the above reasons is quite high and accounts for up to 40% of all accidental opening of network elements.

The integration of renewable energy sources, especially wind turbines, into the power system creates conditions for the malfunctioning of the decision-making bodies of the protection system at the power grid nodes. So, since the energy production of renewable sources changes uncertainly and is intermittent, the uncertain changes of the regime parameters for these reasons lead to the emergence of significant difficulties in the single-value adjustment of the protection parameters. The results of the analysis of the operation of the complex node with asynchronous load in the event of a phase failure [2,3] suggest that, depending on the degree of asymmetry, in the conditions of the uncertainty of the initial data, it is possible that the existing protections do not work selectively, and the automatic devices work incorrectly. Therefore, in the conditions of current asymmetry, it is necessary to develop appropriate measures to increase the reliability of protection.

Based on the principles of creating intelligent networks, the relay protection device should be coordinated with the functions of the information-measurement system. As a technical system, the application of microprocessor protection is considered. These microprocessor devices have the same requirements as other protections. This is achieved by selecting the appropriate operating current and endurance to meet these requirements when looking at current protections. Application of fuzzy sets and fuzzy logic theory in order to create a more flexible tuning model of time-current function parameters is considered as one of the main perspective development directions of protection.

In the presented scientific-research work, processing of theoretical-practical issues of protection working on the basis of fuzzy sets and fuzzy logic is considered. So, today, in the technical literature, adaptive relay protection, preventive function protection, multi-dimensional relay protection, artificial intelligence protection, protection based on neural networks, etc. issues are given ample space. Fuzzy logic theory is the basis of these protection devices, which are still in the idea stage.

Analysis of protection against incomplete phase and non-symmetric modes on the characteristic nodes of the energy system

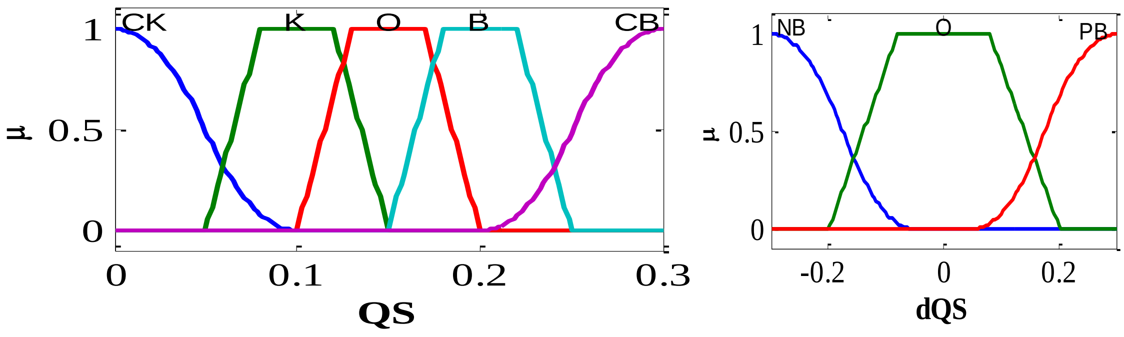
Various devices have been proposed for the protection of three-phase motors from unsymmetrical and incomplete phase modes [4,5]. The analysis of these devices has shown that in conditions of probable-uncertain changes of mode parameters, they do not fully satisfy the condition of selectivity, their structures are complex and they cannot ensure robust operation of protection against insignificant side currents. For this purpose, there was a need to improve the reliability and sensitivity of protection of the electric motor and other demanding loads from phase failure and also from overloading with reverse sequence currents.

The scheme of the existing protection system is depicted in figure 1.1 [6]. The protective device is equipped with a system consisting of forward and reverse sequence filters, an analog-to-digital converter, a commutator, a reporting unit for the ratio of forward and reverse currents, a fuzzy controller and an executive body. The fuzzy controller consists of a sequentially coupled fuzzifier, a linguistic rule table block, and a defuzzifier. The input of the converter is connected to the transmitters, and the output of the fuzzy controller is connected to the input of the executive.

