ECONOMIC ESTIMATION OF UPDATING THE BUSHINGS OF HIGH-VOLTAGE TRANSFORMERS

AUGSTSPRIEGUMA TRANSFORMATORU CAURVADU MODERNIZĀCIJAS PASĀKUMU EKONOMISKAIS NOVĒRTĒJUMS

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Introduction

Latvian Power Company (Latvenergo) have almost half from 254 power high-voltage transformers works 25-40 and more years. The peak of high-voltage transformer building according to historical development has fallen 50th-60th and 80th years of the past century. Naturally today the most part of those transformers is in operation more than 25 years, i.e. the normative resource of transformers (t_{norm}) already is developed and this equipment requires replacement. Under the conditions of investments' deficit in Latvian power branch a rate of transformer replacement is very slow. So for the period from a restoring of Latvian state independence at 1991 year till 2005 year only 4 transformers are replaced and 7 are installed at new 110-330 kV substations. At the same time 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to take into account that the condition of transformer base in the time of slow rates of upgrading and replacement of out-of-date transformer equipment can become a source of threat for power safety of the state.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 simultaneous replacement of such plenty of transformers, which have worked out a normative resource, requires the large investments. The impossibility to provide them in necessary sizes carries on to some changes of the purposes and tasks of maintenance of the transformer equipment. One of tasks becomes a prolongation of real resource of transformers over normative terms (till 35-40 years and more) through diagnostics, modernization, repair and other measures. The experience of electrical network confirms possibility of lifetime prolongation for transformers over normative term. It is necessary to note, that prolongation lifetime of transformers is a provisional measure and only remove the replacement term. From all above stated it is possible to draw a conclusion that the problem of increase in lifetime of transformers is very important and topical. Certainly, the decision on prolongation lifetime is accepted for each transformer separately. The solution about the prolongation of transformer resource should be accepted on the basis of careful inspection of a state of the equipment, estimation of aging of isolation, detection and elimination of imperfections. The search of optimum solution for the considered task is spent among set of measures on prolongation of transformer lifetime. In this article the technical and economic estimations of measures on replacement or modernization of 110 kV transformer bushings is given.

Decision-making procedure

The decision-making at the choice of an optimum alternative E_0 to increase the reliability of the transformer equipment functionality can be represented by such procedure [2]:

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

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 justified risk.

In the Institute of Power Engineering of the Riga Technical University the methods is developed for an economic estimation of any measures to increase of 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 realization of various measures [2-5].

The objective function by the way the total annual discounted costs at the choice of measures to increase the reliability of the transformer equipment functionality look like

$$NPV_n = \sum_{t=0}^{T} C_{nT,t} \cdot \frac{1}{(1+i_d)^t} = C_{n0} + \sum_{t=1}^{T} C_{nT,t} \cdot d_t \quad (2)$$

where $C_{nT,t}$ – are actual costs for a user of a power transformer in t year of calculated period; C_{n0} – are actual costs for a user of a power transformer at the initial moment of calculated period; T – is the calculated period; d_t – is a discounting factor; i_d – is a discount rate [1,4].

The minimum of total annual discounted costs for a measure is the optimum solution of the given task, i.e.

$$E_o = opt \left(oper \; e_{ij} \right) = \min \; NPV_i \quad . \quad (3)$$

New transformer purchase costs

The choice of an optimum alternative of purchase of new transformer for existing objects is considered as the task on choice of equipment supplier on a basis of competition among some firms - suppliers or manufacturing plants (set of variants E_m).

The total annual discounted costs for a user of a power transformer for the first task NPV_1 with allowance for separate components of costs look like:

$$NPV_1 = C_{1O} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \sum_{j=1}^{m} \left[\frac{i}{100} \cdot K_{1T\Sigma,tj} + \frac{1}{100} \cdot (p_{1a} + p_{1r}) \cdot K_{1T\Sigma,tj} \right] + \\ + \left[\left(\Delta P_{1nl} \cdot T_{mt} + \beta_T^2 \cdot \Delta P_{1sc} \cdot \tau \right) \cdot \beta' + \left(\Delta P_{1nl} + \beta_T^2 \cdot \Delta P_{1sc} \right) \cdot \beta'' \right] \end{array} \right\} \cdot \frac{1}{\left(1 + i_d\right)^t} \quad , \quad (4)$$

