Method for Estimating a Residual Resource of Induction Motor Winding Insulation Based on Capacitive Leakage Currents

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***Abstract*—The paper presents an approach to estimating resource expenditure and predicting the induction motors windings insulation residual life based on the measurement of capacitive leakage currents created by a continuous sequence of rectangular voltage pulses. Experiments show an exponential decrease in leakage currents due to the development of insulation degradation processes in the long term. It was proposed to estimate the residual resource value using a modeling exponent, whose parameters are determined in the current time mode using parameter identification methods such as the least squares method (OLS) or methods based on the Kalman algorithm. The advantage of the proposed method is the comparative simplicity of the technical means used and the ability to assess the residual life of the winding insulation, relying only on the data experimentally obtained through measurement. The article describes the operation of the algorithm for the prediction of the insulation condition based on the parameters identification of the modeling exponent.**

Keywords—induction motor; stator winding; winding insulation; residual life; leakage currents; diagnostics; insulation condition monitoring; insulation condition prediction; parameter identification; least squares method.

I. INTRODUCTION

Induction motors (IM) are the most common type of electric motors. Despite the reliability of such motors, their annual failure is up to 20–25% [1]. In some industries, the average resource of AC electric motors is much less than the standard one, for example, in agriculture it is 2.5–3.5 times less [2]. A significant proportion of IM failures is associated with damage to the stator winding [3]. This is due to the fact that the stator winding insulation acts as a "weakest element", subject to various kinds of adverse effects, such as temperature, aggressive environment, etc. These circumstances determine the importance of the problem of assessing the residual life of the IM stator winding insulation.

One of the most important factors affecting the durability of a winding insulation is temperature. In [4, 5], an expression was obtained for the T_R time interval during which the insulation reaches its limit state due to thermal aging

$$T_R = k_T \cdot exp(B/Q - G), \tag{1}$$

where k_T – proportionality coefficient (k_T=1, if insulation life is measured in hours); B and G − constants; Q − absolute temperature (Kelvin).

Using expression (1), we can introduce the concept of the residual thermal insulation resource R_{res} as a dimensionless quantity relating the insulation aging rate at a temperature corresponding to the rated mode (ν_N) and a constant value of the influence of other factors with the residual lifetime (T_{res}) in this mode:

$$T_{res} = R_{res} / \nu_N, \tag{2}$$

$$R_{res} = 1 - \int_0^{t_w} \nu(t) dt, \tag{3}$$

where ν − instantaneous insulation aging rate, and t_w − operating time.

The value of R_{res} is proportional to the unutilized insulation life, measured in units of time. At the beginning of the motor's operating life, T_{res} coincides with T_R.

Although temperature is the most important factor determining the insulation durability, it is necessary to note the existence of other factors affecting the insulation condition − vibration, humidity, aggressive environment, electric field [4, 6-9]. In existing thermal protection systems, including those using direct measurement of the winding temperature, it is difficult to ensure that the whole variety of other influencing factors is taken into account. Therefore, it is of interest to obtain such methods of monitoring the current winding insulation condition, according to some measured values, would make it possible to evaluate the current insulation condition and predict changes in this condition.

There are works that offer approaches to monitoring the condition and determining the residual life of electric motors based on some complex criteria [1, 10, 11]. In many cases, such solutions require a whole set of sensors, and often complex mathematical support. In addition, such approaches, as a rule, are not able to take into account the effect of PWM in the frequency converter-IM system and some other factors on the degradation processes in winding insulation.

There is also a large number of works related to the experimental assessment of the insulation condition of motor windings. For this purpose, various methods are used, such as measurement of dielectric loss tangent, partial discharge method, methods based on the transients analysis when a voltage pulse is applied to the winding, etc. All these methods have their advantages and disadvantages.

So, the dielectric loss tangent allows you to judge the insulation condition, however, this indicator is very sensitive to insulation moisture, in addition, the disadvantage of this approach is the complexity of the measurement process automation.

Partial discharge method makes it possible to obtain information about the presence of various defects in the motor insulation at an early stage of their development. However, applying this method to low voltage motors is problematic [12]. In addition, this method has low noise immunity and is difficult to automate.

A number of works propose diagnosing the motor windings insulation based on an analysis of the leakage current transient process that occurs when testing a winding with a voltage pulse [1, 13–16]. The disadvantages of this approach are associated with the need to record transients, which have a very short duration (look at the time scale in Fig. 1.). So, in [14], as an integral parameter characterizing the stator winding insulation condition, it is proposed to use the ratio of the damping decrement to the damping period of the transient. In [1], it is proposed to evaluate the insulation condition by the amplitudes of the first and second half-periods and the duration of the first and second periods of oscillations.