The inverse sequence digital current filters used here are quite simple and reliable. However, the protection that works only according to the value of the reverse sequence current is not effective due to the low informativeness of these currents. The protection against incomplete phase modes, which operates according to the ratio of reverse and direct sequence currents in the load supply circuit, has great sensitivity. $K_{2I} = \frac{I_2}{I_1} = 0{,}6$ presence (a 3-fold increase in the load in one of the phases) may cause emergency conditions in the electrical network, here $K_{2I} -$ the reverse sequence is the unsymmetrical coefficient with respect to the current. This ratio in incomplete phase mode $K_{2I} = \frac{I_2}{I_1} = 1$ and in normal modes $K_{2I} \ll 1$. Therefore, the starting body of the protection is superior to the incomplete phase modes, which work according to the ratio of reverse and direct sequence currents. If the asymmetry changes in the range of 0-1.0, the obtained results confirmed that it is possible to ensure the intelligence of the protection against the mentioned damages and the more reliable operation of the equipment protection. However, in the existing system with one input and one output, the QSC makes decision based only on the absolute value of the asymmetry. Ignoring the rate of change (derivative) of the asymmetry does not ensure the full intellectual operation of the protection device. As a result, it is possible to make unjustified positive decisions for circuit changes at various degrees of current asymmetry.

Synthesis of the control system of intelligent protection from asymmetric modes in the Matlab environment

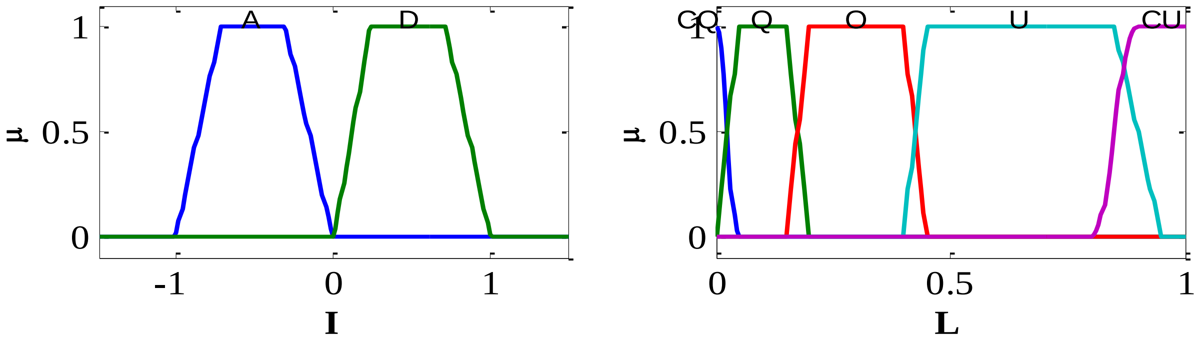
The issue of protection against asymmetric modes that may arise in complex load nodes is considered by modeling and synthesizing with the help of the Fuzzy Logic Toolbox module of the Matlab software package. Figure 1 and Figure 2 show the modeling results based on the adopted parameters of the membership functions of terms of two input and two output linguistic variables in clause 1.2.



a) b)

Figure 1. Program description of membership functions of input linguistic variable (asymmetry) terms

a - "asymmetry"; b - "Dynamics"



a) b)

Figure 2. Program description of the membership functions of the terms of the output linguistic variables (Direction and Delay) a - "Direction"; b - "Delay"

Intervals and forms of term changes for the design and synthesis of intellectual protection are described in the simulation model in the pictures. Table 1 lists the forms and parameters of linguistic variable terms.

