Mathematical Models for Economic Estimation of Measures on Transformer's Modernization

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***Abstract* — In paper the economic estimation of measures on modernization of transformer base using the generalized mathematical model is given. The particular mathematical models for estimation of concrete measures have been received from the generalized mathematical model. The total annual discounted costs for transformer's whole life cycle are offered as the objective function and its optimum decision is the maximum of profit from measure's realization. This task is solved under the conditions of deficit of the investments in the Latvian Power Company. The comparison of economic estimations for different technical measures on basis of the generalized mathematical model are fulfilled.**

***Keywords*: transformer, measures, objective function, discounted costs.**

I. Introduction

The majority of energy companies stand in front of the fact of mass transformers' ageing. Similar situation is observed in Latvian Energy Company «Latvenergo». Today on 129 substations of the Latvian power supply system with a voltage 110-330 кV 254 power transformers as the total power 6905 MVA work. Approximately half of transformers have developed a normative resource. Service life 8 % on total power transformers exceeds 40 years, 43 % have service life 25-40 years and only at 49 % of transformers term operation of less than 25 years. Mass ageing of the maintained equipment becomes hard problem for a power supply system which demands the cardinal decision. To maintain normal and reliable work of power transformers in power supply system it is necessary to lead a number of actions among which the most effective are:

- replacement of morally and physically out-of-date transformers on new, meeting modern requirements;
- real service life's prolongation of maintained power transformers after diagnostics, elimination of defects, modernization or major overhaul.

In conditions of market economy all technical measures directed to renovation and modernization of electrical equipment may be established on technical and economic accounts for rational use of money resources. Radical solution for renewal of the transformer fleet could be replacing the outdate equipment, but simultaneous replacement of a large number of transformers would require a huge capital investment. As the energy companies experience currently funding shortage in adverse economic situation it is necessary find the right balance between the transformer fleet renewal and extending the transformers' physical resources beyond the regulatory life-span for a part of the transformers. However, the pace of equipment renovation shall not be slower than the rate of aging. In addition, the transformer fleet upgrade measures should ensure maintained or risen capacity of the transformers at substations, in order to guarantee reliability of the power supply to consumers [1-3].

II. Structure of the Technical Measures Selection Methods

A developed method is divided into three main modules each meant for a relevant solution. The main tasks of each module are presented in Figure 1.

Module one is an analysis of the condition of the transformer fleet facilities. Based on the data analysis of the energy company engineering services and having regard to the short-, medium- and long-term development plans, investment amounts and available own funding, the amount of work and deadlines for the integration of new facilities and reconstruction of existing ones within the whole power system or separate energy companies are developed. Integration of a new power transformer or substation reconstruction makes a large part of the work scope within transmission or distribution network development plans. Within the first module the set of technical measures E_m is formed.

Module two is an in-depth technical analysis of the measures to be taken at specific objects. Analysis of equipment technical condition is carried out based on the inspections, scheduled maintenance, diagnostics and technical expert survey.

According to the results of the analysis, depending on the extent to which the technical requirements to the existing facility are going to be met, and, based on the workload level, the following alternative measures could be undertaken: building a new substation, replacement of the existing transformers with new ones or extension of the existing transformers' life. Within the second module the set of technical measures E_n is formed. The set of possible technical measures E_n aimed at increasing operational reliability of a transformer is represented in Figure 2.

Module three is economic evaluation of the possible technical measures. In the third module, a set of technical measures is formed from the separate prospective technical measures in order to carry out their economic evaluation (See Figure 1). For the evaluation modern economic analysis methods will be applied. As a result of the evaluation selection of the technical activities to be implemented and recommendations for the energy companies will be made.

III. Methods of Economic Analysis of the Prospective Measures

Figure 1 Unit 3 displays the main phases of the economic analysis of the prospective technical measures. For implementation of these phases an economic analysis method should be chosen.

