Bulgarian Society for NDT
**International Journal "NDT Days"**
Volume 1, Issue 3, Year 2018 ISSN: 2603-4018

# Determination of the Marginal Exploitation Lifespan of Transformers Based on a Comprehensive Diagnostic Survey

Alexandr N. NAZARYTHEV, Dmitriy A. ANDREEV,
Alexey I. TADJIBAEV, Svetlana P. VYSOGORETS

Federal State Educational Establishment "PEIPK", Saint-Petersburg, Russia, s-151075@yandex.ru

**Abstract**
The article examines the methods for calculating the marginal exploitation lifespans of power transformers based on the use of an integral estimation of the factual state – the state index. Basic principles of the developed methods and a block diagram of the calculation of the transformers marginal exploitation lifespan are shown. A general calculation model and a model for calculating the marginal exploitation lifespan of transformers based on linear approximation of the values of the state index change function are given. A methodical approach for the use of the methods in the production assets management systems as well as an example showing the possibility of using the methods in electric grid companies of the Russian energy industry are presented.

**Keywords:** Power industry; Marginal exploitation lifespan of transformers.

## 1. Introduction

In the context of the course on digital technologies in the Russian power industry, the development and implementation of smart grid elements, power transformers (autotransformers) become one of the most important elements on the electric power systems on which reliability and safety of consumers' power supply depend [1].

In the power grid complex of Russia, a significant part of the power transformer park is approaching the exhaustion of the standard service life, and a rather large group of transformers is currently operated outside of it. This determines the need for both determining the possibility of extending the standard service life of transformers and determining the marginal exploitation lifespans from the perspective of ensuring the reliability and safety of energy facilities in general.

The main way to ensure operational reliability and safety of power facilities is to carry out a complex diagnostic survey (CDS) of transformers in order to obtain objective and reliable information about their technical condition (TC) based on diagnostic methods. Diagnostics involves the use of various methods and devices for monitoring the parameters of transformers, which would allow a detailed analysis of the presence of defects, their location and determine the integral indicator of technical condition (IITC). In [2-7] it is shown that at the present time as the quantitative IITC of transformers, the indicator – state index (SI) is applied. To assess the SI the methods [8,9] is approved by the Decree of the Government of the Russian Federation and by the order of the Ministry of Energy of Russia.

To determine the marginal exploitation lifespan of transformers based on CDS, taking into account the earlier studies [2-7] and [10-13], a Methods was developed whose main purpose is to establish unified, for electric grid companies in Russia, the calculation of the marginal exploitation lifespan of transformers.

In this article, the basic provisions of the Methods are discussed aiming to explain its main principles and to understand the implementation of the inner algorithm for calculating the technical resource and the marginal exploitation lifespan of the transformers. The methods is based on the methods, algorithms, models, automated systems and other elements of the production assets management system (PAMS) already developed, implemented and approved in the Russian power grid complex.

For transformers, a single text algorithm for calculating the technical state indexes (TSI) is generated, which, on the basis of the whole set of diagnosed parameters, can be done through logical and mathematical formulas:

- calculate the transformer SI that takes into account operating conditions and effects on the vehicle during maintenance and repair activities (MRA) by means of technical parameters determined by CDS results, routine diagnostics, tests, inspections and measurements;
- establish recommended types of necessary actions on the transformer, for its reliable functioning.

Calculations based on TSI are based on the use of reference books of equipment groups, parameters, normative values, defects and other reference books regulated in a single centralized system of regulatory and reference information (RRI) of the electric grid company.

The following requirements are imposed on the indicator of transformer SI:

- exponent: The SI should provide an accurate picture of the general condition of the transformer, including in retrospect, and the possibility of continuing the operation of the transformer;
- objectivity: SI should be based on objective, instrumental measurements, calculations, and not on subjective observations and assumptions;
- simplicity: The SI should be understandable and easily interpretable;
- compliance with current legislation [8, 9].

Thus, the SI must reliably reflect the level of the transformer's TC and its change within the established limits, and also have a clear technical sense and unambiguous interpretation in all electric grid companies.

The state of the transformer is marginal when the SI is 0. The marginal state also corresponds to the moment when the transformer's resource is fully exhausted, i.e. the actual generated resource is equal to the normative one. The state of the transformer, at which the SI = 1, corresponds to the state of the new transformer, the operation of which has not yet begun. For this transformer, the actual generated resource is 0.

The actual transformer TC is degraded during exploitation. When carrying out the actions within the existing MRA, the transformer TC is improved. Nevertheless, the overall trend of transformer TC changes over the whole period of its operation has a decreasing character.