Table 1

Terms of input and output linguistic variables, their parameters and membership functions

Term-subset	Membership function	Parameters
Asymmetry, K_I		
Very small	Z-shaped	[0 0,0994]
Small	Trapezoid	[0,05 0,08 0,12 0,15]
Medium	Trapezoid	[0,1 0,13 0,17 0,2]
Large	Trapezoid	[0,15 0,18 0,22 0,25]
Incomplete phase mode	S-shaped	[0,2015 0,3]
Rate of change of asymmetry (Dynamics), dK_I/dt		
Large	Z-shaped	[-0,3 -0,05]
Medium	Trapezoid	[-0,199 -0,08 0,08 0,202]
Small	S-shaped	[0,05 0,302]
Direction, I		
Alarm	Trapezoid	[-1,006 -0,7164 -0,3066 -0,0064]

Open	Trapezoid	[0,0086 0,2376 0,7196 1,0026]
Delay, *L*		
Very short	Z-shaped	[0 0,05]
Short	Trapezoid	[0 0,05 0,15 0,2]
Middle	Trapezoid	[0,15 0,2 0,4 0,45]
Long	Trapezoid	[0,4 0,45 0,85 0,95]
Very long	S-shaped	[0,8 0,9]

Figure 3 shows the structure diagram of the fuzzy controller synthesized on the basis of the simulation model. As it can be seen, a derivation mechanism consisting of fifteen rules according to the Mamdani algorithm is provided for organizing the operation of the two-input and two-output controller.

The synthesis of a two-input and two-output fuzzy controller for security control can be performed using the following simple linguistic fuzzy model:

$$\text{IF } X_1 \quad A_{1i} - \text{ and } X_2 \quad A_{2i} \text{ THEN } Y \quad B_j \text{ and } Z \quad C_k -. \qquad (1)$$
$$i = \overline{1, n}, \qquad j = \overline{1, m}, \qquad k = \overline{1, l}$$

Here X_1 və X_2 – are the state variables, is the control parameter of the process, and they are linguistic variables; A_1, A_2, B and C – E_1, E_2 and E_3, E_4 in universal sets X_1, X_2, Y və Z are linguistic values consisting of terms of variables, other words, $\forall x \ A \in E_1$, $\forall y \ B \in E_2$ and $\forall z \ C \in E_3$.

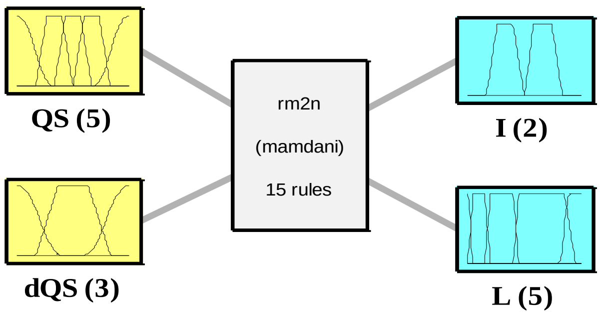


Figure 3. Structural diagram of the fuzzy controller

The term subsets for the first input “Asymmetry” linguistic variable of the fuzzy controller are given below, here $T_i(K_I)$, where $K_{I,i} \in E_{1i}$ c $i = \overline{1,5}$:

$$\begin{aligned}
E_{11} &= SB \quad \text{(Incomplete phase mode)} \quad \underline{\underline{\Delta}}(K_I, \mu_{11}(K_I)) \\
E_{12} &= B \quad \text{(Large)} \quad \underline{\underline{\Delta}}(K_I, \mu_{12}(K_I)) \\
E_{13} &= M \quad \text{(Medium)} \quad \underline{\underline{\Delta}}(K_I, \mu_{13}(K_I)) \\
E_{14} &= S \quad \text{(Small)} \quad \underline{\underline{\Delta}}(K_I, \mu_{14}(K_I)) \\
E_{15} &= VS \quad \text{(Very small)} \quad \underline{\underline{\Delta}}(K_I, \mu_{14}(K_I))
\end{aligned} \qquad (2)$$