Cash flow value changes in time and the value of same amount of money may vary in different time periods. Inflation and market condition are the factors that mainly affect the money value through time.

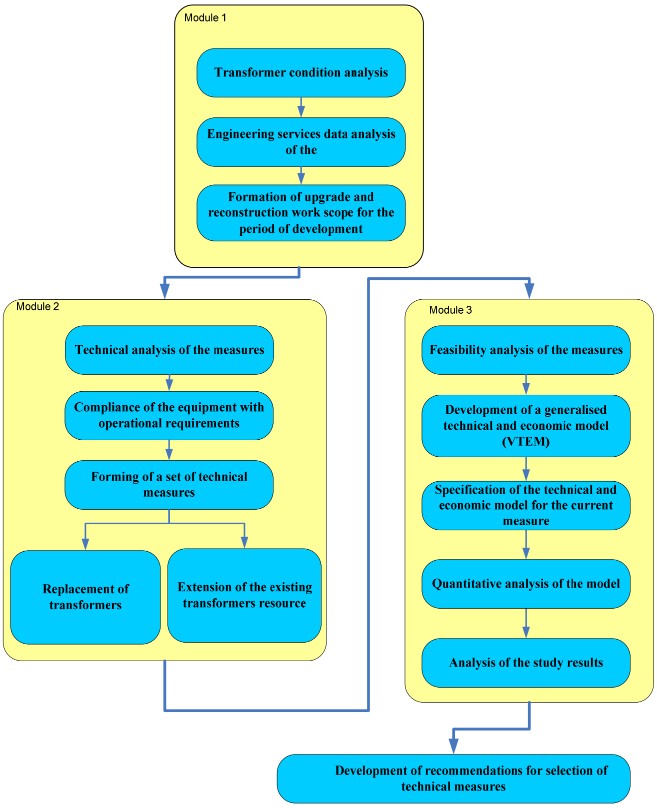

Fig. 1. Structure of methods for technical measures‘ selection.

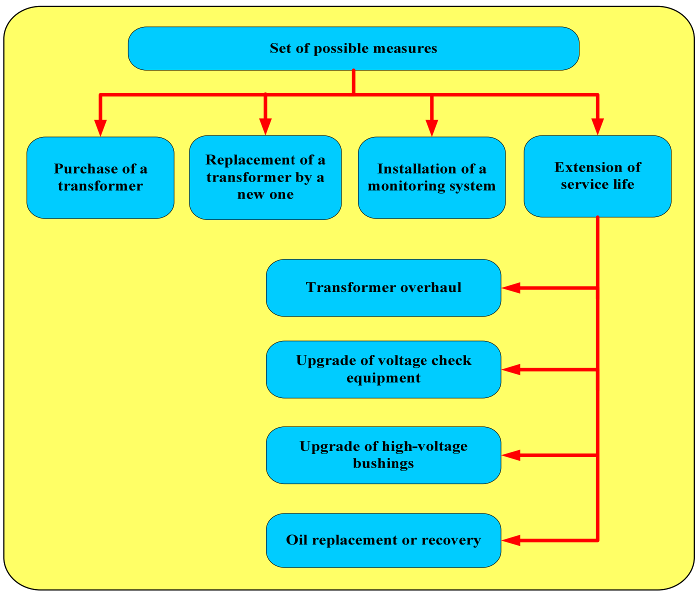

Fig.2. Technical measures aimed at increasing a transformer operational reliability.

Therefore, the necessary economic calculations should be made using the net present value method, meaning that all costs should be reduced to the beginning of the calculation period.

Project study methods differ from one country to another. In Latvia, to evaluate feasibility of technical measures capitalized cost method and the total discounted annual cost method are commonly used. In this paper the total discounted annual cost method is applied.

IV. THE GENERALIZED MODEL FOR ESTIMATION OF MEASURES

To ensure normal and safe operation of power transformers the following measures might be taken:

- replacement of out-of-date transformers with new, meeting modern requirements, ones;
- prolongation of actual physical resources of the transformers based upon diagnostic tests, defect prevention, upgrade and repair.

