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DETERMINATION OF RESIDUAL RESOURCE OF MEASURING CURRENT TRANSFORMERS USING FUZZY SIMULATION

The article analyzes the damage of the main elements of current measuring transformers (CMT) and proposes a mathematical model of the residual life of CMT obtained by fuzzy modeling using Matlab software.
Key words: current transformer, residual resource, mathematical modeling, neural networks.

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ВИЗНАЧЕННЯ ЗАЛИШКОВОГО РЕСУРСУ ВИМІРЮВАЛЬНИХ ТРАНСФОРМАТОРІВ СТРУМУ З ВИКОРИСТАННЯМ НЕЧІТКОГО МОДЕЛЮВАННЯ

Розвиток промисловості в Україні в останні роки обумовлює збільшення споживання електричної енергії та, як наслідок, зростання навантаження на електроенергетичне обладнання. У той же час велика кількість вимірювальних трансформаторів, які є важливим обладнанням електроенергетики, експлуатуються з перевищенням призначеного ресурсу. Дійсно, парк вимірювальних трансформаторів в Україні на 50% – 60% складався з такого обладнання. І, незважаючи на постійне збільшення витрат, що виділяються на оновлення парку енергетичного обладнання, на сьогоднішній день істотно змінити цю ситуацію не вдалося. З іншого боку, багато фахівців відзначають, що замінювати трансформатор після закінчення його призначеного ресурсу найчастіше виявляється недоцільно. За минулі роки була проведена велика робота по створенню методів діагностики трансформаторного обладнання, що дозволяють при комплексному їх застосуванні адекватно оцінити технічний стан обстежуваного об'єкта з надійністю, що досягає 98%.

Однак, незважаючи на це, кількість трансформаторів, "допрацьовують" до відмов через термохімічне старіння твердої ізоляції, складає за різними джерелами від 7% до 20%, тобто причиною відмови від 80% до 93% трансформаторів є різні своєчасно не виявлені дефекти. Дана ситуація обумовлена низькою ефективністю традиційної схеми діагностики. Отже, дослідження та розробка сучасних системи діагностування високовольтного обладнання є актуальною задачею.

Так, зокрема, в статті досліджено можливість використання методів нейро-нечіткого моделювання в задачі визначення коефіцієнту загального залишкового ресурсу вимірювальних трансформаторів струму в умовах неповноти початкових даних.

Ключові слова: вимірювальний трансформатор струму, залишковий ресурс, математичне моделювання, нейронні мережі.

Introduction

A sign of today is the transition from centralized to decentralized electricity supply. In particular, in recent years there has been a noticeable tendency to increase the installed capacity of generating power plants running on renewable energy sources [1–5]. Such stations are installed in electrical distribution networks designed under the conditions of centralized power supply [6–10]. In turn, a number of scientific works of domestic scientists have shown that such stations can affect the quality of electricity and be one of the reasons for their failure [11]. For example, as the frequency increases, the current in the winding will decrease, so the appearance of low-frequency harmonics in the current at the voltage of the transformer (less than 50 Hz) can lead to an increase in current that significantly exceeds the maximum allowable limits (under certain conditions) can damage the transformer winding [11–13]. The current control systems of current measuring transformers (CMT) use known mathematical models of CMT in their calculations, but these models have a significant disadvantage - they cannot determine and take into account the functional relationships between many of their controlled diagnostic parameters simultaneously, in one mathematical model. The problem is complicated by the incompleteness of the initial data, when some of the parameters are known at the time of calculation, for example, due to the need for additional research. Fuzzy modeling is a very constructive technology for establishing such connections. This modeling allows to obtain more reliable results compared to the results of existing diagnostic systems. If as a result of the analysis of the data provided by representatives of shop of repair of CMT, from literature sources or according to isolation service, etc. the information on some reasons of removal in repair of high-voltage oil-filled (with paper-oil isolation of condenser type) CMT will be collected, such data can be arranged, for example, as shown in table 1 for CMT 35 kV [14–17].

1Determination of the total residual life of the current transformer

The results of comprehensive studies of the damage of current transformers are shown in Table 1. In Table 1, under the controlled diagnostic parameter we understand the parameter, the deviation of which from the norm contributed to the removal of CMT for repair or was taken into account when removing CMT for repair. As diagnostic parameters in table 1 are given: parameters that characterize the state of the paper-oil insulation, the state of the parts of the PTS, which are responsible for sealing the CMT, the state of the pressure compensator.