In [15, 16], a winding insulation condition indicator is proposed, based on the amplitude spectrum analysis of the current oscillatory component after the supply of a stepwise signal. At the signal oscillation frequencies (about MHz) characteristic of such processes, all these approaches require equipment that provides a very high resolution in time. So, in [15] it is noted that the frequency of signal measurements should be at least 20 times higher than the maximum frequency used to calculate the indicator of the insulation condition.

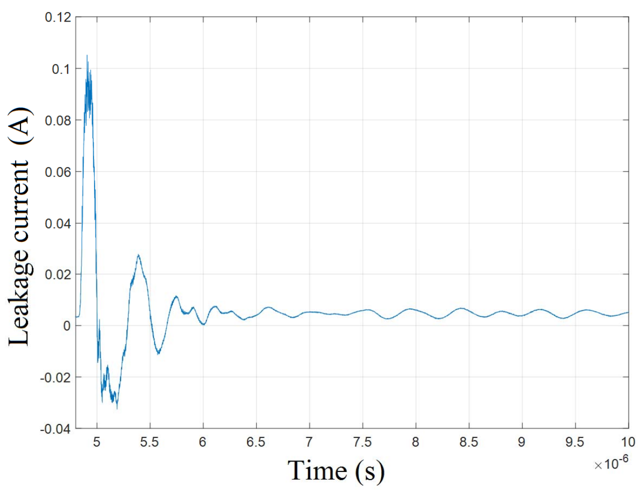

Fig. 1. Capacitive leakage current at the rising voltage front.

The disadvantage of such methods is also the reliability of the calculation of such indicators as the decrement of oscillations attenuation, their period, the construction of the amplitude spectrum of signals under noise conditions. There are also difficulties with the problem of automating the diagnostic process.

The aforementioned allows us to conclude that the problem of finding simple methods for diagnostics of winding insulation is urgent, including methods using testing voltage pulses, which would impose less requirements on equipment, mathematical methods of signal processing, and make it easier to automate measurements. One of such methods may be a method based on not a single testing voltage pulse, but on their sequence long enough to talk about some average or RMS values of such process parameters that could be related to the winding insulation condition and used for it diagnostics [17].

Fig. 2 shows a scheme of the experimental installation for detecting capacitive leakage currents. Here is denoted: 1 − transformer; 2 − frequency converter SEMIKRON; 3− PCI-6221 National Instruments card; 4 − block-shaper; 5 − A constant voltage source 15 V; 6 − analog-to-digital converter; R_1 and R_2 − measuring resistance; A, B and C − motor winding phases. Fig. 3 shows graphs of these currents when applying a sequence of rectangular voltage pulses (voltage levels of 15 V).

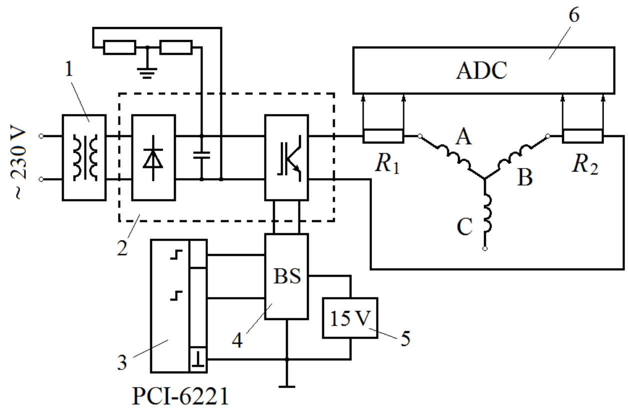

Fig. 2. Scheme of the experimental installation.

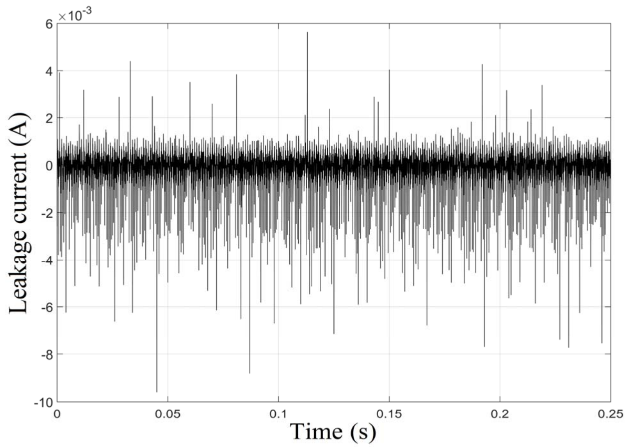

Fig. 3. Leakage current at 1 kHz in 0.25 sec.