In market economy, all the technical measures taken within an energy system including improvement of a transformer's operational reliability should be based on a thoroughly made feasibility calculations to ensure rational use of funding. Such calculations can be most effectively carried out with the help of mathematical and technical and economic models, using appropriate software. Technical and economic models (TEM) aimed at ensuring qualitative assessment of feasibility of the measures and quantitative assessment of an appropriate objective function have been developed within this paper based on the Net Present Value (*NPV*) of the transformer operator's total discounted annual costs through the calculation period (the equipment life cycle) [1,2]. When choosing the appropriate technical measures all the equipment lifecycle costs should be taken into account, because operating expenses are often close to equal to the measure implementation costs, or even exceed them. For all the technical and economic models single approach is used, which makes it possible to create a generalized technical and economic model. For quantitative evaluation of the technical measures intended to achieve the following objective function has been developed on the basis of NPV_n:

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

where $C_{nT,t}$ is real total annual costs of the transformer's user of t-th year (incomes and costs) for implementation of measure n; C_{n0} is costs of measure n during the initial moment of calculation period T; d_t is discount factor (factor for reduction of costs of different years at the initial moment); i_d is discount rate.

Total annual costs of the operator of the transformer $C_{nT,t}$ of the *t-th* year for implementation of measure n in expression (1) include several components:

$$C_{nT,t} = C_{nK,t} + C_{nOp.c,t} + C_{nOp.v,t} + C_{nR} \quad , \quad (2)$$

in addition:

$$C_{nK,t} = \frac{i}{100} \cdot K_{nT\Sigma,t};$$
$$C_{nOp.c,t} = \frac{p_{na} + k_{r,t}\, p_{nr}}{100} \cdot K_{nT\Sigma,t};$$
$$C_{nOp.v,t} = k_{E,t}\,(\Delta P_{nnl} \cdot T_d + \beta_T^2 \cdot \Delta P_{nsc} \cdot \tau) \cdot \beta' + (\Delta P_{nnl} + \beta_T^2 \cdot \Delta P_{nsc}) \cdot \beta'';$$
$$C_{nR} = c_{nR} \cdot A_n = c_{nR} \cdot \chi_n \cdot A_{n,\max} \quad ,$$

where $C_{nK,t}$ are capital costs deductions on capital investments of measure $K_{nT\Sigma,t}$, including the market interest rate i (weighted average rate of return on capital); $C_{nOp.c,t}$ are constant operating depreciation, maintenance and repair expenses including corresponding percentage deductions for depreciation p_{na} and repair p_{nr}; $C_{nOp.v,t}$ are variable working costs for compensation of losses of the electric power in the transformer; $\Delta P_{n\,nl}$, $\Delta P_{n\,sc}$ are no-load and short-circuit losses of the transformer; T_d - operating time of the transformer per year; τ - time of the maximal losses; β_T – planned factor of the transformer workload; β' is the price of 1 kWh losses of the electric power; β'' is the price of 1 kW capacities during the maximal loading a power supply system; C_{nR} are loss related to the electricity undelivered to the consumers; c_{nR} are the specific costs related to the electricity non-delivery to the consumers; A_n is quantity of undelivered electricity per year; χ_n - probability of the transformer emergency downtime (relative units); $A_{n,\max}$ is maximum transferable power through the transformer per year. Weighted average rate of return on capital i:

$$i = i_p \frac{K_p}{K_p + K_{kr}} + i_{kr} \frac{K_{kr}}{K_p + K_{kr}}, \qquad (3)$$

where i_p is power company own capital rate of return; i_{kr} is rate of return on borrowed capital; K_p is own capital, and K_{kr} is borrowed capital.