In some basic (normative) exploitation conditions, the TC deteriorates as planned (in accordance with the technical documentation of the manufacturing plants for the transformer). Under light operating conditions, the transformer TC is deteriorating less intensively, and in the heavier ones it is more intensive, in comparison with the base conditions.

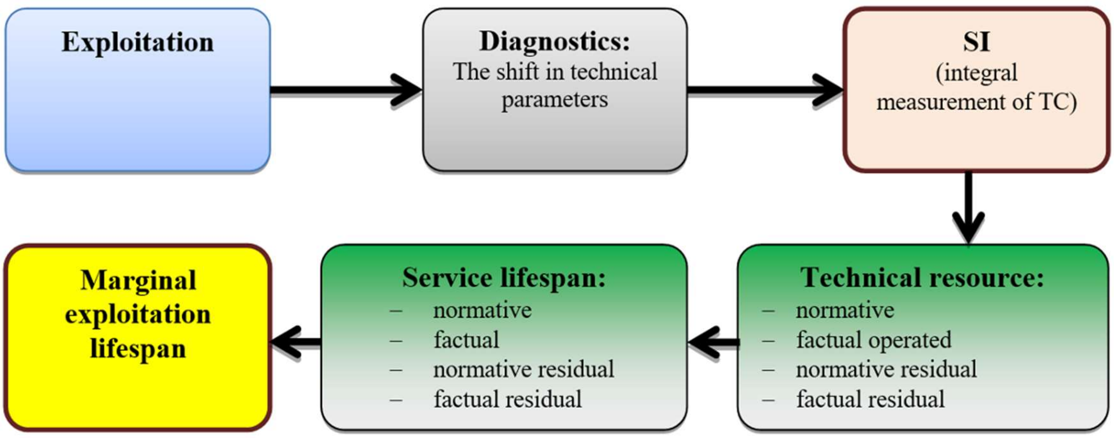


**Fig. 1. Block diagram of the calculation of the marginal exploitation lifespan of transformers**

In [10], a functional relationship was established between the technical resource, the service lifespan, the calendar operating time, the deadline for operation and the level (value) of the transformer TC. A block diagram of the service life of the transformer is shown in Fig. 1.
Virtually all failures of transformers can be divided into sudden and wear.
Sudden failures occur under the influence of various sudden factors, for example, such as: natural effects (unaccounted wind loads, "ice rain", ice formation, etc.); vandalism; failures caused by a malfunction of equipment installed near other equipment, etc.
Wear failure is due to an unacceptable decrease in the level of the transformers TC. Wear failures occur, as a rule, on the basis of accumulation and development of defects during operation, i.e. they develop gradually.
The technical resource allows to take into account wear failures due to bringing the actual operating conditions of the transformers to the normative ones by using the factual operating time (factual operated resource) in the calculation expressions instead of the calendar operating time.
To bring the operating conditions into effect, the calculation expressions developed in [10] are used that relate the calendar work, the factual technical resource and the values of the transformer SI. The methodology for calculating the actual exhausted resource is given in [10, 13]. Based on the received value of the actual exhausted resource, the normative residual or factual residual life is calculated. Summarize the factual and residual resource and bringing the unit of measurement of the operating time to the time, the transformer marginal exploitation lifespan is calculated.
Mathematical models for calculating the transformers marginal exploitation lifespan are given in the Methods, taking into account the different completeness and composition of the initial data. Next, consider the general model for calculating the deadlines for operation, which takes into account all possible options for changing the transformer SI. The factual operated resource generally depends on the operating r and the change in the value of the SI according to the function S(r) and is determined in accordance with [10, 13]. In this case, the calculation should be performed in time units of the operating time. The factual spent resource R for working $t_c$ (point of control) corresponds to the factual lifespan of transformer $T_c$ during calendar time $t_c$.
Normative residual lifespan is determined by the expression:

$$Tres.0=T0-Tc, \qquad (1)$$

where $T_0$ – normative lifespan of the transformer.
If the transformer is further operated in the standard exploitation conditions, the transformer marginal exploitation lifespan $T_m$ will be determined as follows:

$$Tm=tc+Tres.0 \qquad (2)$$

or:

$$Tm=tc+T0-Tc \qquad (3)$$

If the transformer is further operated in conditions other than the normative, the transformer marginal exploitation lifespan will be determined as follows:

$$Tm=tc+Tm.res, \qquad (4)$$

where $T_{m.res}$ – marginal residual lifespan (calendar time) of transformer service, corresponding to normative residual lifespan $T_{0.res}$, is determined by numeric method from equation:

$$T_{0.res} = \int_{T_c}^{T_{m.res}+T_c} \frac{1-S(t)}{1-S_0(t)}\,dt \Rightarrow T_{m.res} = \ldots. \qquad (5)$$

