A Technique For Calculation Of Life Limits Of Electrical Network Equipment

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***Abstract* — The main attention in the article is paid to the method of calculating the limiting values of the life of the main electrical equipment based on a comprehensive assessment of the actual condition of the equipment, that is, its condition index. The basic principles of the developed technique are given and a structural diagram of calculating the maximum service life of electrical equipment is shown. A general model is proposed for calculating the resource limits of electrical equipment based on a linear approximation of the state index change function. The applicability of this method is illustrated by an example of calculation for a transformer unit.**

***Index Terms* — main electrical equipment, service life, condition index function.**

Introduction

A significant portion of the main electrical equipment (EE) of power systems in the Russian Federation (oil-filled power transformers, high-voltage circuit breakers. etc.) has reached or is approaching its life limit.

This paper considers the basic results of developing a technique for determining the EE life limits (hereinafter referred to as the "technique"), which is to be used by electricity network companies in Russia. The application of this technique will allow selecting the electrical equipment for retrofitting and upgrading based on the level of equipment condition and forecasts on its lifetime extension beyond the rated limits. This technique is based on the developed, adopted and approved algorithms and models. It involves the automated systems and other components of the production asset management systems and complies with the current legislation of the Russian Federation [1 – 5].

An analysis of the papers [6 – 20] shows that the studies aimed at developing the calculation methods and determining the EE lifetime characteristics and life limits are carried out both in Russia and in other countries. It also indicates that the current transition towards a digital model of the energy industry contributes to the development and implementation of the methods based on the risk-oriented approach to making decisions on retrofitting and upgrading. Thus, it follows that the development of a technique for determining the EE life limits is an urgent issue.

II. Methodology

According to the Decree of the Russian Government [1], the technical condition index (CI) of electrical equipment should be determined and reliably define a technical condition of equipment and its changes within a stated range. It should have a clear technical sense and a single interpretation. The index of equipment (technical) condition is an integrated indicator of equipment state, which is a single value that incorporates the values of some other indices of the condition and is convenient for comparison and evaluation. For the calculation of the EE life limits, the said technical condition index is regarded as a known value determined according to the current regulations and specifications.

The electrical equipment is considered to have a limit condition when its condition index is equal to 0. The limit condition also corresponds to the expired service life of the equipment. The EE condition, when the condition index equals 1, corresponds to the condition of new equipment, whose operation has not started yet. The actual technical condition of electrical equipment deteriorates in the process of its operation. When the actions are performed according to the current system of maintenance and repair, the technical condition of the equipment improves. However, the general trend of the EE condition change over its total operation period is towards deterioration.

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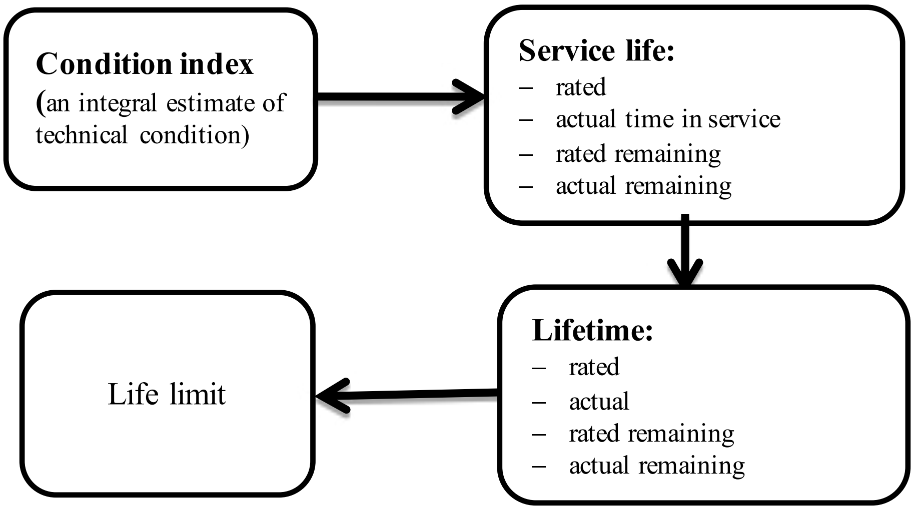

Fig. 1. A block diagram of the EE life limit calculation.

In [2], the authors have established a functional interdependence between the EE service life, lifetime, calendar time, life limit and technical condition level (the condition index value). The block diagram of determining the EE life limit is shown in Fig. 1:

Almost all failures of electrical equipment can be subdivided into unexpected and wear-out ones. Unexpected failures take place due to the effects of different unexpected factors, for example, such as the exposure to the elements (off-design wind loads, freezing rain, icing, etc.), acts of vandalism, failures caused by malfunction of some other equipment installed nearby, and others.