where C_{1O} – are costs for a measure on purchase of the new transformer in an initial moment of a calculated period, equal to the total investments $K_{1T\Sigma}$; j – is a number of the next in turn investment, $j = \overline{1, m}$; $K_{1T\Sigma, tj}$ – are total capital investments in a measure per calculated year t with allowance for j investments; i – is the market interest rate; $\Delta P_{1nl}, \Delta P_{1sc}$ – are the no-load and short-circuit losses of new transformer; T_{mt}– is the utilization time of the transformer per year; τ– is the utilization time of maximum losses per year; $\beta^{/}$ – is the cost of 1 kWh of electric losses; $\beta^{//}$ - is the cost of 1 kW of power at power system maximum; β_T - is a expected loading factor of the transformer.

Estimation of measures on modernization transformer′s high-voltage bushings

Among the measures directed on increase of service life of the transformer the actions connected with replacement or modernization of high-voltage bushings are considered. High-voltage bushings serve to connect high-voltage winding of the transformer to same voltage network and to isolate a conductor from the case of the transformer. As show to statistic data practically third of all failures of transformers is caused by damages of high-voltage bushings. These failures can lead to heavy consequences: to damages of transformers, explosions, fires, technical and functional refusals.

In the Latvian Power Company the transformers with 110 or 330 kV voltage are maintained. The significant number of transformer bushings exploited in Latvia was made at Moscow factory "Mosizolyator". It is oil-filled bushings of GBMT type. The special equalizers, built in bushings, serve for indemnification of temperature changes of oil volume. Internal isolation is executed from paper tape impregnated by insulating oil. Paper isolation is divided into layers by leveling facings and placed in a porcelain tire cover. All internal capacity of porcelain tire cover is filled by oil. The outlets for the control and measuring of a tangent of a corner of dielectric losses and capacities of internal isolation are located in the bottom part of the bushing. The gate for adjustment of pressure settles down. The bushing constantly is under superfluous pressure.

During exploitation term of transformer and high-voltage bushings there is gradual deterioration of properties of isolation, caused by ageing of oil, pollution of a surface of internal isolation and an internal surface of porcelain tire cover. It is possible a loss of tightness of bushings, humidifying, easing of contact connections.

Traditionally developed technique of the control of a condition of high-voltage bushings, as has shown experience of its application, does not provide early detection of defects in the oil channel. It creates a risk factor of damage of the equipment working in a zone of normalized values of parameters of high-voltage bushings.

The main lacks of bushings of GBMT type are leaks of oil in condensations. Defect is caused by lack of bushing design and does not manage to remove it completely. The application of GK, TKR, Nitro 11 GX and Shell Diala D oil marks instead of T-750 oil mark has allowed to exclude damages of bushings because of a yellow strike on an internal surface of a porcelain tire cover which promotes overlapping of isolation on an internal surface.

Now Joint-Stock Company "Mosizolyator" releases a number of the new modernized tight bushings instead of before released and removed from manufacture not tight bushings.

The modernized tight bushings have the constructive changes raising their reliability in operation. These are the bushings of GTT, DTD, GMTB type or gas-filled bushings. The tight oil-filled bushings differ structurally from the bushings of GBMT type. In these bushings oil serves only as a coolant and does not demand the control of electric parameters. Gas-filled inputs have a number of the advantages caused by properties SF6 gas (six-fluoric sulphur SF6). The advantages consist in the following:

- ✓ _hexafluoride sulphur insulation is safe_(does not burn and does not support burning);
- ✓ SF6 gas is ecologically clean - pure gaseous SF6 is absolutely harmless, chemically is not active, therefore in usual operational conditions it does not act on the materials applied in apparatus buildings;
- ✓ SF6 gas, unlike oil, is not subject to ageing and does not demand replacement during all service life.

The given advantages of hexafluoride sulphur insulation allow to increase essentially reliability and to lower breakdown susceptibility of the equipment of stations and substations. New bushings can be installed on before released types of transformers, since the connecting sizes and length of the bottom part of modernized bushings correspond to bushings removed from manufacture. Lifetime of high-voltage bushings below lifetime of transformers therefore is expediently to pay these units. The risk factor of damage of the equipment forces to give enhanced attention to questions of an estimation of a technical condition, to choose and carry out repair-preventive measures.