The expression for the value of $T_{m.res}$ from equation (5) determines the time that the transformer will still work in the expected operating conditions before the transition to the limiting state, i.e. when the factual residual resource (the actual lifespan $T_{res}$) will reach the normative residual resource (the normative residual lifespan $T_{0.res}$).
Since for a transformer it is difficult to predict the conditions and modes of its exploitation in the future, it is advisable to assume that after the control point the transformer will operate in the same modes as before the control point. Therefore, its TC and, accordingly, SI will change in a similar way. The determination of the exploitation extension limits for a new transformer $T_m$ under known future exploitation conditions is carried out by numerical methods from equality:

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

It was shown in [10] that the absence of full-fledged retrospective data on the values of transformer SI can be a significant problem in determining the marginal exploitation lifespan. To be able to apply the Methods during its implementation, validation, and accumulation of the necessary initial data on the SI, it is possible to use the calculation model by applying the linear approximation of the function of changing the SI S(r):

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

where m, $m_0$ – coefficients of linear approximation of the data set intended to obtain the SI change functions for the factual exploitational conditions S(t) and for the basic regulatory operating conditions $S_0(t)$ respectively.
The factual operated resource in the general case depends on the operating time r and the change in the value of the SI according to the function S(r) [10]. In this case, the calculation should be performed in time units of the operating mesurement (r = t). The factual operated resource R for working $t_c$ (point of control) corresponds to the factual service life of the transformer for a calendar time $t_c$.

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

Then the normative residual lifespan of the transformer:

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

where $T_0$ – normative lifespan of the stransformer.
or

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

If the transformer is further operated in conditions other than the normative, the transformer marginal exploitation lifespan will be determined as follows:

$$T_m=t_c+T_{res.0} \quad (11)$$

or

$$T_m= T_0-t_c(1-A). \quad (12)$$

If the transformer is further operated in conditions other than the normative, the transformer marginal exploitation lifespan will be determined as follows:

$$T_m=t_c+T_{m.res} \quad (13)$$

where $T_{m.res}$ – marginal residual lifespan (calendar time) of transformer service, corresponding to normative residual lifespan $T_{0.res}$, is determined as follows:

$$T_{m.res}=t_{0.res} / A \quad (14)$$

Then marginal exploitation lifespan of transformer is determined by expression:

$$T_m = t_c + \frac{T_0.res}{A} . \quad (15)$$

The value $T_{m.res}$ from equation (5) is the time that the transformer will still work in the expected exploitational conditions before the transition to the marginal state, i.e. when the factual residual resource (the factual service life $T_{res}$) will reach the normative residual resource (the normative residual service life $T_{0.res}$).

The determination of the exploitation extension limits for a new transformer $T_m$ under known future exploitation conditions is carried out by expression:

$$T_m=T_0 / A. \quad (16)$$

In the first approximation, in the absence of data to obtain the coefficient $m_0$, it is advised to use the relation:

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

The determination of the functional dependence of the SI values on the operating time is performed in accordance with [10]. In this case, the time t is taken as the measuring unit of the operating r.

The recalculation of the marginal service life of the transformer is recommended in the electric grid companies at each significant change in the values of the transformer SI (or when obtaining a new SI value), including calculations before and after each current, medium and major overhaul. Thus, the periodicity of the calculation is recommended to be taken in accordance with the frequency of calculation of the transformer SI. Approximation of the data by the values of the SI with the aim of obtaining the function of changing the SI from the operating time, respectively in this case, must be performed after each update of the SI data (obtaining new values, updating old ones, etc.).

In addition, it is recommended to recalculate the values of the technical resource of the transformer when other data, including normative ones, included in the calculation model of the transformer marginal lifespan are changed.

Since the value of the transformer marginal exploitation lifespan is a predictable value, the final procedure for calculating the marginal exploitation lifespan of transformers in electric grid companies is determined by internal instructions. In the PAMS, the results of the marginal exploitation lifespan evaluation of power transformers are used in strict accordance with the approaches set forth in the normative technical documentation (NTD).

