2012 / 30

Mathematical Models for Choice of Measures on Functioning Reliability Increase of Power Transformers

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***Abstract*— In the paper the generalized mathematical model for estimation of the efficiency of measures on the increasing of reliability of the transformer equipment's functioning is developed. The particular mathematical models for economic estimation of measures on purchase and modernization of transformer equipment are given also on the base of generalized model. This task is solved under the conditions of deficit of the investments in the Latvian Power Company. The search for the optimum solution for the considered task is made among the set of modernization alternatives of the transformer base and prolongation of transformer lifetime. The total annual discounted costs for transformer whole life cycle are offered as the objective function for estimation of measures on modernization.**

***Keywords*: transformer, objective function, total annual discounted costs.**

I. Introduction

The peak of high-voltage transformer building according to historical development took place at the end of the past century. Naturally today the largest part of those transformers is in the operation more than 25 years, i.e. the normative resource of transformers (t_{norm}) already is developed and this equipment requires replacement. The problem of the lifetime increasing of the transformers is very important and topical in many power companies. It is necessary to take into account that the condition of transformer base in the time of slow rates of upgrading and replacement of out-of-date transformer equipment can become a source of threat for power safety of the state.

The further reliable functionality of the transformer equipment is possible to be provided with such measures:

1) replacement of out-of-date transformers at the existing objects;

2) lifetime prolongation for the already installed transformers after diagnostic and preventive measures.

The simultaneous replacement of such plenty of transformers, which have worked out a normative resource, requires large investments. The impossibility to provide it with necessary amount results in some changes of the purposes and tasks of maintenance of the transformer equipment. One of the tasks becomes a prolongation of real resource of transformers over normative terms (till 35-40 years) through diagnostics, modernization, repair and other measures. Other direction consists in refusal of carrying out periodic scheduled preventive works due to the control of the transformers condition by monitoring systems.

However, it is necessary to note that prolongation lifetime of transformers is a provisional measure only removing the replacement term.

In the work the methods is developed for an economic estimation of any measures to increase the reliability functioning of the transformer equipment. This estimation is based on comparison of the total annual discounted costs for a user of power transformer at the realization of various measures [1-3].

II. Decision-making procedure

The search of optimum solution for the considered task is spent among the set of modernization alternatives of the transformer base and prolongation of transformer lifetime (Fig.1.). The decision-making on the selection of an optimum alternative E_0 to increase the reliability of the transformer equipment functionality can be represented by such procedure:

$$E_o = \left\{ E_{io} \mid E_{io} \in E_m \wedge \left(e_{io}, R_{io} \right) = opt\ e_{ij} = \underset{j}{opt} \left(opere_{ij} \right) \right\}, \quad (1)$$

where E_{io} is the set of optimum alternatives of solution; E_m is the set of all alternatives; e_{io} is optimum (minimum or maximum) estimations; e_{ij} is the estimations, accounting different conditions j of the task; *oper* e_{ij} is the appropriate objective function; R_{io} is the justified risk.

As the set of alternatives E_m possible measures on the increasing of reliability of functioning of the transformer equipment and as e_{io} (*oper* e_{ij}) - value of measures' objective function (the total annual discounted costs NPV_i) are used.

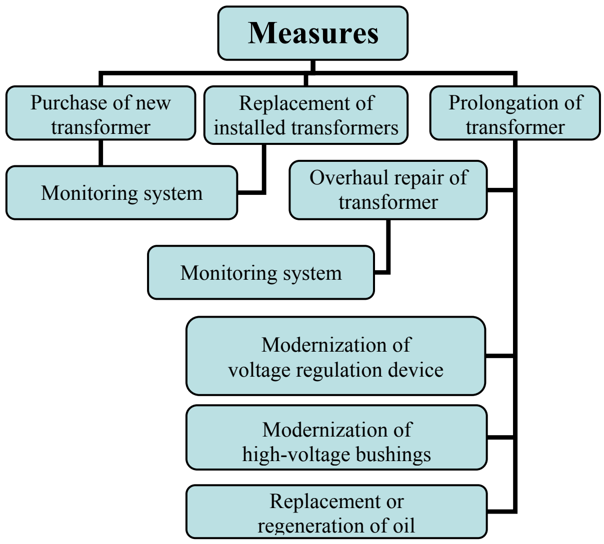

Fig.1. Measures on increase of reliability's functioning of transformers

Then, $$E_o = \underset{j}{opt}\left(oper\ e_{ij}\right) = \min(\max) NPV_i \ , \tag{2}$$

III. The Generalized Model for Estimation of Measures

In the paper the generalized mathematical model for estimation of the efficiency of measures on the increasing of reliability of the transformer equipment's functioning is developed. Selecting the measure it is necessary to consider both present and the future costs for operation of the equipment because these costs per calculated period are commensurable or even surpass initial expenses on realization of this measure.