There are set of possible measures *Em* for bushings with the worsened parameters of oil:

- E_1 - the further operation of bushings till failure;
- E_2 - replacement of oil in bushings;
- E_3 - disassembly of input with replacement of oil and clearing of an internal surface of a porcelain tire cover;
- E_4 - replacement by new bushings.

The search of optimum solution for the considered task is spent among set of measures on prolongation of transformer lifetime. The quantitative assessment of a measure can be fulfilled with the objective function.

The objective function as the total annual discounted costs for a user of power transformer NPV_3 at the given task with allowance for separate components of costs look like:

$$NPV_3 = C_{3O} + \sum_{t=1}^{t'} \left\{ \begin{aligned} & \sum_{j=1}^{m} \left[\frac{1}{100} \cdot (p_{3a} + k_t p_{3r}) \cdot K_{3T\Sigma,\, tj} \right] + C_{3R} + \\ & + k_t \left[\left(\Delta P_{3nl} \cdot T_{mt} + \beta_T^2 \cdot \Delta P_{3sc} \cdot \tau \right) \cdot \beta' + \left(\Delta P_{3nl} + \beta_T^2 \cdot \Delta P_{3sc} \right) \cdot \beta'' \right] \end{aligned} \right\} \cdot \frac{1}{(1 + i_d)^{t'}} \qquad (5)$$

where C_{3o} - is the costs on a measure of on prolongation of transformer lifetime at an initial moment of a calculated period equal to the total investments $K_{3T\Sigma}$ by measure; t' -is the prolongation term of transformer ($t = (t_{norm} + 1) - t_{norm}$; $t' < t_{norm}$, usually t' till 15 years); p_{na} un p_{nr}; - on operating repairs and service in view of corresponding percentage deductions; C_{3R} - the additional losses connected with risk of damage of the equipment and which probability of occurrence p_i ; ΔP_{3nl}, ΔP_{3sc} – no-load and short-circuit losses of the transformer; T_{mt} - an operating time of the transformer in a year; β_T - the planned factor of loading of the transformer; τ- time of the maximal losses; β' - the price of 1 kWh losses of the electric power; β'' - the price of 1 kW capacities during the maximal loading a power supply system [2-4].

The total investments $K_{3T\Sigma}$ can include the cost of overhaul K_{ov}, modernization K_{mod}, diagnostic K_{diag} of transformer state and other costs K_{add} on preparation for prolongation of transformer resource, i.e.

$$K_{3T\Sigma} = K_{ov} + K_{\mathrm{mod}} + K_{diag} + K_{add} \quad (6)$$

The economic expediency on prolongation of transformer actual resource for the term t' over normative period can be detected comparing the costs of considered variant with variant on replacement of installed transformers after ending of normative term by new one. Thus it is necessary to take into account that the resource prolongation carries on at 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 at comparing, that in the third variant the increase of costs for maintenance and repair of transformers submits to the linear law $k_t = 1 - bt'$, where factor b approximately is equal $b = 0.1 - 0.2$ [2].

The risk factor also can be taken into account at the choice of the optimal variant.

Objective presence of risk of damage of the equipment and necessity of its estimation at operation of high-voltage bushings demands precise definition of concept of the risk considering probable character of possible consequences and expression in quantitative units. It is expedient to define risk as product of size of event A on a measure of an opportunity of its origin q.

$$R = Aq \quad (7)$$

In considered task size A is estimated as losses in case of appearance of possible consequences of development of the defect what numerically equal e_i, and as a measure of an opportunity of approach q the probability p_i approaches of these consequences serves, i.e.

$$R_i = e_i p_i \quad (8)$$

Risk level enters into the equation (5) as C_{3R}.

Realization of measure E_1 leads in further to breakdown of transformer and risk level R_i can be taken (70 - 100 %) cost of new transformer.

Realization of measure E_2 restores isolation properties of oil, but actually does not allow lowering probability of the further development of considered defect as does not restore isolation property of an internal surface of a porcelain tire cover. Hence, the risk level of development of defect is commensurable with 50% cost of new transformer.