Parameters that characterize the state of paper-oil insulation [13]: W - moisture content in transformer oil CMT, C_X - capacity of paper-oil insulation, R - active resistance of paper-oil insulation, tg (δ) - tangent of the dielectric loss angle in paper -oil insulation, P_1 - a constant decrease in pressure in the CMT, which is due to the presence of places leakage of transformer oil, P_2 - fluctuations in the pressure in the CMT when the ambient temperature changes, which are due to damage to the bellows CMT, T_1 - increase in excess temperature in the upper part of the CMT due to the defect of the coupling unit of the pressure compensator, T_2 - increase in temperature in the area of the measuring terminal, T_3 - total heating of the inlet tire, for example, due to deterioration of insulation parameters of the CMT, T_4 with typesetting upper tires, due to disturbances in the circulation of transformer oil in the CMT, CADG (chromatographic analysis of gases dissolved in oil) - excessive change in the content of dissolved gases in the transformer oil CMT or excessive change in the ratio of dissolved in the transformer oil CMT gases. After analyzing the data in Table 1 and the literature, we created a diagram that shows the dependent or independent influence of diagnostic parameters on the coefficient of the total residual resource of the CMT (Fig. 1) [18–20].

With the help of computer mathematics - MATLAB system it is possible to create a mathematical model of the residual life factor of the current transformer, using which to edit the previously created probabilistic sample of educational data which can further obtain an analytical dependence of the residual life factor of the current transformer on diagnostic parameters in the form of polynomial.

The coefficient of residual resource k_i on the i-th diagnostic parameters:

$$k_{i1} = \left| \frac{x_{i1,lim} - x_{i1,cur}}{x_{i1,lim} - x_{i1,initial}} \right| .$$

where $x_{i1,lim}$ - the limit normative value of the i1th diagnostic parameter, $x_{i1,cur}$ - the value of the i1th diagnostic parameter at the time of control, $x_{1,initial}$ - the initial value of the i1th diagnostic parameter (at the time of commissioning of new equipment or after repair), i1 - diagnostic parameter.

Table 1

Reasons for the conclusion of the repair of transformers

CMT element	Diagnostic parameter		Number of repaired CMT that have an excess value of the diagnostic parameter	
	Designation	The name of the parameter	units	%
Paper and oil insulation	C_X	capacity of paper and oil insulation	2	1
	W	moisture content	8	5
	R	active insulation resistance of primary and secondary CMT windings	2	1
	$tg(\delta)$	the tangent of the dielectric loss angle in the paper-oil insulation	14	10
	T_3	heating of the CMT tire near the hardware inputs	3	1
Transformer oil	*CADG*	according to the results of chemical analysis of gases dissolved in transformer oil	32	15
Hardware input	T_1	increase in excess temperature in the contact part of the CMT input due to a contact defect in the hardware input	5	5
Porcelain tires	P_1	constant decrease of pressure in CMT which is caused by leakage of transformer oil	65	55
	P_2	fluctuations in the value of the pressure in the CMT when the temperature changes (daily pressure fluctuations in the CMT, etc.) of the environment, which are due to damage to the bellows of the CMT	3	3
	T_4	heating of the upper part of the tire (above the connection) in the CMT, due to disturbances in the circulation of transformer oil in the CMT	3	1
Pins of a terminal knot of secondary windings	T_2	temperature rise in the area of the terminal node (outputs of the secondary windings)	3	3
		Total	140	100

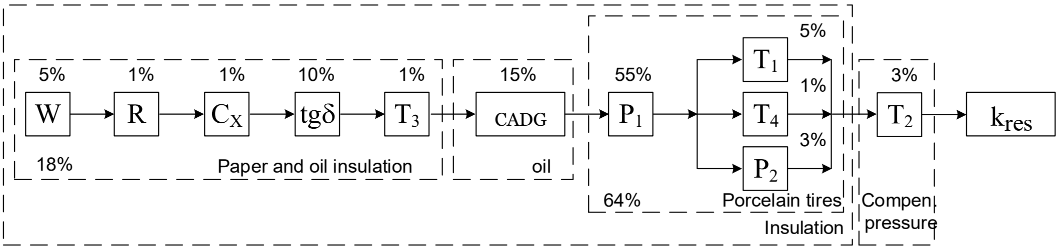

Fig. 1. Block diagram of the model of the coefficient of the residual resource of CMT

The probability of deviations of the controlled parameter from the maximum allowable normalized value of this parameter:

$$p_\tau = \frac{y_\tau}{m_2},$$

where y_τ - the number of deviations of the controlled parameter from the maximum allowable normalized value of this parameter, which were detected by the control τ -th diagnostic, m_2 - the total number of detected deviations of the controlled diagnostic parameters from their maximum allowable normalized values.