II. Relationship of Capacitive Leakage Currents with the Winding Insulation Condition

In an experimental study, the results of which are set out in [18], it was shown that magnitude of insulation winding capacitive leakage current of an electric motor is closely related to the insulation aging process.

This was established in the course of detailed experiments on the accelerated aging of the stator winding insulation of an induction motor (480 V, 73.5 kW, 1200 rpm) with stator winding insulation class F.

Fig. 4 shows graphs of the total leakage current according to experimental data from [18] (here the time interval corresponding to the suspension of the experiment is removed) and an exponential approximation of the envelope of this graph. The time scale along the horizontal axis here corresponds to the process of artificially accelerated aging of insulation under the influence of elevated temperature.

The decrease in the leakage current with time is due to the fact that during thermal aging of the insulation, a decrease in the capacitive properties of the insulation occurs [19]. This causes a decrease in the capacitive component of the leakage current, which here constitutes the dominant part of the total current.

In Fig. 4 clearly traces the possibility of describing the graph of the leakage current (I_l) as a result of degradation changes in insulation using the approximating expression

$$I_l = \Delta I_{l.max} e^{-\alpha_l t} + I_{l0} . \quad (4)$$

III. Monitoring and Forecasting Algorithm with the Use of Capacitive Leakage Currents as a Diagnostic Sign

Dependence (4) is a kind of model of the insulation aging process, therefore, for brevity, we will call this dependence "modeling exponent".

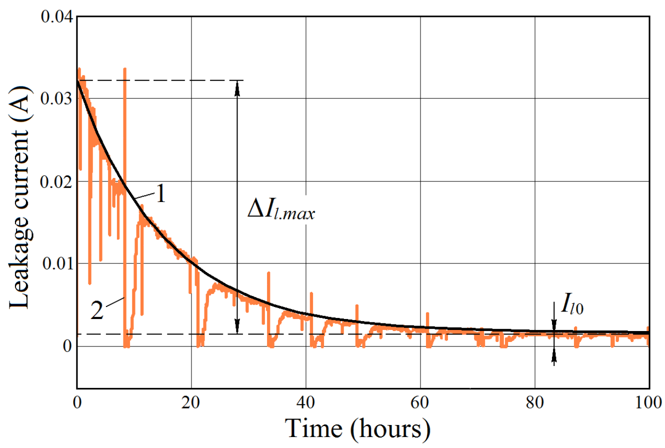

Fig. 4. Approximation of the total leakage current by the exponential (1) superimposed on the experimental dependence for one of the motor phases (2).

The revealed nature of the leakage current dependence in the insulation aging process allows building a system for monitoring the insulation condition based on control the excess of the measured I_l value over a certain level of $I_{l.lim}$, a decrease below which indicates the exhaustion of the insulation resource. The problem here is the strong noise in the useful signal due to interference in the information channels and the influence of environmental parameters on the leakage currents.

According to experimental data [18], insulation breakdown occurs after a time greater than 5–6 exponential time constants in expression (1). By a time greater than 4-5 constants, the exponential value becomes very small, which complicates the problem of determining the moment of crossing the $I_{l.lim}$ level under the influence of interference. This can be clearly seen in Fig. 5, where the noisy and filtered signal is shown at two different values of the first-order filter constant T_f (Δt – sampling interval of 100 hours). In Fig. 6 shows a set of implementations of a noisy signal $I_l(t)$ with a sampling interval of Δt=100 hours after filtering using a first-order filter with a constant T_f=4Δt. It can be seen here that for different implementations of the noisy process, the curve $I_l(t)$ crosses the threshold level at significantly different times.

Thus, conventional filtering and signal smoothing do not allow to reliably solve this problem; therefore, it seems appropriate to use approaches related to the identification of the parameters of the modeling exponent $I_l(t)$ for the subsequent assessment of the predicted threshold level crossing time (t_{lim}). In this case, it is possible to predict the residual resource, expressed in units of time (T_R), as the difference between the predicted time t_{lim} and current point in time t_c:

$$T_R = t_{lim} - t_c , \quad (5)$$

where current time (t_c) here means operating time.