Wear-out failures result from an impermissible decline in the condition index of the electrical equipment and normally occur due to the accumulation and development of defects during the equipment operation, i.e., they develop gradually. The considered technique takes into account the wear-out failures by reducing the EE actual operating conditions to the rated ones by using the actual operating time in calculation expressions instead of the calendar time.

The operating conditions are reduced to the rated ones by using the expressions developed for calculation in [2]. These expressions relate the calendar time, actual service life, and the values of the EE condition index. The methods of calculating the actual time in service are presented in [3, 5]. The obtained value of actual time in service is used to calculate the rated remaining or actual remaining service life. By summing the actual service life and the remaining service life and by reducing the units for operating time measurement to time-based units, we can calculate the EE life limit. Now, we will define the above-mentioned terms.

Technical service life is the total operating time of electrical equipment from the start of its operation until its limit condition is reached.

Actual time in service is the time of electrical equipment operation under actual conditions. The actual remaining service life is the operating time of electrical equipment under certain conditions, starting with the moment of calculation until the limit condition is reached.

Rated service life is the time of electrical equipment functioning under rated (estimated, design) conditions. Rated remaining service life is the operating time of electrical equipment under rated conditions from the moment of calculations until the limit condition is reached.

The considered technique employs the mathematical models for calculating the EE life limits, given a varying degree of initial data completeness and composition. Further, we will consider a general model for calculating the life limit values, which takes account of all the probable changes in the values of the EE condition index. In a general case, the actual time in service depends on the operating time r and a change in the condition index with respect to function *S(r)*, and it is determined according to [10, 13]. Besides, the calculation should be made using the units for operating time measurement. In this particular case, the actual time in service *R* during the operating time t_c (the control point) corresponds to the EE actual lifetime Tc during the calendar time tc. The rated remaining lifetime is determined by the following expression:

$$T_{rem.0} = T_0 - T_c, \quad (1)$$

where T_0 is the EE rated lifetime.

If the electrical equipment is further operated under rated conditions, its life limit Tlim will be determined as follows:

$$T_{lim} = t_c + T_{rem \cdot 0}, \quad (2)$$

or:

$$T_{lim} = t_c + T_0 - T_{lim} \quad (3)$$

If the electrical equipment is to be operated under the conditions other than the rated ones, its life limit will be determined by the following expression:

$$T_{lim} = t_c + T_{lim.rem}, \quad (4)$$

where $T_{lim.rem}$ is the EE remaining lifetime (calendar time) limit, which corresponds to its rated remaining lifetime $T_{0.rem}$, and is determined numerically from the equation:

$$T_{0.rem} = \int_{T_c}^{T_{lim.rem}+T_c} \frac{1-S(t)}{1-S_0(t)} dt \Rightarrow T_{lim.rem} = \dots \quad (5)$$

By expressing value $T_{lim.rem}$ from equation (5), we determine the time during which the electrical equipment can run under the supposed operating conditions until the limit condition is reached, i.e., when its actual remaining service life (actual lifetime T_{rem}) reaches the rated remaining service life (rated remaining lifetime $T_{0.rem}$).

Since it is rather difficult to forecast the electrical equipment operating conditions and parameters for the future period, it is appropriate to assume that after the control point the EE operating conditions will be the same as before the control point. Consequently, the EE technical condition and, accordingly, condition index will change in the same way. The extension of the life limit T_0 under known future conditions can be determined numerically using the equation:

$$T_0 = \int_0^{T_{lim.}} \frac{1-S(t)}{1-S_0(t)} dt \Rightarrow T_{lim.} = \dots \quad (6)$$

The study presented in [2] indicates that the absence of true retrospective data concerning the values of the EE condition index is a serious problem when determining the life limit. To enable the use of the proposed technique at the stage of its adoption, testing, and collection of the required input data on the equipment condition index, it is possible to apply a calculation model using the linear approximation of the condition index variation function *S(r)*:

$$\frac{1-S(t)}{1-S_0(t)} = \frac{m}{m_0} = A, \quad (7)$$

where m, m_0 are the coefficients of linear approximation of a set of data intended to obtain the functions of condition index variation for the actual operating conditions *S(t)* and the rated operating conditions $S_0(t)$, respectively.