Therefore, the coefficient of the total residual resource of the CMT is determined by the expression:

$$k_{tot.res} = k_W^{p_W} \cdot k_R^{p_R} \cdot k_{C_X}^{p_{C_X}} \cdot k_{tg(\delta)}^{p_{tg(\delta)}} \cdot k_{T3}^{p_{T3}} \cdot k_{CADG}^{p_{CADG}} \cdot k_{P1}^{p_{P1}} \cdot \left\{1\text{-}\left[\left(1\text{-}k_{T1}\right) \cdot p_{par.p.T1} + \left(1 - k_{T4}\right) \cdot p_{par.p.T4} + \left(1 - k_{P2}\right) \cdot p_{par.p.P2}\right]\right\}^{p_{tot.p.T1,T4,P2}} \cdot k_{T2}^{p_{T2}} \quad (1)$$

where k_W, k_R, k_{CX}, $k_{tg(\delta)}$, k_{T3}, k_{CADG}, k_{P1}, k_{T2}, k_{T1}, k_{T4}, k_{P2} – known at the time of calculation of the values of the coefficients of the residual resource, respectively, by parameters W, R, C_X, $tg(\delta)$, T_3, $CADG$, P_1, T_2, T_1, T_4, P_2 ; p_W, p_R, p_{Cx}, $p_{tg(\delta)}$, p_{T3}, p_{CADG}, p_{P1}, p_{T2} – probability of deviations of values of diagnostic parameters from maximum admissible normalized values taking into account the total number of deviations of all diagnostic parameters; $p_{par.p.T1}$, $p_{par.p.T2}$, $p_{par.p.P2}$ – probabilities of deviations of values of diagnostic parameters from maximum admissible normalized values taking into account the total number of deviations of diagnostic parameters of only a parallel part of the scheme; $p_{TOTAL.P.T1,T4,P2}$ – the probability of deviation of the values of diagnostic parameters from the maximum allowable normalized values for the generalized (parallel part of the scheme) block (in the sequential part of the scheme) taking into account the total number of deviations of diagnostic parameters. Yes, according to table. 2: p_R=0,05 *r.u.*, p_{Cx}=0,01 *r.u.*, $p_{tg(\delta)}$=0,1 *r.u.*, p_{T3}=0,01 *r.u.*, p_{CADG} =0,15 *r.u.*, p_{P1}=0,55 *r.u.*, p_{T2}=0,03 *r.u.*, p_{T1} =0,05 *r.u.*, p_{T4} =0,01 *r.u.*, p_{P2} =0,03 *r.u.*, $p_{par.p.T1} = p_{T1}/(p_{T1}+p_{T2}+p_{P2})$ = 0,55 *r.u.*, $p_{par.p..T4} = p_{T4}/(p_{T1}+p_{T2}+p_{P2})$ = 0,11 *r.u.*, $p_{par.p..P2} = p_{P2}/(p_{T1}+p_{T2}+p_{P2})$ = 0,33 *r.u.*, $p_{total.P.T1,T4,P2} = p_{T1}+p_{T2}+p_{P2}$=0,09 *r.u.*

The theory of fuzzy sets was created a long time ago, but it began to be actively applied in our time. Its advantages are that it operates with fuzzy inputs, the connections between which are not known in advance, their accuracy and veracity are not always known. Part of the calculation results are shown in table 2.

Table 2

The results of calculations of the coefficient of residual resource of the CMT

Diagnostic parameter											Coefficient of residual resource of the CMT
k_W, *r.u.*	k_R, *r.u.*	k_{CX}, *r.u.*	$k_{tg(\delta)}$, *r.u.*	k_{T3}, *r.u.*	k_{CADG}, *r.u.*	k_{P1}, *r.u..*	k_{T2}, *r.u.*	k_{T1}, *r.u.*	k_{T4}, *r.u.*	k_{P2}, *r.u.*	
0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1
0	1	1	1	1	1	1	1	1	1	1	0
…	…	…	…	…	…	…	…	…	…	…	…
0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,93	0,930063
1	1	1	1	1	0,07	0,93	1	1	1	1	0,644808
…	…	…	…	…	…	…	…	…	…	…	…
0,2	0,5	0,3	0,4	0,7	0,5	0,5	0,2	0,4	0,3	0,8	0,446311
0,5	0,3	0,4	0,3	0,4	0,7	0,5	0,5	0,3	0,4	0,6	0,492952
…	…	…	…	…	…	…	…	…	…	…	…
1	1	1	1	1	1	1	1	1	0,92	0,08	0,924798

The full table contains 3012 combinations of the options considered diagnostic parameters and corresponding values of total residual life of MTC data were used as training data in modeling system of computer mathematics MATLAB. The Fuzzy Logic Toolbox was used for this purpose. Using the ANFIS Editor. The structure of the obtained neural network using the method of subclustering is shown in Fig. 2.