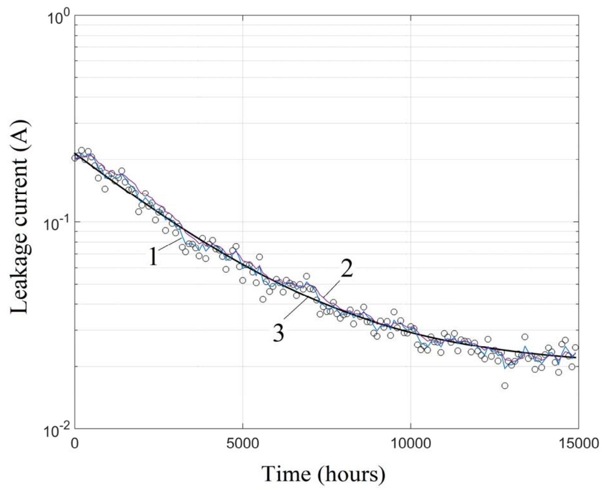

Fig. 5. Noisy (o) and filtered signal at T_f=2Δt (1) and T_f =4Δt (2); 3 – modeling curve.

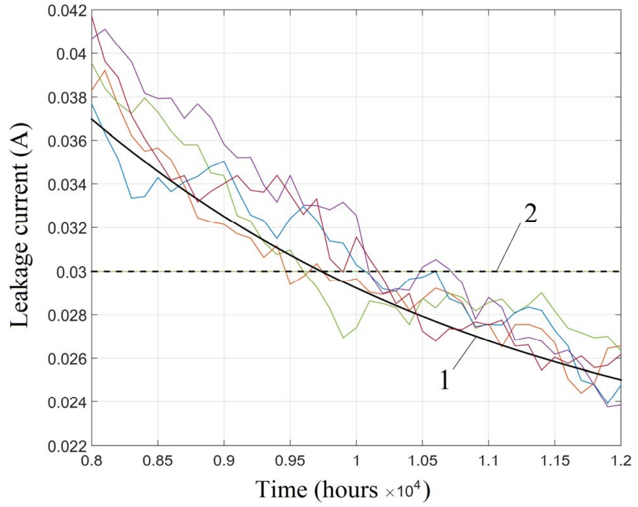

Fig. 6. A set of a noisy signal realizations with a 1st order filter; 1 – modeling exponent; 2 – level $I_{l.lim}$.

From formula (4), we can obtain an expression for the predicted value t_{lim}

$$t_{lim} = \frac{1}{\alpha_l} ln \frac{\Delta I_{l.max}}{\Delta I_{l.lim}}, \quad (6)$$

where $\Delta I_{l.lim}=I_{l.lim}-I_{l0}$ – excess of leakage current over steady-state value.

We can propose the following algorithm for the operation of the system for predicting the insulation condition based on the identification of the modeling exponent parameters. Here we will assume that the processes of motor loading, as well as changes in environmental parameters, are stationary in time intervals exceeding the modeling exponential time constant. The algorithm works with accumulated values $\boldsymbol{I_l}=[I_{l1}, I_{l2}, \ldots, I_{l1k}]$ and $\boldsymbol{t_c}=[t_{c1}, t_{c2}, \ldots, t_{ck}]$, where k – number of the last measurement. Each time after a new I_{yk} measurement, the next pair of t_{ck} and I_{lk} is saved.

The start of processing the recorded data in order to identify the parameters of the modeling exponent does not begin immediately after the start of measurements, since with a limited number of points in conditions of an essential random component it is difficult to reliably determine the parameters of the modeling exponent. Therefore, at the beginning of the algorithm, a check is made to see if the time t_{ck} exceeds a certain initial value $t_{c.init}$, where $t_{c.init}$ is the running time after which it is possible to begin the identification of the modeling exponent parameters. Estimation of $t_{c.init}$ can be performed using an exponent describing degradation processes in insulation at a temperature acceptable for a given insulation class.

We assume that the exhaustion of the resource occurs, as follows from the experimental results [18], for $t_{ck}>(4...5)/\alpha_{lN}$, where α_{lN} – exponential power factor when working with a temperature that is acceptable for a given insulation class. If we calculate the characteristic times of exhaustion of the resource by the formula (1) then, taking these times as $T_R=(4...5)/\alpha_{lN}$, we can determine α_{lN} by the expression

TABLE I. PARAMETER VALUES FOR DIFFERENT INSULATION CLASSES

Insulation thermal class	T_R, hours	α_{yN}·10^4, hours^{-1}
A	18583	2.15 ... 2.69
E	21163	1.89 ... 2.36
B	18215	2.20 ... 2.74
F	21440	1.87 ... 2.33
H	22382	1.79 ... 2.,00

$$\alpha_{lN} = (4...5)T_R, \quad (7)$$

Table 1 shows the calculated values of T_R and α_{lN} for different insulation classes.