The actual time in service, in general, depends on the operating time r and the variation in the condition index with respect to function *S(r)* [5]. In this case, the calculations are to be made using the operating time measurement units ($r = t$). Then, the actual time in service R during the operating time t_c (control point) will correspond to the EE actual lifetime during the calendar time t_c.

$$T_c = At_c, \quad (8)$$

Then the EE rated remaining lifetime will be:

$$T_{rem.0} = T_0 - T_c, \quad (9)$$

where T_0 is thee rated lifetime

or

$$T_{rem.0} = T_0 - At_c. \quad (10)$$

If the electrical equipment is further operated under the rated conditions, its life limit can be determined as follows:

$$T_{lim} = t_c + T_{rem.0}, \quad (11)$$

or

$$T_{lim} = T_0 - t_c(1-A). \quad (12)$$

If the electrical equipment is further going to be run under the conditions that differ from the rated ones, its life limit will be determined as follows:

$$T_{lim} = t_c + T_{lim.rem} \quad (13)$$

where Tlim.rem is the remaining lifetime (calendar time) limit of the electrical equipment, which corresponds to its rated remaining lifetime $T_{0.rem}$, and is determined as follows:

$$T_{lim.rem} = T_{0.rem} / A. \quad (14)$$

In this case, the EE life limit is determined by the following expression:

$$T_{lim} = t_c + \frac{T_{0,lim}}{A} \quad (15)$$

By expressing the value $T_{lim.\ rem}$ from equation (5), it is possible to determine a period during which the electrical equipment will still run under certain presumed operating conditions, before it reaches its limit condition, i.e., when its actual remaining service life (its actual lifetime T_{rem}) reaches its rated remaining service life (the rated remaining lifetime $T_{0.rem}$).

The life extension limit T_{lim} for a new piece of electrical equipment under the known future conditions can be determined by the following expression:

$$T_{lim} = T_0 / A. \quad (16)$$

In the first approximation, in the case of no data available to obtain coefficient m0, it is appropriate to apply the following relation:

$$m_0 = \frac{1}{T_0} \quad (17)$$

The functional relationship between the condition index value and the operating time value is determined according to [2]. In doing so, time *t* is taken as a measurement unit of the operating time *r*.

The EE life limit should be recalculated whenever its condition index values change considerably (or when a new value of the condition index is obtained). The recalculation should include calculations before and after each type of repair (current, medium and major). This means that the periodicity of these calculations should correspond to the periodicity of EE condition index calculations. Accordingly, in this particular case, the data on the condition index should be approximated to obtain the relationship between the condition index variation and operating time, after each updating of the condition index data (after obtaining new values, after specifying old ones, etc.).

Additionally, the recalculation of the EE service life values is recommended when changes occur in the other data (including the rated data used in the models for calculation of the EE life limits).

Since the EE life limit is a forecast value, the final procedure for its calculation is determined by internal guidelines. The calculation of the EE life limits starts with the preparation of initial data. The basic initial data for this calculation are the information on the condition index values S and S_0 of a considered equipment unit. If the functions $S(t)$ and $S_0(t)$ are known, no additional initial data preparation is required and the calculation can be started. If either of the two functions, $S(t)$ or $S_0(t)$, is unknown, it should be determined using [5] by approximating the data according to the condition index values.

Depending on the completeness and quality of the initial data, it is necessary to choose a model for calculating the EE life limit. In the case that functions $S(t)$ and $S_0(t)$ are known, a general model is used for the calculation. In the initial stage of the proposed technique implementation, when there are no reliable retrospective data on the changes in the condition index depending on the EE operating time, it is appropriate to apply a model for calculating the life limit using linear approximation of data with respect to the condition index values for each unit of equipment.

After preparing the initial data and selecting a model for calculation of the equipment life limit, it is required to choose a certain date (hereinafter referred to as the "date of calculation"), when the calculation is to be made. The calculation for the considered electrical equipment requires that the following functions be known:

- Function $S_0(t) = S_{0.T}(t)$, where $S_{0.T}(t)$ is the basic function of the condition index variation depending on the operating time;
- Function $S(t) = S_T(t)$, where $S_T(t)$ is the actual function of the condition index variation depending on operating time.

Based on the date of EE commissioning, it is necessary to determine the EE calendar time in years, from the date of commissioning to the date of calculation:

$$t = t_c \tag{18}$$

Thus, the life limit is calculated in the following order:

1. The actual time in service (the actual lifetime) is calculated.
2. The value of the EE rated remaining service life is determined by applying either expression (1) or (10), depending on the selected model.
3. In the case it is planned to operate the electrical equipment under rated conditions, the remaining life limit corresponds to the rated remaining lifetime, while the total life limit is determined by either expression (2) - (3) or (11) – (12), depending on the selected model.
4. If it is further planned to operate the equipment under the conditions other than the rated ones, the EE remaining life limit is determined numerically from equation (5) or based on expression (14), and the total life limit is determined using either expression (4) or (15).