As can be seen from (2.2), the fuzzy linguistic model is composed of fifteen simple implications, and the final *R* fuzzy relation between parameters can be defined as a combination of fuzzy relations R_i (i=1,2,...,5):

$$R = \bigcup_{\substack{i,l=1,5\\ j=1,3\\ k=1,2}} R_i = \bigcup_{\substack{i,l=1,5\\ j=1,5\\ k=1,2}} E_{1i} \times E_{2j} \times E_{3l} \times E_{4k} \tag{3}$$

In this case, the membership function of the fuzzy relation is defined as follows:

$$\mu_R\left(K_I, \frac{dK_I}{dt}, L, I\right) = \max\left\{ \begin{matrix} \min\left[\mu_{E_{11}}(K_I), \mu_{E_{21}}\left(\frac{dK_I}{dt}\right), \mu_{E_{31}}(L), \mu_{41}(I)\right], \min\left[\mu_{E_{12}}(K_I), \mu_{E_{22}}\left(\frac{dK_I}{dt}\right), \mu_{E_{32}}(L), \mu_{42}(I)\right] \\ ,\ldots, \min\left[\mu_{E_{15}}(K_I), \mu_{E_{23}}\left(\frac{dK_I}{dt}\right), \mu_{E_{35}}(L), \mu_{42}(I)\right] \end{matrix} \right\} \tag{4}$$

Here $\mu_{1i}(K_I)$, $\mu_{2j}\left(\frac{dK_I}{dt}\right)$, $\mu_{3l}(L)$, $\mu_{4k}(I)-$ in accordance with E_{1i}, E_{2j} , E_{3l} və E_{4k} set in universal sets $K_I, \frac{dK_I}{dt}$, L, və I are membership functions of term-subsets of linguistic variables.

Results of computer modeling

Based on the algorithm described above, reports of computer modeling of intellectual protection developed on the basis of fuzzy logic theory from non-symmetrical modes were conducted. For the purpose of making reports, the Simulating model of the intelligent protection system was established and is given in figure 4. The model consists of a fuzzy controller (rm), executive body (subsystem) and recording measuring devices.

Figure 4 shows a fragment illustrating the decision-making procedure of the fuzzy controller. Fraqments - of asymmetry $K_I = \frac{I_2}{I_1} = 0{,}15$ and of its change rate $\frac{dK_I}{dt} = 0$ according to their values $L = 0{,}3\,san$ makes the decision not to open the circuit with a delay ($I = 0{,}494$).

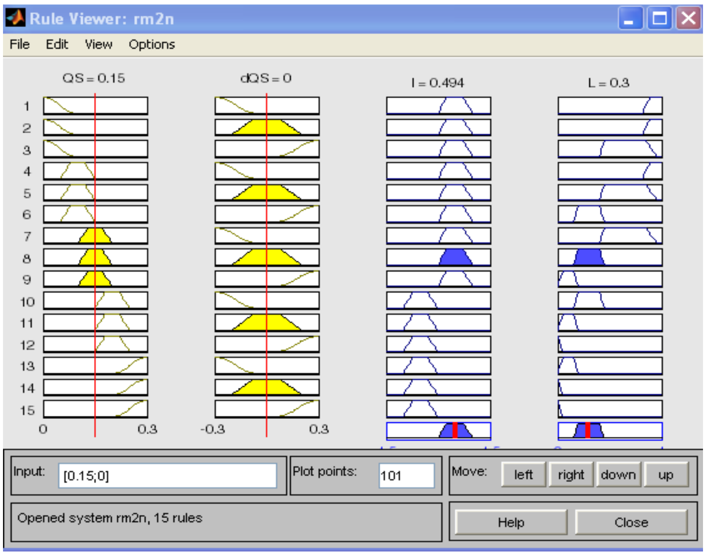


Figure 4. Decision making procedure fragment

In order to obtain the set of values of the asymmetry variable K_I, which expresses the ratio $\frac{I_2}{I_1}$ as an input fuzzy parameter, the asymmetric regimes were probabilistically modeled by the

Monte Carlo method, and the loading rates of the phases are given in figure 5. As can be seen from Figure 5, a, the values of the quantity K_I vary in the $0 \div 1{,}0$ interval. On the basis of these values, the endurance period obtained in the Simulating model is produced in the interval $0 \div 2{,}5s$.

