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PREDICTION OF WEARING OUT OF POWER TRANSFORMER WINDING INSULATION

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Importance of the different parameters of wearing out of power transformer insulation prediction structure, operating factors, selection of configuration and parameters of paper insulation and transformer oil technical state models is investigated. Prediction of wearing out of power transformer winding insulation is reduced to the stochastic prediction of load dynamics and ambient temperature, simulation of the changes of technical states of paper insulation and transformer oil, aging calculations and probabilistic estimation of insulation wearing out. Computer simulation of power transformer insulation wearing out for the next ten years of operation is performed. References 6, figures 2.
Key words: power transformer, insulation wearing out, prediction, models of technical states and operating factors.

During operation of power transformer (PT) its insulation, in particular, winding insulation, is an object of diagnose (OD) for which technical state (TS) is determined. TS of insulation paper (IP) and transformer oil (TO) are distinguished. Important features of TS of these objects are wear factor and residual resource.

The wear factor of IP is characterized by aging factor, which can be represented by initial and final values of cellulose polymerization degree [1]. Residual resource of IP – is the time during which its polymerization degree is reduced to the critical value. Dynamics of changes of wear factor is characterized by the rate of wearing out. Standard [2] defines the relative speed of wearing out as the ratio of the wearing out velocity at the current hot spot temperature θ_h to the wearing out rate at temperature 98 °C (non-thermally upgraded paper) and 110 °C (thermally upgraded paper). The key factor, determining the rate of V, ceteris paribus, is the temperature θ_h. Other conditions are characterized by TO parameters, such as moisture content W, acid number K etc.

In [3,4] actual insulation resource is determined by calculation based on monitoring data values θ_h, W, K and other parameters for several intervals of observation, equaled to one year, for example. For obtaining of the time series of annual wearing out statistical characteristics (expectation, variance and standard deviation) are defined. These characteristics are used for prediction of the insulation residual life. Having obtained in such a way evaluation accuracy decreases with the change of the load prediction period and technical state of PT.

In [5] the method of estimation of residual life of PT winding insulation by prediction of the impacts of PT operating factors (OF) to TS of insulation is proposed. Because of the limited size of publication this methodology wasn't detailed and investigated.

The purpose of this work is to study the importance of various parameters of prediction structure, OF, and selection of the configuration and TS parameters of IP and TO models.

Block diagram of the model is shown in Fig. 1. It contains a vector of predicted parameters (PP), models of the OF, maintenance, TS of IP and TO, as well as the time-marker (TM) generator and the unit of wear evaluation (WE).

TS IP model is based on the heat balance equation of PT. It allows determining the temperature trend θ_h based on trends of load current I_d, ambient temperature θ_a and a binary variable of cooling, named "COOLING MODE". Parameters of TS IP model are load voltage U_d, no-load loss P_{xx}, and thermal parameters defined by results of PT thermal tests: thermal capacity C, thermal resistance "PT - environment" in natural R_N and forced R_F cooling modes. Dependence of resistance R_F upon time simulates the cooling performance degradation.

TS TO model calculates trend parameters W and K based on expert judgments [1] by formulas:

$$W(t) = W_0 + M_W(t - T_{TO}); \qquad (1)$$

$$K(t) = K_0 + M_K(t - T_{TO}), \qquad (2)$$

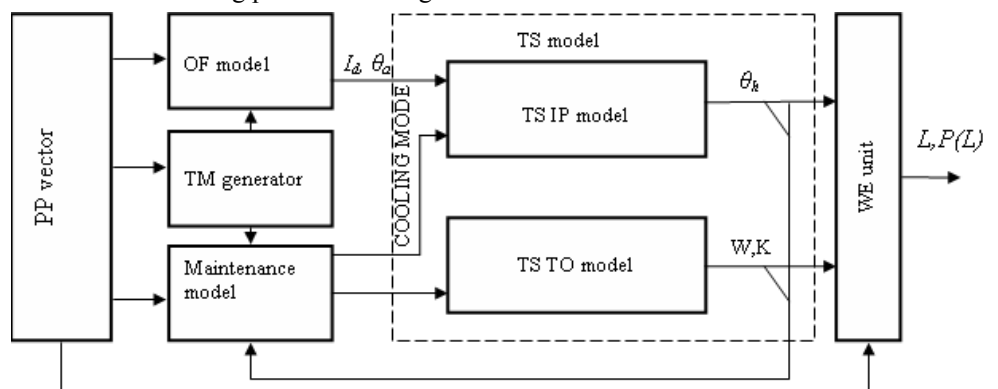where W_0, K_0 − W and K parameters at the beginning of PT life and after its main-