III. Example

Now, let us consider an example of the life limit calculations for the TMN-6300/110/10 transformer, which is installed in the power system of the "Komienergo" power grid company. Figure 1 shows the condition index change versus time for the above-mentioned transformer.

The time dependence of the condition index (p.u.) for the considered transformer at linear approximation has the form:

$$S(t) = 1 - 0.0267t \tag{19}$$

Given expression (7), coefficient A for this transformer is equal to 0.0267 / 0.04 = 0.67.

The calendar time of this transformer is t_c = 32 years. The actual lifetime, considering expression (8) will be determined as follows:

$$T_c = 0.67 \cdot 32 = 21.44 \text{ years.} \tag{20}$$

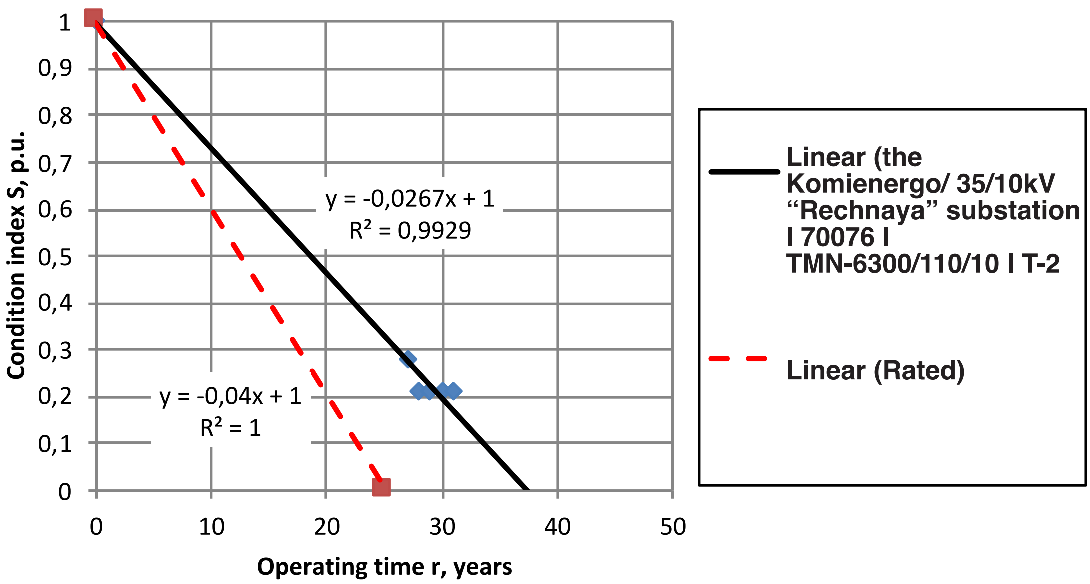

Fig. 1. Change in the condition index versus time for the TMN-6300/110/10 transformer (its rated lifetime is 25 years).

Then the rated remaining lifetime of this transformer, given expression (9), will be determined as follows:

$$T_{rem.0} = 25 - 21.44 = 3.56 \text{ years.} \quad (21)$$

If the said transformer is further operated under the rated conditions, its life limit will be determined by expression (11):

$$T_{lim} = 32+3.56 = 35.56 \text{ years.} \quad (22)$$

In the case that this transformer is operated under the conditions other than the rated ones (in this particular case, under the conditions it has been operated for 32 years), the life limit for this transformer will be determined based on expression (15):

$$T_{lim} = t_c + \frac{T_{0.rem}}{A} = 32 + \frac{3.56}{0.67} = 32 + 5.13 = 37.13 \text{ years.} \quad (23)$$

IV. Conclusions

The focus of the paper is a technique for calculating the EE life limits based on the integrated evaluation of equipment actual condition, i.e. its condition index. The basic principles of the developed technique are shown, and a block diagram of the EE life limit calculation is demonstrated. A general model is proposed to calculate the EE life limits based on the linear approximation of the condition index change function. The applicability of this technique is illustrated by a calculation example for an operating transformer unit.

References

[1] The Decree of the RF Government of December 19, 2016. No. 1401 “On the Comprehensive Determination of Technical/Economic Status Indexes for Power Industry Facilities, including the Indexes of the Physical Wear and Energy Efficiency of Power Systems Facilities and the Execution of Monitoring of these Indexes,” (in Russian).