The value $t_{c.init}$ can be taken equal to $1/\alpha_{lN}$. When the drive is underloaded, the value of α_l will be less than α_{lN}, however, the number of points ($\boldsymbol{t_c}$, $\boldsymbol{I_l}$), recorded during $t_{c.init}$, depends only on the measurement interval Δt. In addition, the algorithm provides verification to evaluate the reliability of the parameters of the exponent reconstructed from the recorded data.

After reading the array of source data ($\boldsymbol{t_c}$, $\boldsymbol{I_l}$) the data is prefiltered and the average value $I_{l.av(tc)}$ for the previous period is calculated, which is necessary to perform one of the verification in the future.

At the next stage, the parameters of the modeling exponent are identified. The following verifications are performed:

a) The conditions $\Delta I_{l.max}>0$, $\alpha_l>0$ and $I_{l0}>0$, must be satisfied, which follows from obvious physical considerations (if at least one condition is not fulfilled, we ignore the current point);

b) A fairly obvious condition must be met $\Delta I_{l.max}+I_{l0}>I_{l.av(tc)}$.

After determining the parameters of the modeling exponent, the predicted time t_{lim} of resource exhaustion is calculated and the sign of the difference $t_{lim}-t_{ck}$, which is the value of the residual resource, is checked. With a negative value of this difference, a decision is made that the resource has been exhausted.

IV. MODELING RESULTS

Fig. 7 shows the results of modeling the operation of the described above algorithm in Matlab/Simulink. The parameters of the modeling exponent were identified using OLS.

The horizontal axis in Fig. 7 – time from the start of operation. The dashed lines show the levels corresponding to the true values of $\Delta I_{l.max}$, α_l, I_{l0} and the calculated values t_{lim} relating to these values. The algorithm was simulated with a measurement interval of 100 hours without prefiltration, with a Gaussian law of the error distribution with an standard deviation of 20% of the I_l value in the modeling exponent. In Fig. 7 denoted: 1 – $\Delta I_{l.\text{-}lim}=0{,}0067\Delta I_{l.max}$ (o); 2 – $\Delta I_{l.\text{-}lim}=0{,}0183\Delta I_{l.max}$ (Δ). As seen in Fig. 7, the values of the calculated modeling exponent parameters and t_{lim}, as the registered values of the leakage current accumulate, converge quite well to their true values.

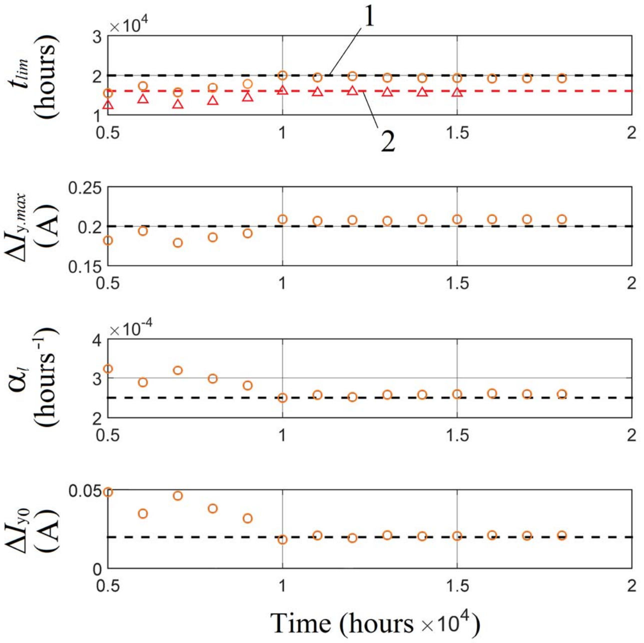

Fig. 7. Simulation results of the insulation condition prediction system operation ($1 - \Delta I_{l.lim}$=0,0067$\Delta I_{l.max}$; $2 - \Delta I_{l.lim}$=0,0183$\Delta I_{l.max}$).

V. Conclusions

1. An approach to monitoring and predicting the insulation condition of the motor winding based on the use of information on capacitive leakage currents is proposed.

2. The algorithm of operation of the system for predicting the insulation condition using information on capacitive leakage currents based on the identification of the parameters of the modeling exponent is described.

3. The proposed algorithm was simulated in Matlab/Simulink, which confirmed its operability.

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