Fig. 1

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tenance; M_W, M_K − increment coefficients of parameters W and K during TO aging.

In future it is planned to develop a TS TO model based on equations of moisture balance and balance of chemical reactions of acid formation and decomposition.

The OF model synthesizes predicted trend of current I_d and temperature θ_a. As the model of temperature θ_a "double sine curve" model [6], supplemented by long-lasting climatic changes component is used.

Input parameters and the structure of I_d trend depend on the accuracy requirements to the prediction of insulation resource duration, availability of monitoring data parameters of PT for the periods preceding the prediction moment, data detailing about expected PT loads in the prediction period. As the most detailed model the model [5] is used:

$$I_d = P_г \cdot I_{гav} \cdot N_г + \Delta I_{dг} \cdot P_c \cdot (N_{дг}) + \Delta I_{dc} \cdot P_д(N_c) + \Delta I_{dч} \cdot P_ч(N_ч) + \Delta I_{di} \cdot K_i(N_i) , \qquad (3)$$

where $P_г$ − coefficient of variation of average annual current; $I_{гav}$ − the average annual load current in the time of prediction; $\Delta I_{dг}$ − average annual change of load current; P_c − average daily rate changes; ΔI_{dc} − average daily change of the load current; $P_d(N_{дн})$ − coefficient depending on the day of the week; $N_{дн}$ − day of the week number; $\Delta I_{dч}$ − hourly average change of the load current; $P_ч$ − coefficient depending on the number of hours; ΔI_{di} − amplitude of the inrush load current; K_i − interval of the inrush load current; N_i − number of inrush load current interval.

In the case of reduction of the requirements to prediction accuracy, reducing of monitoring data amount, increasing uncertainty of the expected load, variables in the formula (3) are replaced by constants in the following order:

$$\Delta I_{di} = 0 , \quad \Delta I_{dч} = 0 , \quad \Delta I_{dc} = 0 , \quad \Delta I_{dг} = 0 , \quad P_г = 0 .$$

TM generator generates time marks $N_г$, N_c, $N_ч$, $N_{дн}$, which are used by OF and maintenance models. Input data for TM generator are date, time and interval of prediction.

Maintenance model generates commands for turning on the COOLING MODE and maintenance of the TO based on input data of cooling set point θ_o and maintenance modes (scheduled and on-condition maintenance), TO baselines ($K_{БАЗ}$, $W_{БАЗ}$) and TS model output data(θ_h, W, K). In the temperature control loop maintenance model contains relay controller. At the part of TO maintenance model contains blocks, which comparing the current model time with scheduled maintenance time; current values W, K with the maximum allowable W_{max}, K_{max}.

Maintenance command is the logical OR of the listed above comparison results. At this command current values K and W in TS TO block reduced to $K_{БАЗ}$, $W_{БАЗ}$.

WE unit calculates the insulation wear index L in simulation time interval based on TS model output data:

$$L(t_0, t+T) = \frac{1}{T} \int_{t_0}^{t+T} \left(\frac{K(t)}{K_{БАЗ}} \right)^{2,05} \left(\frac{W(t)}{W_{БАЗ}} \right)^{1.493} \exp[\ln 2 \frac{\theta_h(t) - 98}{\Delta}]dt, \qquad (4)$$

where $K_{БАЗ}$ − acid number of oil, taken for the baseline value; $W_{БАЗ}$ − baseline value of moisture content of the solid insulation.

