Neural Network Multistage Method for The Forecasting Electrical Insulating Materials Characteristics

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Abstract. The solution to the problem of non-destructive monitoring of thermal processes in insulating materials is shown. The main configuration parameters of the artificial neural network are determined. A mathematical model and architecture of a neural network for the forecasting thermal fluctuation processes are developed. The architecture of a neural network with a consistently distributed structure is synthesized. A forecasting technique is proposed and functions are obtained for assessing the long-term permissible heating values of the cable current-carrying core insulating material. Temperature monitoring will allow to monitor both the condition and the throughput of the lines.

1. Review of systems for the forecasting thermal processes
Insulation materials (IM) during operation are subject to thermal, electrical, chemical, mechanical and other types of influences [1]. The temperature rise increases the likelihood of a decrease in the IM electrical strength, which further promotes their breakdown. Therefore, the main task of the operating personnel is to control and maintain the IM electrical insulating properties at a level that excludes their emergency failure [2, 3]. The direct destruction of the polymer is explained by cracks formation in the stress concentration places and the initiation and development of cracks is considered as a consequence of the kinetic process of thermofluctuation breaking of bonds [1]. It was found that the source of breaks in the structure of an insulating polymer is thermal fluctuation processes, which sharply increase the kinetic energy of individual atoms vibrating around the equilibrium position, as a result of which the chemical bond of the polymer backbone sometimes breaks [2-4]. Chemical degradation will cause changes in the mechanical properties of polymer insulation [5]. A thermodynamic approach is needed in the study of the processes of the insulating materials destruction. The IM low thermal conductivity of the power cable line (PCL) in Fig. 1 leads to a high temperature gradient, therefore, the temperature of the most heated part in the PCL section (near the core \( \Delta c \)) significantly differs from the IM temperature on the casing (\( \Delta p.c \)), and in transient modes this difference can increase several times [3, 6]. The object of the research is APvPu g-1x240 / 25-10 [3] IM with cross-linked polyethylene (XLPE) insulation. The CL thermal field is described by the differential equation of thermal conductivity (1), which in the general case determines the change in the temperature distribution in the volume of the object under consideration depending on time [7]. In [8], another solution was obtained that allows to determine the cable surface temperature using an integral exponential function. The proposal to calculate the temperature on the cable surface using an exponential integral was implemented in [9], where the temperature difference between the cable surface and the soil surface was calculated using the theory...
[8], and the temperature difference between the core and the outer casing, as in [10], was calculated using a thermal equivalent circuit. But the calculation of its parameters in [12] is performed using the Van Wormer method [11]. Since the heat wave from the core and the screen does not immediately reach the cable surface, a certain coefficient $a(t)$ (“attainment factor”) was introduced in [9] for matching between the two calculated regions. To calculate the core and screen temperatures, considering the constantly changing core current and screen temperature, the authors of [12, 13] presented them in the form of a stepped graph. The influence of each current jump and screen temperature was considered. The review has shown that most of the methods have low forecasting accuracy, are difficult to forecast the thermal processes in PCL, and are not capable of operating in real time; therefore, it is necessary to search for a promising non-destructive method.

1.1 Influence of the inclusions presence on the thermal processes

There are inclusions in the IM and they arise during operation (Fig. 1) [7], which affect its heating and deterioration. Let’s simulate the IM resource (service life) depending on the temperature, formula (4).

Figure 1. The investigated PCL insulating material

The total electric field intensity in the IM for different sizes of the inclusion ($r_{VKL1}$, $r_{VKL2}$, $r_{VKL3}$) is equal to

$$E = E_v + E_{oi}, nru \ r_{VKL} = \text{variable}$$

(1)

Considering that the intensity on the inclusion for the radius $r_{INC1}$, $r_{INC2}$, $r_{INC3}$

$$E_v = UC_1 \left/ 2r_{VKL}C_v \log \left( \frac{h}{2r_{VKL}} \right) \right.$$  

(2)

Intensity on the residual insulation layer for the radius $r_{VKL1}$, $r_{VKL2}$, $r_{VKL3}$

$$E_{oi} = U \left/ \frac{C_{v1}C_{oi1}}{C_{v1} + C_{oi1}} \right/ 4\pi \epsilon_0 \epsilon_{VKL} \left( h - 2r_{VKL1} \right) \log \left( \frac{h}{D_{oi1}} \right) \left( h - r_{VKL1} \right)$$

(3)

When calculating the IM residual service life, it was considered that one monomer contains two CC bonds and four CH bonds. The breaking energies of one bond were taken, respectively, $W_{CC} = 84$ [kJ/(mol)] and $W_{CH} = 99$ [kJ/(mol)].

The calculation of the CL insulating material service life is performed according to the formula

$$\tau = \tau_0 \exp \left( \frac{W_{cp} - \chi E}{RT} \right), \text{where } W_{cp} = \frac{2W_{CC} + 4W_{CH}}{6}.$$  

(4)

where $\chi$ – structural parameter [kJ mm/mol kV] = 0.447; $E$ – field intensity.

Forecasting results of the PCL IM residual life are shown in Figure 2.