Expected income can be calculated using the formula:

$$I_n = \sum_{t=1}^{T} \left[\beta_E \cdot P_T \cdot \beta_T \cdot T_m + \beta_R \cdot P_T \cdot (1-\beta_T)\right] \cdot k_{E,t} \cdot k_p \;, \qquad (4)$$

where I – total annual income from the sale of electricity and power supply services; P_T – transformer active capacity; T_m – maximum workload time per year; β_E –transmission tariff for 1kWh of electricity; β_R – power system capacity maintenance costs; k_p - income ratio showing the proportion of the income When income is introduced the event selection criterion is changing for the target function. Now, the maximum total discounted annual costs (max NPV_n) for the calculation period is the criterion for selection of the optimal measure [5,6]. In addition, assessment of the measures based on the payback period criterion taking income into account is available. Be the calculation results displayed in a chart or tabular form, the year for which NPV_n value is positive, is the year of payback of the invested funding. Combining the costs and income in one formula we obtain:

$$NPV_n = -C_{n0} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \left[P_T \cdot \beta_T \cdot \beta_E \cdot T_m + P_T \cdot (1-\beta_T) \cdot \beta_R\right] \cdot k_{E,t} \cdot k_p - \\ -\left[\dfrac{i}{100} \cdot K_{nT\Sigma,tj} + \dfrac{1}{100} \cdot (p_{na} + k_{r,t}\, p_{nr}) \cdot K_{nT\Sigma,tj}\right] - \\ -k_{E,t} \cdot \left[\begin{array}{l} \left(\Delta P_{nnl} \cdot T_d + \beta_T^2 \cdot \Delta P_{nsc} \cdot \tau\right) \cdot \beta' + \\ +\left(\Delta P_{nnl} + \beta_T^2 \cdot \Delta P_{nsc}\right) \cdot \beta'' \end{array}\right] - k_{r,t} \cdot C_{nR} \end{array} \right\} \cdot d^t \;, \qquad (5)$$

where j – current investment in implementation of a measure, moreover $j = 1, ..., m$; $k_{r,t}$ - factor describing a transformer's operating expenses increase during operation; $k_{E,t}$ - factor, which describes the energy loss value increase under the period of operation. Factor $k_{E,t}$ is a time function $k_{E,t}(t) = k_{E,0}(1+bt)$, where factor b factor is obtained by approximation of statistical data and taking into account the energy loss value increase during recent years and b=0,03; $k_{E,0}$ is initial costs of the energy loss of the calculation period. Factor $k_{r,t}$ is a time function too. It is obtained approximating statistical data and taking into account the transformer operating expenses increase due to aging and the growing risk of failure during operation. Factor $k_{r,t}$ is determined for two time intervals: for the first interval, 0…25 years of operation is $k_{r,t}(t) = 1+bt$, where $b = 0{,}02$; for the second interval, 25...40 years of operation is $k_{r,t}(t) = at^2+bt+c$, where $a=0.01$, $b=0{,}02$, $c=1{,}3$. The maximum total discounted costs (max NPV_n) under the calculation period are the optimum measure selection criterion, regarding of the income from sales of production (electricity), in case that these are not identical in all measures.

V. PARTICULAR MATHEMATICAL MODEL

Detailing of different components of objective function on years of 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 on Fig.2 are created and approved. The components of the particular mathematical models are given in Tab.1.

1. An estimation of competitive offers of the equipment suppliers at purchase of new transformers for new objects (NPV_1).

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 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 to all technical requirements to the equipment.

Total capital investments $K_{1T\Sigma}$ components in the initial moment of the calculated period for the given measure can include 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.

An example of practical calculation for a target function NPV_1 for the purchase of new 110 kV, 63 MVA transformers is shown in Figure 4. Calculations are made according to (53) for the measure *n*=1 taking into account the expected income. There were four suppliers who participated in the tender. NPV_1 calculations were made for each option offered by the applicants and results were compared in a chart. The winner was the first bidder's offer with NPV_1=max.