Using the described model computer simulations of PT insulation wear over the next ten years of operation was performed. It was assumed that the value of the coefficient $P_г$ − is a random variable that obeys the normal distribution law. To estimate the probability of given recourse duration exceeding in prediction interval a number of M random values of $P_г$ coefficient corresponding to mathematical expectations of 2% of average annual increment of PT load current was generated. As a result of PT insulation wearing out simulation with using proposed model and with predicted currents I_d, depending on coefficient $P_г$, M wearing out values of L were obtained. For these values probability density functions and probability distributions of wearing out are defined. With increasing of M these functions become more "smooth". Changes in wearing outs probability values for the selected wearing outs interval are reduced. Specified property allows estimating the minimum number of M − about 200. Herewit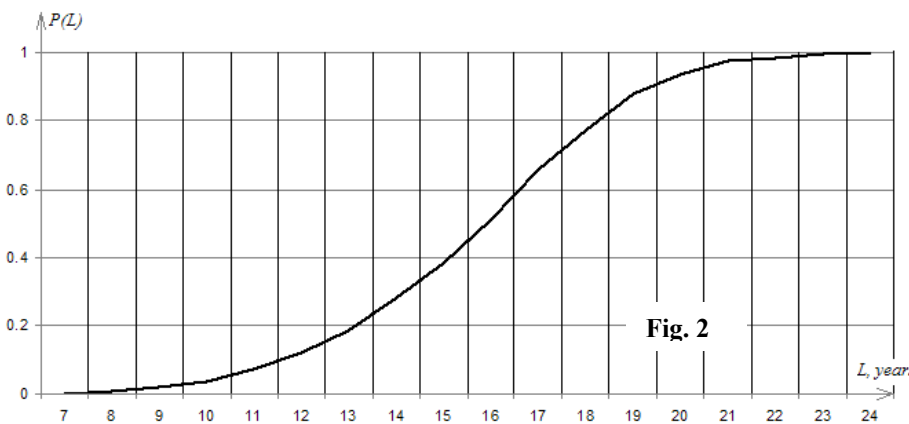h a cost of computer time did not exceed one hour for personal computer with the base performance index 3.5. Graph of obtained $P(L)$ function of the wearing outs probability distribution is shown in Fig. 2.

Fig. 2

Thus, the prediction of wearing out processes of PT winding insulation bases on the model of OF, TS IP and TO dynamics, methodology of the relative PI wearing out rate estimation, on-condition maintenance strategy. The parameters of these models are determined by the technical documentation, monitoring data and PT examination and expert judgment. Some of the model parameters, and hence the result of the simulation - the probability of specified insulation wearing out exceeding - are random variables. Probability distribution function of the PT winding insulation

wearing out is obtained by Monte Carlo modeling method. Modern personal computers allow performing this simulation with sufficient precision and accuracy of the prediction in a reasonable time. Described approach to prediction of wearing out processes can be useful for other types of electromechanical equipment.

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ПРОГНОЗИРОВАНИЕ ПРОЦЕССОВ ИЗНОСА ИЗОЛЯЦИИ ОБМОТОК СИЛОВОГО ТРАНСФОРМАТОРА

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Исследована значимость различных параметров структуры прогноза износа изоляции силового трансформатора, факторов эксплуатации, произведен выбор структуры и параметров моделей технического состояния бумажной изоляции и трансформаторного масла. Прогнозирование износа изоляции обмоток силового маслонаполненного трансформатора сведено к стохастическому прогнозированию динамики нагрузки, температуры окружающей среды, имитационному моделированию изменений технического состояния бумажной изоляции и трансформаторного масла, расчету старения и вероятностной оценке величины износа изоляции. Выполнено компьютерное моделирование износа изоляции силового трансформатора в течение предстоящих десяти лет эксплуатации. Библ. 6, рис. 2.
Ключевые слова: трансформатор, износ изоляции, прогнозирование, модели технического состояния и факторов эксплуатации.

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