The dependence of the IM resource on the inclusion size is obvious (Fig. 2), and, consequently, the energy loss in the IM and its heating. Therefore, the problem of temperature monitoring is relevant, considering the inclusions in the IM [3].
2. Experimental researches
In order to identify the defects occurrence during the cable operation, conditions for its artificial aging were created. For this, at the first stage, the samples of the cable under study were kept at the same temperature, but with different time durations in a heating cabinet. After heat treatment, the cables were subjected to current loading, which resulted in the cable insulating material heating. Graphs of temperature changes (experimental and forecasted) of one of the investigated cables before and after aging (stages 1 and 2) are shown in Fig. 3.

Further the comparing of the temperature difference was made. The research results for "new" (training sample) and "aged" (control sample) cable samples are summarized in Table 1.

| Parameter | № cable sample | 1 | 3 | 4 |
|-----------|----------------|---|---|---|
| Temperature difference ΔT | New | 1.73 | 2.8 | 2.3 |
|           | Aged           | 1.2 | 1.46 | 1.6 |
| Error, %  | New            | 4.2% | 5.2% | 3.8% |
|           | Aged           | 3.8% | 2.3% | 3.1% |

Analysis of the results showed that the longer the aging time, the greater the temperature difference between the original and the aged sample. With increasing aging time, the temperature difference ΔT increases. The temperature difference (ΔT) allows to determine the insulating material residual life [7]. At the same time, the forecast error of the neural network decreases, that is, the accuracy of forecasting the cable core temperature increases.

We believe that this is due to the loss of the material electrical insulating properties due to the accumulation of the destroyed structure fragments, containing, in ever greater quantities, the inclusion of pure carbon and other conductive inclusions. The reaction of incomplete oxidation of polyethylene with the formation of carbon:

\[-CHCH2n + nO2 \rightarrow 2nC + 2nH2O\]  \(\text{(5)}\)
Thus, the dependence of the increase in the temperature difference $\Delta T$ on the deterioration degree of the material electrical insulating properties has been revealed and investigated, which makes it possible to forecast its resource.

2.1 Multipurpose optimization of NN forecasting method
The result of the carried out multipurpose optimization showed that the efficiency of the NN methods using is 1.6-1.9 times higher than that of traditional methods [14]. The solution to the forecasting problem using models based on artificial neural networks is proposed [19-20].

2.2 Mathematical description of the algorithm
In the mode of dynamically changing load of the power cable, it is necessary to forecast its temperature regime. A transformation algorithm has been developed that allows from the members of the time series $(X(n))$ of the input parameters of the PCL: $\theta_{p.c}$ (1 ... n) is the temperature of the protective casing, $\theta_e$ (1 ... n) is the environment temperature, $I_c$ (1 ... n) - current in the PCL core to form a “window”, which is a training set for building a forecast. The window is a time interval containing a set of values ($\theta_{p.c}$ (1 ... n), $I_c$ (1 ... n), $\theta_e$ (1 ... n)), which are used to form a training example.

A serial two-network architecture of a neural network with a sequentially distributed structure is synthesized. The first network forecasts the PCL surface temperature, the second forecasts the core temperature. The mathematical model of the NN is given below.

\[
\begin{align*}
g_i &= f \left( \sum_{j=1}^{n} w_{ij} x_j + Q_j \right), \\
y_j &= f \left( \sum_{i=1}^{m} w_{ij} g_i + T_k \right), \\
w_{ij}(t+1) &= w_{ij}(t) + \alpha \frac{\partial E}{\partial w_{ij}(t)}, \\
T_k(t+1) &= T_k(t) + \alpha \frac{\partial E}{\partial T_k(t)}, \\
\frac{mN}{1+\log_2^m} \leq Lw \leq \left( \frac{N}{m} + 1 \right)(n+m+1) + m; L = \frac{Lw}{n+m}
\end{align*}
\]

2.3 Consideration of magnetic interference with dynamic current change
The process of the core current changing is dynamic, although time is not explicitly included in the dynamic law of the current in the core ($I_c$), written in differential or recurrent form, therefore the process is called stationary.

The diagrams of the surface experimental and forecasted temperature and the temperature of the PCL central core are presented (Fig. 4, b) depending on various values of the current in the core (Fig. 4, a) and considering the interference from the neighboring cable.

The results of the temperatures comparison and the forecast error are shown in Table 2.

| Magnetic interference | Average temperature / forecast error | Experimental, °C / average, °C | Forecasted, °C / t, % |
|------------------------|--------------------------------------|---------------------------------|------------------------|
| No interference        | 61.2 °C / 1.06 °C                    | 61.47 °C / 1.73%                |
| With interference      | 61.2 °C / 1.62 °C                    | 60.68 °C / 2.64%                |
Thus, the results of the NN forecast showed that for cables with XLPE insulation it is possible to forecast the current-carrying core temperature. Considering the influence of magnetic interference on the cable showed that the presence of magnetic interference on the cable (taking them into account as an input parameter of the NN) increases the error by 1.3 degrees (or 0.8%).

**Conclusion**
A set of studies was carried out to improve the accuracy of the thermal processes forecasting in the cable lines insulating materials, considering changes in the current load of the line and external conditions of heat removal, air temperature and magnetic field strength. The comparisons of the forecasted values with the actual ones allow us to speak about the adequacy of the selected network model and its applicability in practice. The developed methods and algorithms are elements of an integrated diagnostic system and are aimed at efficient and reliable power supply to consumers. The use of the developed neural network system for the power cable temperature forecasting contributes to the planning of operating modes of power supply networks for consumers.

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