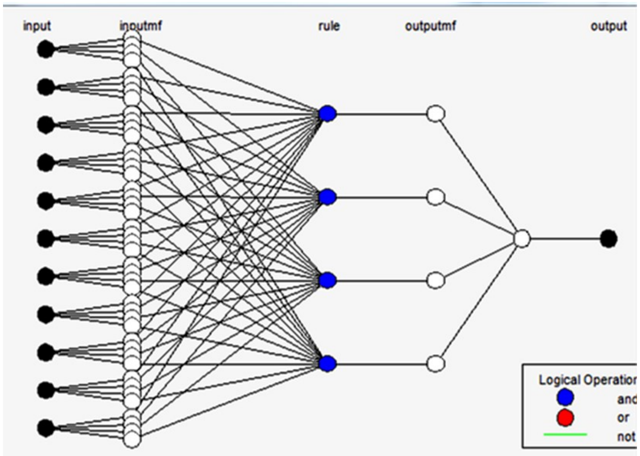

Fig. 2. Structure of Anfis-network of the CMT

From fig. 2 shows that during the formation of the structure of the neuro-fuzzy CMT model, eleven inputs and one output of this model were specified. Each of the eleven entrances has four terms. That is, each set of possible values of input parameters of the model is conventionally divided into four subsets: "normal" values of the input parameter, "slight deviations" of the input parameter, "pre-emergency" values of the input parameter, "emergency" values of the input parameter. The degree to which each value of the input parameter belongs to the set of values corresponding to this parameter is determined by the Gaussian membership function. The model is designed to find the numerical value of the coefficient of the total residual resource of the CMT, so it has one output. This numerical value is found by solving a linear equation that describes the dependence of the coefficient of the total residual resource of the CMT on the input parameters.

Next we teach the model. Training involves 30 epochs. A sign of termination of training is the invariance of the root mean square error of training. The standard error of training, which lasted 30 epochs, is equal to 0.011 r.u. The obtained neuro-fuzzy model allows to determine the value of the coefficient of the total residual resource of the CMT depending on the values of the input parameters - the coefficients of residual resources for each of the controlled diagnostic parameters. Thus, if each of the coefficients of the residual life of the diagnostic parameters will be equal to 0.5 r.u., the coefficient of the total residual resource is equal to 0.64 r.u., if each of the coefficients of the residual life of the diagnostic parameters will be equal to 1 r.u., then the coefficient of the total residual resource is equal to 1.01 r.u. The complexity of the dependences of the output parameter of the developed model on the set of input parameters is confirmed by the graphs of the surfaces of these dependences, which are shown in Fig. 3, 4.

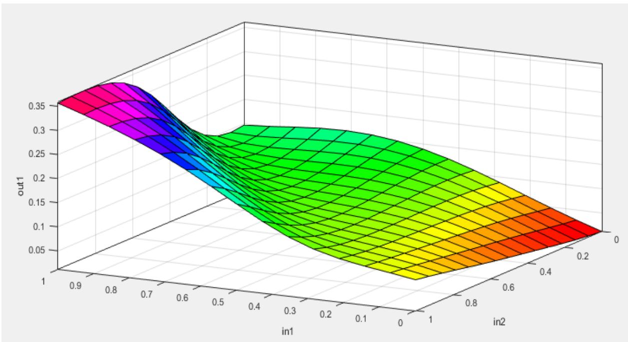

Fig. 3. Dependence of the residual resource of CMT on k_W and k_R

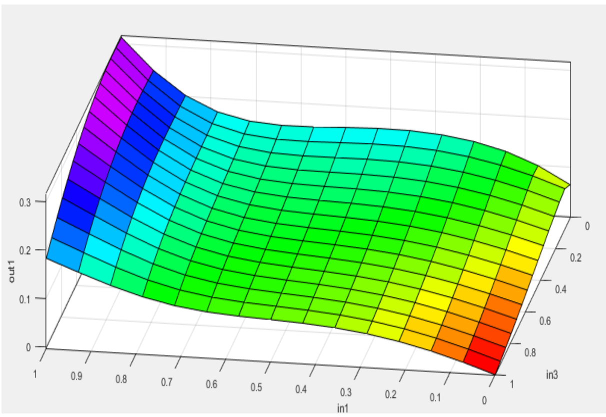

Fig. 4. Dependence of the residual resource of CMT on k_W and k_{CADG}

Conclusions

Despite the complexity of the dependencies, which are shown in Fig. 3, 4 mathematical model of the coefficient of residual resource CMT can be used to program a fuzzy controller in order to create a device for rapid determination of the state of CMT by analyzing the value of the coefficient of residual CMT.

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