Realization of measure E_3 allows restoring isolation properties of oil and a porcelain tire cover that allows providing a risk level of development of defect is commensurable with a risk level is commensurable with (20 - 30 %) cost of new transformer.

Realization of measure E_4 allows prolongation of exploitation of transformer. The risk level determines probability of damage of whole transformer. In this comparison of measures the risk level of measure E_4 does not take into account.

The measure on the prolongation of transformer actual resource over normative period (the calculated period $T = t^{/}$) is economically expedient, if the condition (8) is true, i.e.

$$NPV_3 \leq NPV_2 \quad \text{or} \quad NPV_3 - NPV_2 \leq 0 \qquad (9)$$

where NPV_2 - are costs on replacement of installed transformer by the new one.
Costs NPV_2 approximately can be taken as equal to costs NPV_1 on purchase of new transformer if to accept:

$$K_{2T\Sigma} = \left(K_{1T\Sigma} - K_{liq}\right) + K_d = K_{1T\Sigma} \qquad (10)$$

where liquid cost K_{liq} – is liquid cost of the established transformer; K_d – is costs of dismantling.

Practical solution

The technical end economic estimation of measures on modernization of high-voltage bushings of transformers are presented in Table 1. The negative costs are taken as positive. The estimated calculation on purchase of 110 kV and 60 MVA transformers for replacement of installed transformers after ending of normative term (variants 1) is fulfilled. A ten-year credit with market interest rate i = 10 % as the source of the investments was accepted. The costs for measures E_4 on the prolongation of transformer resource (t'= 5, 10, 15 years) as largest and on following replacement (in ending of prolongation term) on new transformer are given at variants 2, 3 and 4.

Table 1.
The total annual discounted costs for 110 kV the power transformer's user

№	Unit	Marking unit	**Costs**, thous. EUR			
			variant 1	variant 2	variant 3	variant 4
1	Cost of transformer and transportation	K_T+K_{tr}	669,7	1078,6*	1737,3*	2797,5*
2	Installation cost	K_i	70	112,7*	181,6*	292,7*
3	Amortisation and maintenance deductions	C_a+C_r	65,4	2,6 110,3**	1,6 161,5**	1,3 301,4**
4	Costs on electric losses compensation	$C_{op.v}$	7,8	10,6	10,6	10,6
5	**Total annual discounted costs**	***NPV***	**1611**	**1855**	**2475**	**3623**

* - costs are compounded for the moment of installation of new transformer;
** - amortisation and maintenance deductions before installation of the new transformer (above) and after installation of the new transformer (below)

The risk level in the lead calculations was not carried out, as there are no necessary statistical data on failures and infringements of working capacity of transformers. This information is mostly inaccessible in a kind of closeness. Comparison of variants shows, that modernization of transformers only a provisional measure. Replacement of the transformer fulfilled the service life at early stages economically is more favorable, than its replacement at late operation phases.