The procedure for calculating the marginal exploitation lifespan of transformers begins with the preparation of the initial data. The basic initial data for the calculation of the marginal exploitation lifespan of the transformer are information on the values of the SI S, $S_0$ of the equipment unit (EU) under consideration. If the functions S(t) and $S_0(t)$ are known, then additional preparation of the initial data is not required and one can proceed to the calculation. If one of the functions S(t) or $S_0(t)$ is not known, then they should be determined by [10] by approximating the data by the SI values.

Depending on the completeness and quality of the input data, a model should be chosen to calculate the marginal exploitation lifespan of the transformer. In the case of known functions

$S(t)$ and $S_0(t)$, a general model is used to calculate the transformer marginal exploitation lifespan. At the initial stage of the implementation of the Methods, in the absence of full-fledged historical data on the functions of changing the IS values from the time of the transformer, a model of the calculation of the service life limit with linear approximation of the data by the SI values for each EU should be applied.

After the initial data have been prepared and the model for calculating the marginal exploitation lifespan has been selected, the date (hereinafter the "calculation date") when it to be calculated is to be determined. For the transformer under consideration, the following should be known:

- function $S_0(t) = S_{0.T}(t)$, where $S_{0.T}(t)$ is the basic function of the SI change depending on the operating time for the transformer;
- function $S(t) = S_T(t)$, where $S_T(t)$ is the factual function of the SI change depending on the operating time for the transformer.

Knowing the date of commissioning of the transformer, it is necessary to determine the calendar lifespan of the transformer from the date of commissioning to the date of calculation in years.

$$t = t_c. \qquad (18)$$

The calculation date cannot be earlier than the commissioning date of the transformer. The calculation of the transformer marginal exploitation lifespan is carried out in the following order.

1. The calculation of the factual operated resource (factual service life) of the transformer is performed in accordance with [10].
2. Depending on the model chosen, the value of the normative residual resource (the normative residual service life) of the transformer is determined by expression (1) or (10).
3. If further operation of the transformer is planned in the normative exploitation conditions, the marginal residual lifespan of the transformer corresponds to the normative residual service life, and the total marginal exploitation lifespan is determined by the expression (2)-(3) or (11)-(12) according to selected model.
4. If further operation of the transformer is planned in conditions other than the normative, the marginal residual lifespan of the transformer is determined by numerical methods from equality (5) or expression (14), and the total marginal exploitation lifespan is determined by the expression (4) or (15).

For a new newly installed transformer, the following procedure for calculating the marginal exploitation lifespan should be followed. After preparing the initial data and selecting the model for calculating the marginal exploitation lifespan, it is necessary to determine the date (hereinafter the "calculation date") for which the calculation will be performed. For the transformer under consideration, the following should be known:

- function $S_0(t) = S_{0.T}(t)$, where $S_{0.T}(t)$ is the basic function of the SI change depending on the operating time for the transformer;
- function $S(t) = S_T(t)$, where $S_T(t)$ is the factual function of the SI change depending on the operating time for the transformer.

The marginal exploitation lifespan of the transformer is determined from equation (6) or expression (15), depending on the model chosen.

Let us consider an example of calculating the service life of a transformer.

Suppose, the transformer has worked for 7 years in the normative operating conditions. In this case, its actual service life is also 7 years. If the transformer had worked these 7 years in the heavier operating conditions at A = 1.1, then for 7 years it would have factually operated 7.7 years. If the transformer had worked for 7 years under light operating conditions at A = 0.8, then for 7 years it factually operated only 5.6 years.

Thus, with a calendar service life of 7 years for light operating conditions, the actual service life is 5.6 years, for weighted ones – 7.7 years.

If the transformer is further operated under the normative exploitational conditions, the marginal service life will be determined accordingly:

$$T_m = 25 - 5.6 + 7 = 26.4 \text{ years (light condition)};$$

$$T_m = 25 - 7.7 + 7 = 24.3 \text{ years (heavy condition)}.$$

If further exploitation of the transformer is continued in similar lightened ($A = 0.8$) or heavier conditions ($A = 1.1$), then it is necessary to determine the marginal residual service life:

$$T_{m.res} = (25 - 5.6) / 0.8 = 26.4 \text{ years (light condition)};$$

$$T_{m.res} = (25 - 7.7) / 1.1 = 15.7 \text{ years (heavy condition)}.$$

Then the marginal service life will be determined as follows:

$$T_m = 26.4 + 7 = 33.4 \text{ years (light condition)};$$

$$T_m = 15.7 + 7 = 22.7 \text{ years (heavy condition)}.$$

If, for example, the transformer was operated for 7 years in light conditions ($A = 0.8$), and then it will be operated in heavy ($A = 1.1$), its marginal residual service life will be:

$$T_{m.res} = (25 - 5.6) / 1.1 = 17.6 \text{ years},$$

And marginal service life accordingly:

$$T_m = 17.6 + 7 = 24.6 \text{ years}$$

## Conclusion

The article considers the Methods for calculating the marginal exploitation lifespans of power transformers based on the use of an integral estimation of the factual state – the state index. Basic principles of the developed Methods and a block diagram of the calculation of the transformers marginal exploitation lifespan are shown. A general calculation model and a model for calculating the marginal exploitation lifespan of transformers based on linear approximation of the values of the state index change function are given. A methodical approach is presented for the use of the Methods in the PAMS. An example is given of calculating the marginal exploitation lifespan of a power transformer, showing the possibility of using the Methods in electric grid companies of the Russian energy industry.

**References**


1. Voropai N.I., G.F. Kovalev, Yu.N. Kucherov, et al. The concept of providing reliability in the electric power industry. M.: LLC ID "ENERGY", 2013, 304 p.
2. Tadjibaev A.I., A.N. Nazarythev, D.A. Andreev. The Analysis of Methods for Assessing the Integral Indexes of Electrical Equipment Technical Status. Научни Известия на НТСМ „Дни на безразрушителния контрол 2016", Созопол, България, Година XXIV, Брой 1(187), 2016, pp.405-407.
3. Nazarythev A.N., A. Tadjibaev, D. Andreev. The Methodology of Determining the Probability of Electrical Equipment Failures Considering the Technical Status Index. Научни Известия на НТСМ „Дни на безразрушителния контрол 2017", Созопол, България, Година XXV, Брой 1(216), Юни 2017, pp.160-165.
4. Nazarythev A.N., E.V. Novomlinsky, D.A. Andreev. Valuation of the electrical equipment technical condition based on the calculation of integrated indicators. Methodological issues

of reliability research of large energy systems. Issue 67. Problems of reliability of energy systems, 2016, pp. 171-179.

5. Berdnikov R.N., D.B. Gvozdev, I.A. Kuzmin, A.N. Nazarythev, D.A. Andreev, A.I. Tadjibaev. Methods for valuating the probability of failures of the main electric grid equipment considering its technical condition. Collection of scientific and technical articles of the employees of the “Rosseti” Group of Companies. M.: "Electricity. Transmission and distribution", 2017, pp.151-163.
6. Nazarythev A., A. Tadjibaev. Inspection and Diagnostics Methods as a Basis to Control the Technical Status of Electrical Equipment. Proc. of the International Seminar on Learning from Differences in the Energy Sector, Saint-Petersburg, Kotka: PEIPK, KYAMK, 2016, pp.63-72.
7. Nazarythev A., A. Tadjibaev, D. Andreev. Evaluation of electrical equipment service life on the basis of its status index trend. Methodological Problems in the Reliability Study of Large Energy Systems (RSES 2017), Bishkek, Kyrgyzstan, September 11-15, 2017, E3S Web Conf., Vol. 25, Article Num. 04004, 2017, 7p., DOI https://doi.org/10.1051/e3sconf/20172504004
8. Decree of the Government of the Russian Federation of December 19, 2016 No. 1401 "Of the comprehensive determination of indicators of the technical and economic status of power facilities, including indicators of physical wear and energy efficiency of electric grid facilities, and the procedure for monitoring such indicators" (Meeting of Legislation of the Russian Federation Federation, 2016, No. 52, Article 7665).
9. Order of the Ministry of Energy of Russia of July 26, 2017 No. 676 "On approval of the methodology for assessing the technical condition of the main technological equipment and power transmission lines of power plants and electrical networks."
10. Andreev D.A., A.N. Nazarythev, A.I. Tadjibaev. Determination of the probability of failure of equipment of electric grid enterprises on the basis of technical condition assessment. FSEE "PEIPK", SPb., 2017, 194 p.
11. Nazarythev A.N., D.A. Andreev. Methods and mathematical models of a comprehensive assessment of the technical condition of electrical equipment. Ivanovo State Power Engineering University, 2005, 224 p.
12. Nazarythev A.N., D.A. Andreev. Methodological basis for determining the marginal exploitation lifespan and the order of technical re-equipment of power facilities. Ivanovo State Power Engineering University, 2005, 168 p.
13. Nazarythev A.N., A.I. Tadjibaev, D.A. Andreev. Evaluation of the electrical equipment resource by the trend of the state index change. Methodological issues of reliability research of large energy systems. Issue. 68. Research and provision of reliability of energy systems, ISEM SB RAS, 2017, pp.613-623.