The developed generalized objective function for an economic estimation of technical measures (*n*=*i*) is created on the basis of the total annual discounted costs NPV_n (Net Present Value) for a user by the transformer for all calculation period (life cycle of the equipment) [1-3]:

$$NPV_n = \sum_{t=0}^{T} C_{nT,t} \cdot \frac{1}{(1+i_d)^t} = C_{n0} + \sum_{t=1}^{T} C_{nT,t} \cdot d_t \ , \tag{3}$$

where $C_{nT,t}$ are actual costs for a user of power transformer in *t* year of calculated period; *T* is the calculated period; d_t is a discounting factor; i_d is a discount rate; C_{n0} are actual costs for a user of power transformer at the initial moment of calculated period; *n* is number of measures.

The minimum of the total annual discounted costs ($NPV_n = min$) for the calculation period is a criterion for the selection of an optimum variant without taking into account identical to all variants of incomes on realization of production (sale of the electric power). At the account of incomes on realization of production the variant providing the maximal income is accepted for optimum ($NPV_n = max$).

The total annual costs can be represented as:

$$C_{nT,t} = C_{n0} + C_{nC,t} + C_{nOp,c,t} + C_{nOp,v,t} + C_{nR} \ , \tag{4}$$

where $C_{nC,t}$ are capital expenses (deductions from total capital investments in measure $K_{nT\sum,t}$ in view of the market interest rate *i*); $C_{nOp.c,t}$ are constant operating costs on amortization, maintenance repair and service; $C_{nOp.v,t}$ are variable operating costs for compensation of losses of the electric power in the transformer; C_{nR} is probable damage to the consumer because of interruptions of power supply.

The total annual discounted costs for a user of power transformer with allowance for separate components of costs look like:

$$NPV_n = C_{n0} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \sum\limits_{j=1}^{m} \left[\begin{array}{l} \frac{i}{100} \cdot K_{n\,T\Sigma,tj} + \frac{1}{100} \times \\ \times (p_{na} + k_t p_{nr}) \cdot K_{n\,T\Sigma,tj} \end{array} \right] + \\ + k_t \cdot \left[\begin{array}{l} \left(\begin{array}{l} \Delta P_{n\,nl} \cdot T_{n,m} + \\ + \beta_T^2 \cdot \Delta P_{n\,sc} \cdot \tau \end{array} \right) \cdot \beta_n^{/} + \\ + \left(\begin{array}{l} \Delta P_{n\,nl} + \\ + \beta_T^2 \cdot \Delta P_{n\,sc} \end{array} \right) \cdot \beta_n^{//} \end{array} \right] + C_{nR} \end{array} \right\} \cdot \frac{1}{(1+i_d)^t} \tag{5}$$

where $K_{nT\sum,tj}$ are total capital investments on measure in calculated year *t* with allowance for *j* investments; *i* – is the market interest rate; p_{na}, p_{nr} are corresponding percentage deductions on amortization, maintenance repair and service; ΔP_{1nl}, ΔP_{1sc} are the no-load and short-circuit losses of new transformer; $T_{n,m}$ is the utilization time of the transformer per year; τ is the utilization time of maximum losses per year; β_n' is the cost of 1 kWh of electric losses; β_n'' is the cost of 1 kW of power at power system maximum; β_T is an expected loading factor of the transformer.

It is necessary to note also, that major overhaul, as well as other measure on modernization of the equipment, can be made without attraction of bank credits, i.e. from own accumulation of the enterprise. At attraction of own means of the customer the interest rate *i*. considerably below the bank credit interest rate.

The probable damage to the consumers because of interruptions of power supply C_{nR} can be represented as

$$C_{nR} = c_R \cdot A_n = c_R \cdot \chi_{n,dam} \cdot A_{n,\max} \ , \tag{6}$$

where C_R is a cost of 1 kWh of not delivered electric power to consumers; A_n is a quantity of not delivered electric power; $X_{n,dam}$ is a probable duration of emergency switching-off of the transformer per year; $A_{n,\ max}$ is a maximum quantity of the power transferred through the transformer per year.

The economic expediency on prolongation of transformer actual resource can be detected comparing the costs of considered variant with variant on replacement of installed transformers after finishing of normative term by a new one. In the given models the calculated period $t^{/}$ (instead *T*) is the term of prolongation of operation of the transformer after the ending of normative service life also varies.