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

Necessity of replacement of installed power transformers on 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 complex measure at the choice of the supplier of power transformers through tenders among 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 (about 10 % from its initial cost), and installation of the new transformer. Another components of NPV_2 are given in Tab. 1. If K_d is taken approximately equal to K_d , then the total capital investment $K_{1T\Sigma} = K_{2T\Sigma}$. In this case the objective function NPV_2 is not different from NPV_1 .

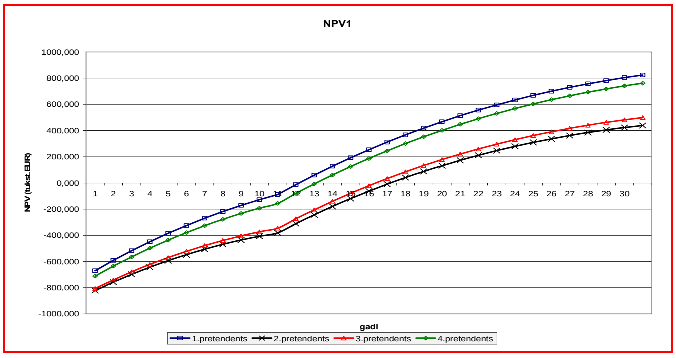

Fig.3. Practical implementation of calculations for measures *n*=1 and *n*=2.

Having analysed the results for four options of measures n=1 and n=2 we conclude:

- the highest NPV_1 through the whole period of calculation is in the first option;
- the lowest NPV_1 is in the second option;
- the shortest payback period, which is six years, is in the first option;
- the winner is the bidder who offered the first option.

TABLE 1

COMPONENTS COSTS AND EXPRESSIONS OF COMPONENTS FOR ALL PARTICULAR MATHEMATICAL MODELS

Cost components	Components calculation formula
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 $C_{n\,Op.c,\,t}$	$C_{n\,Op.c,\,t} = 1/100 \cdot (p_{n\,a} + k_{nr,t}\, p_{n\,r}) \cdot K_{n\,T\Sigma}$, $k_{1r,t} = 1 + bt'; k_{2r,t} = 1 + bt'; k_{3r,t}..k_{7,t} = at'^2 + bt' + c;$ $p_{3a} \cdots p_{7a} = 0$
Variable operating costs $C_{n\,Op.v,\,t}$	$C_{n\,Op.v,\,t} = k_{nE,t} \cdot \left[\begin{matrix} \left(\Delta P_{n\,n\,l} \cdot T_{n,\,m} + \beta_T^2 \cdot \Delta P_{n\,sc} \cdot \tau\right) \cdot \beta_n^{/} + \\ + \left(\Delta P_{n\,n\,l} + \beta_T^2 \cdot \Delta P_{n\,sc}\right) \cdot \beta_n^{//} \end{matrix} \right]$ $k_{1E,t} = 1; k_{2E,t} = 1; k_{3E,t}..k_{7E,t} = 1 + bt'$
Costs related to the electricity non-delivery to the consumers C_{nR}	$C_{nR} = c_R \cdot A_n = c_R \cdot \chi_{n,dam} \cdot A_{n,\max}$; $n = 1..7$

The following transformer life extension measures are reviewed: replacement and upgrade of voltage regulation devices and high-voltage bushings, recovery or replacement of transformer oil, applying of diagnostic and monitoring systems. For economic evaluation of these measures technical and economic models of feasibility assessment (TEM) created for the specific measures on the basis of the generalized model VTEM (3) are used. If the measures are intended to extend the useful life of transformers, the appropriate objective function calculation period begins from the end of the transformer's regulatory term t_{norm} and this year is accepted as $t=t'=0$. The calculation period for the beyond-regulatory time (the extension period) is $t'_{pag} = T_{vnorm} = 15 - 20$ (See Figure 4).