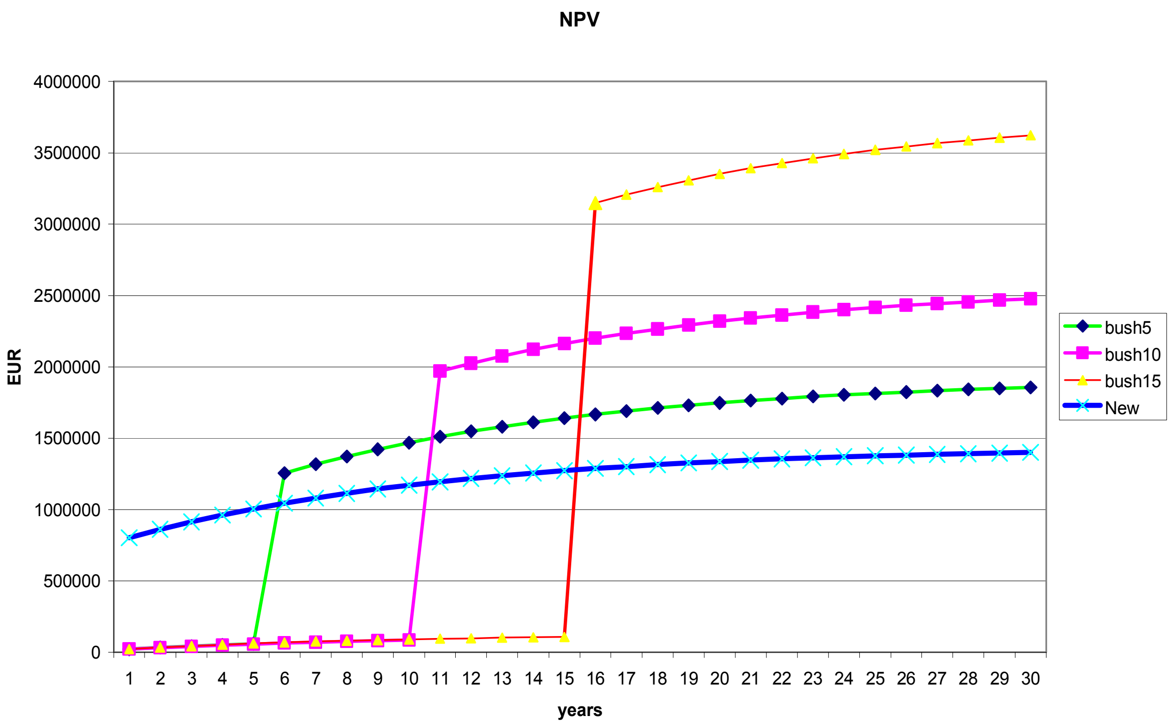

Fig.1. The total annual discounted costs for 110 kV the power transformer's user

Conclusions

1. In the paper the objective functions on basis of total annual discounted costs for the user of power transformer is created.
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 to increase the reliability of the transformer equipment functionality.
3. Application of criterion of the decision-making combining the account of possible risk of damage of the equipment with expenses for realization of this decision allows estimating and proving a choice of repair and preventive measures.
4. Replacement of the transformer at earlier stages, on the ending of service life, is economically more favorable. It is connected with increase in the price of the transformer and deductions.

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Guseva S., Breners N., Vindbergs H. Augstsprieguma transformatoru caurvadu modernizācijas pasākumu ekonomiskais novērtējums.

Rakstā dots augstsprieguma transformatoru iekārtu modernizācijas pasākumu ekonomiskā novērtējuma matemātiskais modelis (mērķa funkcija). Augstsprieguma caurvadu nomaiņa vai modernizācija ir apskatīta kā modernizācijas pasākums. Uzdevums ir risināts investīciju deficīta apstākļos Latvijas energosistēmas enerģētikas nozarē. Pasākumu novērtējumam tika izmantotas mērķa funkcijas summāro ikgadējo diskontēto izmaksu veidā transformatora izmantotājam par visu transformatora dzīves ciklu. Summāro ikgadējo diskontēto izmaksu minimums ir piedāvāts kā pasākumu lietderīguma kritērijs. Veikti praktiskie aprēķini dažādiem variantiem, izmantojot mērķa funkciju.

Guseva S., Breners N., Vindbergs H., Economic estimation of updating the bushings of high-voltage transformers.

The paper presents a mathematical model (the objective function) for economic estimation of updating the equipment of high-voltage transformers. As the updating measures the replacement or modernization of high-voltage bushings are considered. The problem is to be solved under the conditions of a deficit of the investments in the Latvian Power System. For the estimation the authors employed the objective function of the total annual discounted costs for the users of power transformers for the whole service life, with the least cost as the basic criterion. Based on this model numerical calculation for different updating measures has been performed.

Гусева С., Бренерс Н., Виндберг Х., Экономическая оценка мероприятий по модернизации высоковольтных вводов трансформаторов.

В статье дана математическая модель для экономической оценки мероприятий по модернизации высоковольтного трансформаторного оборудования. Замена или модернизация высоковольтных вводов трансформаторов рассмотрена в качестве мероприятия по модернизации. Задача решается в условиях дефицита инвестиций в энергетическую отрасль в Латвийской энергосистеме. Для оценки мероприятий использована функция суммарных ежегодных дисконтированных затрат. Минимум этих затрат предложен в качестве критерия для оценки мероприятий. Выполнены практические расчеты для нескольких вариантов на базе математической модели.