Thus it is necessary to take into account that the resource prolongation results in the increasing of costs for maintenance and repair of transformers, heightening of electric losses (as contrasted to by new samples) and probable increasing of the parameter of a stream of refusals. It is accepted that in the variants the increase of costs for maintenance and repair of transformers submits to the linear law $k_t = 1 + b \cdot t'$ where factor *b* approximately is equal *b = 0.1 - 0.2* [2].

IV. Particular Mathematical Model

Detailing of different components of objective function per the years of the calculated period leads to the concretization of the generalized mathematical model and to creation of particular mathematical models for an estimation of various technical measures. In work the particular mathematical models on the basis of the generalized model to estimate some measures in Fig.1 are created and approved.

The description on measures is resulted below and different components of all particular mathematical models are displayed in Tab. 1.

TABLE 1

COMPONENTS COSTS AND EXPRESSIONS OF COMPONENTS FOR ALL PARTICULAR MATHEMATICAL MODELS

Costs components	Expressions of components
Initial costs C_{n0}	$C_{10} = K_{1T\Sigma} = K_T + K_{tr} + K_i + K_{sp} + K_{cd} + K_{add}$ $C_{20} = K_{2T\Sigma} = K_{1T\Sigma} - K_L + K_d$ $C_{30} = K_{3T\Sigma} = K_{rT} + K_{tr} + K_{add}$ $C_{40}..C_{70} = K_{4T\Sigma}..K_{7T\Sigma} = K_{rT} + K_{add}$
Capital costs $C_{nC,t}$	$C_{nC,t} = i/100 \cdot K_{n\,T\Sigma}$; $n = 1..7$
Constant operating costs $C_{n\,Op.c,t}$	$C_{n\,Op.c,t} = i/100 \cdot (p_{n\,a} + k_{n,t}\,p_{n\,r}) \cdot K_{n\,T\Sigma}$, $k_{1,t} = 1; k_{2,t} = 1; k_{3,t}..k_{7,t} = 1 + bt'; p_{3a}...p_{7a} = 0$
Variable operating costs $C_{n\,Op.v,t}$	$C_{n\,Op.v,t} = k_{n,t} \cdot \left[\begin{array}{l} \left(\Delta P_{n\,n\,l} \cdot T_{n,\,m} + \beta_T^2 \cdot \Delta P_{n\,sc} \cdot \tau\right) \cdot \beta_n^{/} + \\ + \left(\Delta P_{n\,n\,l} + \beta_T^2 \cdot \Delta P_{n\,sc}\right) \cdot \beta_n^{//} \end{array} \right]$ $k_{1,t} = 1; k_{2,t} = 1; k_{3,t}..k_{7,t} = 1 + bt'$
Damage from interruptions of supply C_{nR}	$C_{nR} = c_R \cdot A_n = c_R \cdot \chi_{n,dam} \cdot A_{n,\max}$; $n = 1..7$

1. An estimation of competitive offers of the equipment suppliers at purchase of new transformers for new objects (*NPV₁*).

The choice of an optimum variant of purchases and deliveries of new power transformers is considered as a task of a choice of the supplier of the equipment on a competitive basis (through tenders) among of some firms-suppliers or manufacturers. It is necessary to note that the economic estimation of offers of equipment's suppliers is made only for those variants which satisfy all the technical requirements for the equipment.

Total capital investments $K_{1T\Sigma}$ components in the initial moment of the calculated period for the given measure can include the following components: cost of transformers K_T and its transportation a manufacturer up to an installation site K_{tr}, the customs duties on production of the state-supplier K_{cd}, cost of spare parts (for maintenance of operation within 5 years after purchase) K_{sp}, possible cost of installation K_i and additional expenses K_{add} (on carrying out of reception tests, etc.).

Another components of NPV_1 are given in Tab.1.

2. Replacement of maintained transformers which have worked out normative resource, for new modern transformers (NPV_2).

Necessity of replacement of the installed power transformers for new with the improved characteristics (smaller loading and losses of idling, smaller weight of steel, etc.) can be caused physical or an obsolescence of the equipment, an emergency exit out of operation and impossibility of restoration of a working condition, discrepancy of rated power to loadings of consumers, etc.

The given measure is considered as a complex measure selecting the supplier of power transformers through tenders among the firms - suppliers or manufacturers, the dismantling of the maintained transformer, the installation new and the further operation of the new transformer during normative service life.

The task of search of the optimum decision in this case essentially does not differ from the first considered task. However, the total capital investment $K_{2T\Sigma}$ should consider additional components, such as expenses for dismantling K_d, liquid cost K_L of the installed transformer (approximately 10 % from its initial cost), and installation of the new transformer K_i.