[2] D.A. Andreyev, A.N. Nazarychev, A.I.Tadzhibaev. “Determination of Probable Equipment Failures in Power Network Facilities based on Technical Status Evaluations,” Edited by A.N. Nazarychev: *FGAEE “PPEIPD,”* p.194, St.Pb., 2017, (in Russian).

[3] A.N. Nazarychev, D.A. Andreyev. “The Methods and Mathematical Models of Comprehensive Evaluations of Electrical Equipment Status,” The Ivanovo State Energy Institute, Ivanovo, p.224, 2005, (in Russian).

[4] A.N. Nazarychev, D.A. Andreyev. “The Methodological Foundations of Determining Operation Limits and the Scheduling of Power Industry Facilities Re-equipment,” The Ivanovo State Energy Institute, *Ivanovo*, p.168, 2005, (in Russian).

[5] A.N. Nazarychev, A.I. Tadzhibaev, D.A. Andreyev. “Evaluation of Electrical Equipment Lifetime based on the Trends of Technical Status Changes,” *“The Methodological Issues of Investigations Concerning the Reliability of Large Power Industry Systems.”* Issue 68. – ISEM of the Siberian Branch of the Academy of Sciences, p.p. 613 – 623, 2017, (in Russian).

[6] The Order of the Ministry of Energy of Russia of July 26, 2017, No. 676 "On the Approval of Methods to Evaluate the Technical Status of Basic Technological Equipment and Power Transmission Lines of Power Stations and Power Systems.”

[7] The Order of the Ministry of Energy of Russia of October 25, 2017, No. 1013 "The Rules of Organization of Technical Maintenance and Repairs of Power Industry Facilities".

[8] Nowlan F. S., Heap H. F. “reliability-centered Maintenance,” San Francisco, *Dolby Access Press*, 1978.

[9] P.G. Grudinsky, S.A. Mandrykin, M.S. Ulitsky. “The Technical Operation of the Main Equipment Units of Power Stations and Substations,” Edited by P.I.Ustinov, Moscow, *The “Energy” Publishers*, p.575, 1974, (in Russian).

[10] “Methodological Indications Concerning the Determination of the Depleted Switching Lifetime of Circuit Breakers during their Operation,” M., *ORGRES*, p.20, 1992, (in Russian).

[11] B.N. Neklepayev, A.A. Vostrosablin. “The Methods of Evaluating the Switching Lifetime of Circuit Breakers during their Operation,” The *“Promyshlennaya Energetika” Journal*, No. 1, p.p. 28 – 35, 1995, (in Russian).

[12] V.F. Sivikobylenko, V.I. Kostenko. – “Ways of Forecasting the Service Life of Electric Motors Insulation,” *The “Elektricheskiye Stantsii” Journal*, No. 1, p.p. 53 – 57, 1977, (in Russian).

[13] F. Baselt, P. Franken – “Reliability and Technical Maintenance. A Mathematical Approach”: Transl. from the German. M., *“Radio i Svyaz” Publishers*, 1988, (in Russian).

[14] B. Dillon, Ch. Singh. – “The Engineering Methods of Securing Systems Reliability”: Transl. from English, M., *“Mir” Publishers*, 1984, (in Russian).

[15] Stoerungs- und Verfugbarkeitsstatistik – Berichtsjahr, FNN Forum Netztechnik und Netzbertrieb im VDE, Berlin, 2011.

[16] Todd Z.G. A Probability Method for Calculation. – *“IEEE Trans. Power. Apparatus and Systems”*, vol. 83, No. 7, p.p. 695 – 701, 1964.

[17] Kloeppel P.W. Berehnunggaverfahren fur die Bestimming der Versorgungssicherheit in electrischen Energienetzen. - “Energietechnik”, 1964, 14, No. 7. – p.p. 289 – 296.

[18] V.V. Smekalov, A.P. Dolin, N.F. Pershina. “Evaluation of the Status and the Extension of Power Transformers Lifetime, Technical Re-equipment and Repairs of Power Facilities,” Edited by V.V. Barilo, M.,

IPKgossluzhby, VIPKenergo, p.p. 120 – 136, 2002.

[19] B.V. Vanin, Yu.N. Lvov, M.Yu. Lvov et.al, "The Methodological Aspects of Evaluating the Degree of Aging of Winding Insulation in Power Transformers by Measuring the Degree of Polymerization," *"Elektricheckiye Stantsii" Journal*, No.1, p.p. 35 – 39, 2001, (in Russian).

[20] L.G. Kovarskiy. "The Calculations Foundations of Optimizing Electrical Equipment Repairs," *"Energoatomizdat," Leningrad Branch*, 1985, (in Russian).