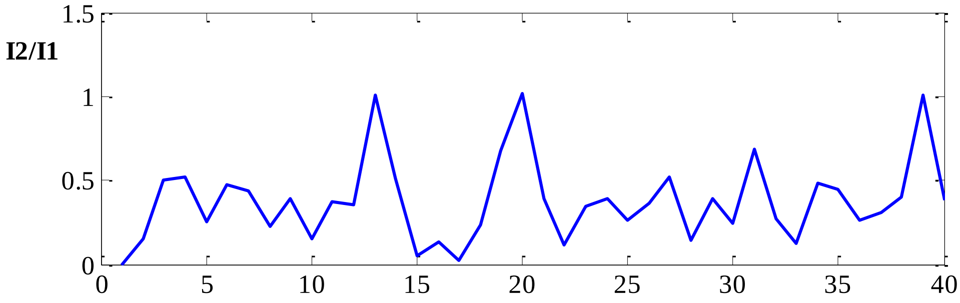


Figure 5. Asymmetric mode and change of asymmetry

The operation diagram of the protection system for different values of asymmetry is illustrated in figure 6.

a)

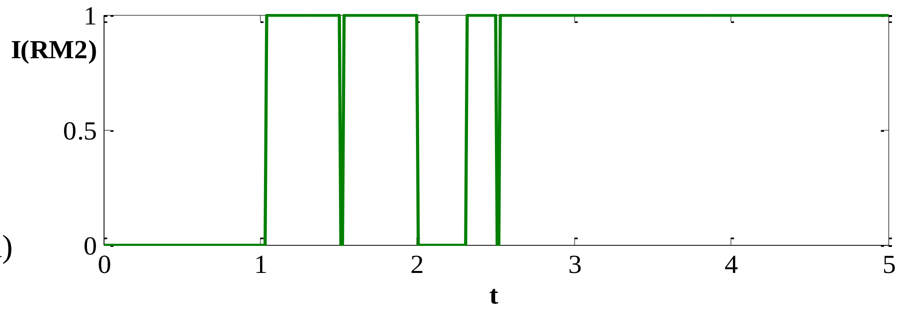


Figure 6. Values of asymmetry and control variables over time

a - when the dynamics are taken into

Fig. 6 shows the working tracts of the protection and the corresponding tolerances when the change dynamics of asymmetry is not taken into account. As it can be seen, up to 0.2 value of asymmetry, the controller does not make any decision to open the circuit. However, asymmetry values exceeding 0.2 produce a control signal to open the circuit with a 2 second tolerance.

For another case, the working diagram of the intelligent protection system taking into account the rate of change of asymmetry is given in figure 6. As can be seen, the fuzzy controller makes similar decisions depending on the different values of asymmetry and the rate of change of these values.

RESULTS

1. An analysis of the modern processing of the non-symmetrical and incomplete phase modes arising in the load nodes of the power grids of the power system was carried out and it was determined that in order to ensure its further intelligence, it is important to include the rate of change of the asymmetry due to the reverse sequence current, which is the input parameter, as an input quantity of the *FLC*. A new structural scheme of protection in two-input and two-output *FLC* database was drawn up, the terms, membership functions and parameters of accepted linguistic variables were determined.

2. Based on the results of the calculated experiments in the range of asymmetry of various temper, it can be noted that it is possible to ensure the intelligent operation of the protection against the considered damage and to further increase the reliability of the equipment protection..

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