Another components of NPV_2 are given in Tab.1.

3. Prolongation of service life of transformers after carrying out of major overhaul (NPV_3).

Major overhaul of transformers allows removing the revealed defects fully and qualitatively. At major overhaul probably restoration or even replacement of isolation of windings. Cost of major overhaul depends on the volume of the completed works and is within the limits of (40-70) % from the cost of the new transformer. The amount of works at major overhaul is installed by the customer after detailed inspection of the transformer and corrected after the survey of internal units. The big influence on initial expenses is rendered with the works spent with magnetic system and windings (repair or replacement). Total capital investments $K_{3T\Sigma}$ for the given action can include the following components at the initial moment of the settlement period: cost of repair of the transformer K_{rT}, cost of it transportation a manufacturer and back up to an installation site K_{tr} as major overhaul is usually made at a factory.

Another components of NPV_3 are given in Tab.1.

4. Prolongation of service life of transformers after modernization or replacements of voltage regulation devices under loading (NPV_4).

Malfunctions of devices of regulation of a voltage under loading (RVUL) are the reason approximately 30 % of emergency switching-off of transformers. Thus, damage of switching devices is fixed as a rule, on transformers with for operating time more than 20 years. Half from these switching-off is connected with refusals of drives of devices RVUL. Other switching-off is connected with malfunctions of directly switches of steps. Among the reasons of such infringements of working capacity, basically, are noted: oxidation of contacts in a zone of seldom included branches, burning contacts, infringement of tightness of the built in switches.

Replacement or modernization of a drive of the switch is technically simple measure and can be realized with small expenses, unlike full replacement of unit of the switch of adjusting windings.

Another components of NPV_4 are given in Tab.1.

5. Prolongation of service life of the transformer after modernization or replacements of high-voltage bushings (NPV_5), replacement or regenerations of oil (NPV_6), installation of system of monitoring (NPV_7).

Practically the third part of failures of power transformers are caused by damages of high-voltage bushings. These failures can lead to heavy consequences: to damages of transformers, explosions, fires, technical and functional refusals of the equipment. New bushings can be installed on earlier released types of transformers as they correspond to the not tight bushings taken off from manufacture on the connecting sizes and length of the bottom part. For this measure the estimation on particular model (NPV_5) with replacement or modernization of high-voltage bushings was spent.

For transformers with service life more than 15 years are characteristic of a deposit which conducts to deterioration of internal isolation of the transformer. To prevent this process probably spending replacement of oil or its regeneration. It is necessary to note that full replacement of oil gives more palpable results, than the regeneration of old oil. For this measure the estimation on particular model (NPV_6) with replacement of oil was spent.

The condition of some transformers demands the continuous control. The decision of this task will be helped by installation of systems of continuous monitoring. On this measure the estimation on particular model (NPV_7) for two various systems of monitoring with different quantity of controllable parameters was spent.

For specified above measures on particular mathematical models the estimated calculations are led. The offered methods take place approbation in the Latvian Power Company (Latvenergo).

Components of NPV_5, NPV_6, and NPV_7 are given in Tab.1.

V. Conclusion

1. In the work the developed mathematical models, both the generalized model, and a number of particular models for estimation of measures to increase the reliability of the transformer equipment functionality are given.
2. The minimum of total annual discounted costs for the user of power transformer are offered as a basic criterion of economic expedience of measures.
3. Replacement of the transformer at earlier stages, after the ending of service life, is economically more favourable. It is connected with the increasing of the price of the transformer and deductions.

Reference

[1] Guseva S., Mahnitko A., Vinbergs H. Economic criteria of an estimation of measures to increase the reliability of transformer equipment functionality // XIIth Intern. Sc. Conf. "Present-Day Problems of Power Engineering" APE´05, Gdansk - Jurata, Poland, 8–10 of June, 2005, Vol. 3 pp. 205 – 212.

[2] Guseva S., Mahnitko A., Breners N., Vinbergs H., Mathematical model of estimation of measures on modernization of high-voltage inputs of transformers // The XIIIth Intern. Sc. Conf. "Present-Day Problems of Power Engineering", Poland, Gdansk-Jurata, 13-15 of June, 2007, pp. 51 – 57.

[3] N. Breners N., S. Guseva S. Analysis of measures to upgrade the transformer equipment // Elektroenergetika Journal, Technical University of Košice, Slovak Repablic, Vol 1, No. 2, December 2008, pp. 9-12 (in Russian).