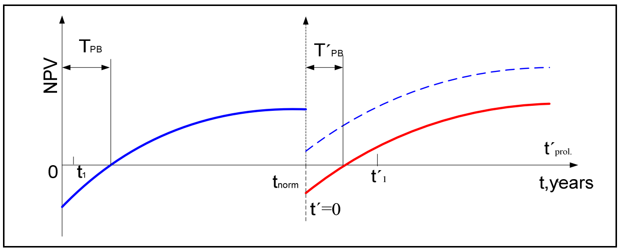

Fig. 4. Assumption of a calculation period for different measures.

3. Economic evaluation of the measure involving transformer overhaul repair (*NPV_3*).

Major overhaul of transformers allows removing the revealed defects most full and qualitatively. At major overhaul probably restoration or even replacement of isolation of windings. Cost of major overhaul depends on volume of made works and is within the limits of (40-70) % from 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 following components in 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. Economic evaluation of the measure involving replacement of voltage regulation devices (NPV4).

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. Economic evaluation of the measure involving upgrade of a transformer's high-voltage bushings (*NPV_5*) replacement or regenerations of oil (*NPV_6*), installation of system of monitoring (*NPV_7*).

Practically a third 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 the 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 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 estimated calculations are lead. 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. Comparison of the calculation results for different technical measures n=1-6 involving 110 kV 32 MVA transformer is shown in Fig. 5.

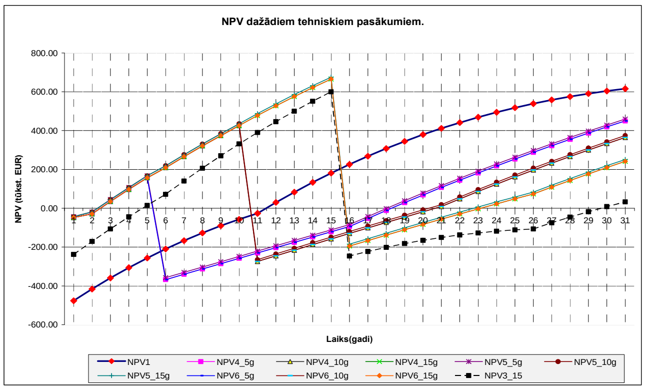

Fig. 5. Comparison of different technical measures available for 110 kV 32 MVA transformers.

For the comparison calculations of the following objective functions were used: NPV_1 – purchase of a new transformer, NPV_3 - transformer overhaul, NPV_4 – upgrade of the voltage regulation equipment, NPV_1 – replacement of high-voltage bushings, NPV_6 – recovery or replacement of insulation oil.

The comparison of different technical measures shows that ones for prolongation of the transformer service life have short-term economic effect at the beginning of the extended life of the transformer, until it is replaced by a new one because later the transformer price is going to increase due to inflation.

VI. CONCLUSION

1. Comprehensive method for selection of the measures aimed at improvement of the transformer fleet operational reliability was developed. The method includes technical and economic analysis of each measure.
2. The developed generalized technical and mathematical model and particular models for concrete technical measures provide a means for qualitative assessment of measures and the corresponding objective function makes it possible to quantitatively evaluate *NPV* and efficiency of the respective measure.
3. For evaluation of the technical measures total discounted annual costs through the whole life cycle should be used with the maximum *NPV* value as optimum criterion.
4. The developed method is applicable for evaluation of replacement and upgrade of various electrical equipment.
5. The offered method provides a means for a more rational and effective use of the investments in the energy companies.