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Nikolajs Breners, Nataļja Skobeļeva. Matemātiskie modeļi spēka transformatoru funkcionēšanas drošuma paaugstināšanas pasākumu izvēlei

Pēdējos gados daudzu attīstītu valstu enerģētikas kompānijas ir spiestas risināt transformatoru aprīkojuma masveida novecošanās problēmu. Šī situācija iespaido elektroenerģijas patērētāju elektroapgādes drošumu. Tās risinājums acīmredzot ir morāli un fiziski novecojušā aprīkojuma aizstāšana ar jaunu, mūsdienīgu, tehniskajiem raksturojumiem atbilstošu. Šāds risinājums uzlabos transformatoru parka kopējo tehnisko stāvokli, bet prasa lielas investīcijas realizācijai.

Finanšu līdzekļu deficīta apstākļos daudzas energosistēmas meklē paņēmienus transformatoru reālā kalpošanas laika pagarināšanai virs normatīviem.

Lai to veiktu, sākumā ir nepieciešamas relatīvi nelielas investīcijas, kas ļaus turpināt transformatoru ekspluatāciju un uz kādu laiku atlikt jautājumu par aprīkojuma aizstāšanu.

Transformatoru dzīves ilguma pagarināšana iespējama tāpēc, ka spēku augstsprieguma transformatori ir viens no enerģētiskā aprīkojuma pašiem uzticamākajiem un ekonomiskākajiem veidiem. Transformatoru ekspluatācijas ilgtermiņa pieredze attīstītu valstu energotīklos apstiprina, ka reāls dzīves ilgums 30 % - 60% ekspluatējamiem transformatoriem pārsniedz normatīvu. Bez tam ekspluatācijas termiņa laikā spēku transformatori parasti strādā ar reālām slodzēm zem nominālajām, kas ļauj saglabāt labus aprīkojuma tehniskos parametrus. Tomēr lēmums par transformatoru ekspluatācijas pagarināšanu virs normatīvajā termiņa var tikt pieņemts tikai pēc to diagnostikas veikšanas. Atkarībā no izpētes rezultātiem nepieciešamības gadījumā tiek veikta atsevišķu transformatora elementu modernizācija.

Tehniski ekonomisko pasākumu analīzi transformatoru modernizācijai un funkcionēšanas drošuma paaugstināšanai ir iespējams veikt piedāvātā apkopotā matemātiskā modeļa bāzē. Mērķu funkcijai ir pieņemtas summārās diskontētās izmaksas lietotājiem pasākuma realizācijai un transformatora ekspluatācijai nākamajā periodā pēc pasākuma realizācijas. Tas ļauj novērtēt konkrētu pasākumu efektivitāti transformatoru aprīkojuma funkcionēšanas drošuma paaugstināšanai.

Николай Бренер, Наталья Скобелева. Математические модели для выбора мероприятий по повышению надежности функционирования силовых трансформаторов.

Многие энергетические компании развитых стран в последние годы вынуждены решать проблему массового старения трансформаторного оборудования. Эта ситуация влияет на надежность электроснабжения потребителей электроэнергии. Очевидным решением этой проблемы является замена морально и физически устаревшего оборудования новым с современными техническими характеристиками. Этот путь радикально улучшает общее техническое состояние трансформаторного парка, но требует для своей реализации крупных инвестиций.

В условиях дефицита финансовых средств во многих энергосистемах ведётся поиск вариантов для продления реального срока службы трансформаторов сверх нормативного.

Этот путь требует относительно небольших инвестиций в начальный момент времени, позволяет продолжить эксплуатацию трансформаторов и отодвинуть на некоторое время решение вопроса о замене оборудования.

Возможность продления срока жизни трансформаторов основывается на том что, силовые трансформаторы высокого напряжения - один из самых надежных и экономичных типов энергетического оборудования. Долгосрочный опыт эксплуатации трансформаторов в энергосетях развитых стран подтверждает, что реальный срок жизни 30 % - 60% эксплуатируемых трансформаторов превышает нормативный. Кроме того, в течение срока эксплуатации силовые трансформаторы работают, как правило, с реальными нагрузками ниже номинальных, что позволяет сохранить хорошие технические параметры оборудования. Тем не менее, решение относительно продления эксплуатации трансформаторов сверх нормативного срока может быть принято только после проведения их диагностики. По результатам обследования, при необходимости, проводится модернизация отдельных элементов трансформаторов.

Технико-экономический анализ мероприятий по модернизации и повышению надежности функционирования трансформаторного оборудования, возможно, выполнить на базе предложенной обобщенной математической модели. В качестве целевой функции приняты суммарные дисконтированные затраты пользователя на реализацию мероприятия и последующий период эксплуатации трансформатора после реализации мероприятий. Это позволяет оценить эффективность конкретных мероприятий по повышению надежности функционирования трансформаторного оборудования.