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Nikolajs Breners, Nataļja Skobeļeva. Matemātiskie modeli spēka transformatoru modernizēšanas pasākumu ekonomiskai novērtēšanai.
Pēdējos gados daudzu attīstītu valstu enerģētiskās kompānijās ir aktuāla problēma saistīta ar transformatoru aprīkojuma masveida novecošanu. Šī situācija pazemina elektroenerģijas patērētāju elektroapgādes drošumu. Šīs problēmas radikālais atrisinājums, kas uzlabo transformatoru parka kopēju tehnisko stāvokli, ir morāli un fiziski novecojušā aprīkojuma aizstāšana pret jaunu ar mūsdienas atbilstošiem tehniskajiem raksturojumiem. Šis ceļš pieprasa realizācijai lielas investīcijas. Finanšu līdzekļu deficīta apstākļos daudzās energosistēmās meklē paņēmienus transformatoru reāla kalpošanas laika pagarinājumam virs normatīvam. Šī virziena energouzņēmumu tehniskajā politikā prasa realizācijai relatīvi nelielas investīcijas sākumu laika momentā, saglāba iespēju turpināt transformatoru ekspluatāciju un uz kādu laiku atlikt jautājuma par aprīkojuma aizstāšanu.
Transformatoru dzīves ilguma pagarinājuma iespēja dibinājās uz spēka transformatora īpatnības: tas viens no enerģētiskā aprīkojuma pašiem uzticamākajiem un ekonomiskajiem veidiem. Transformatoru ekspluatācijas pieredze attīstītu valstu energosistemās apstiprina, ka reāls dzīves ilgums 30 % - 60% ekspluatējamiem transformatoriem pārsniedz normatīvu. Bez tam, ekspluatācijas termiņa laikā spēku transformatori reāli strādā, ar slodzēm zemāk nominālajiem, kas ļauj saglabāt aprīkojuma labus tehniskos parametrus. Transformatoru ekspluatācijas ilguma pagarinājumu virs normatīvajam termiņam var nodrošināt pēc modernizācijas pasākumiem. Tehniski-ekonomisko pasākumu analīze transformatoru modernizācijai un funkcionēšanas drošuma paaugstinājumam ir iespējams izpildīt piedāvātā visparinātā matemātiskā modeļa bāzē. Mērķa funkcijai ir pieņemtas summārās diskontētās izmaksas lietotājiem uz pasākuma realizāciju un transformatora ekspluatāciju nākamā periodā ievērojot ienākumus no elektroenergijas realizācijas. Mērķu funkcijas sastāvdaļu konkretizācija ļauj iegūt atsevišķas mērķu funkcijas konkretiem pasakumiem.Tas ļauj novērtēt konkrētu pasākumu lietderīgumu un efektivitāti transformatoru aprīkojuma funkcionēšanas drošuma paaugstinājumam.

Николай Бренер, Наталья Скобелева. Математические модели для экономической оценки мероприятий по модернизации силовых трансформаторов.
В последние годы проблема массового старения трансформаторного оборудования актуальна для многих энергетических компаний развитых стран. Старения трансформаторного оборудования снижает надежность электроснабжения потребителей электроэнергии. Радикальным решением для улучшения общего технического состояния трансформаторного парка является замена морально и физически устаревшего оборудования новым с современными техническими характеристиками. Этот путь 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.
Такое направление в технической политике энергопредприятий требует относительно небольших инвестиций в начальный момент времени, позволяет продолжить эксплуатацию установленных трансформаторов и отодвинуть на некоторое время решение вопроса о замене оборудования.
Возможность продления срока жизни трансформаторов основывается на надежности и экономичности энергетического оборудования. Опыт эксплуатации трансформаторов в энергосистемах 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. Продление срока службы можно обеспечить проведением мероприятий по модернизации трансформаторного оборудования. Технико-экономический анализ мероприятий по модернизации и повышению надежности функционирования трансформаторного оборудования, возможно выполнить на базе разработанной обобщенной математической модели. В качестве целевой функции приняты суммарные дисконтированные затраты пользователя на реализацию мероприятия и последующий период эксплуатации трансформатора с учетом дохода от реализации передаваемой электроэнергии. Конкретизация составляющих целевой функции позволяет получить частные целевые функции для отдельных мероприятий. Это позволяет оценить эффективность конкретных мероприятий по повышению надежности функционирования трансформаторного оборудования.