RIGA TECHNICAL UNIVERSITY

Nikolajs BRENERS

TECHNICAL AND ECONOMIC ESTIMATION OF MEASURES TO INCREASE RELIABILITY OF TRANSFORMER BASE FUNCTIONING

Summary of Doctoral Thesis

Riga 2011

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Power Engineering

Nikolajs BRENERS
Candidate for a Doctor's Degree in Energy Programme

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Scientific supervisor
Dr. Sc. Ing., Asoc. prof.,
S. GUSEVA

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DOCTORAL THESIS IS PROPOSED FOR ACHIEVING DR.SC.ING. DEGREE AT RIGA TECHNICAL UNIVERSITY

Doctoral Thesis is proposed for achieving Dr.sc.ing. degree and will be publicly presented on the 21th of November 2011, at Faculty of Power and Electrical Engineering of Riga Technical University, 1 Kronvalda boulevard, in assembly hall.

OFFICIAL OPPONENTS

Professor, Dr.sc.ing. Nikolay Djagarov
Varna Technical University,

Professor, Dr. habil. sc. ing. Zigurds Krishans
Latvian Academy of Sciences, Institute of Physical Energetics

Associate Professor, Dr.sc.ing. Olegs Linkevics
RTU, AS Latvenergo

CONFIRMATION

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for achieving Dr.sc.ing. degree. This doctoral thesis has not been submitted to any other University for achieving scientific degree.

Nikolajs Breners …………………………….(signature)
Date: ………………………

The Doctoral Thesis is written in Latvian language, it contains an introduction, 5 chapters, conclusions, bibliography, and one appendix. The total volume of thesis is 126 pages, 53 figures, 1 appendix and 26 tables. The List of bibliography includes 115 sources of literature.

Contents

TOPICALITY OF THE DOCTORAL THESIS

Reliable and economical operation of high-voltage transformers is the key factor in ensuring consumers with good quality power supply. In many developed economies the problem of transformers approaching the end of their normative lifetime has become crucial. Continued operation of such equipment without taking up additional safety measures may have adverse effect upon the quality and continuity of power supply. Therefore, permanent upgrade and refreshment of transformer equipment should be ensured in power system.

In market economy, equipment refreshment and upgrade measures should be selected on the basis of technical and economic calculations to ensure efficient use of financial resources.

Today, Latvian Power Company hasn't adequate and appropriate evaluation methods, which would help to make estimates and choose the appropriate transformer equipment upgrade and reconstruction measures during the operating life of the transformers.

Considering the above mentioned, development of methods for evaluation and selection of technical measures meant for increasing the power transformers base reliability through the whole working lifetime was chosen as a focal point of this Doctoral Thesis research.

GOAL AND OBJECTIVES OF THE THESIS

The goal of this Thesis is developing uniform methods to be used by power companies for selection of technical measures, which could also be applied to substantiate specific technical measures and evaluate the economic efficiency of applying new equipment and renovation and upgrade of the existing.

To achieve the goals the following objectives have been identified and solved:

- analyse the existing condition of the Latvian 330-110 kV power transformer base and probable causes of transformers' breakdowns, as well as make some forecasts related to the aging of the transformer base;
- create technical methods for selection of the measures of renovation and upgrade of transformers base, which include analysis of the current technical condition of the transformers and feasibility study of the afore mentioned measures;
- develop technical and economic models to efficiently evaluate the technical renovation and upgrade measures and objective function on the basis of modern feasibility study methods applied for project development;
- carry out practical calculations to ensure the objective target function approbation for specific technical measures and assess their effectiveness;
- develop recommendations that could be used by power companies to select appropriate technical measures for rising reliability of their transformers base.

SCIENTIFIC NOVELTY

Scientific novelty of this thesis is achieved thanks to the following aspects:

- status analysis with 330-110 kV power transformer aging in Latvia and forecast for the situation with transformer base in Latvian Power Company for the year 2016 have been made.
- uniform complex methods has been developed for selection of technical measures aimed at rise of operational reliability of transformers including technical and economic analysis of each measure;
- a generalized model for feasibility assessment of the measures has been invented and applied to create models for certain measures and corresponding objective functions with specified technical and economic indicators;
- the substantiated choice of the measure to be applied is based on the optimum total discounted annual costs (net present value of the costs) through the whole life cycle of the equipment, taking into account peculiarities of specific measures, temporal changes of indicators, various realization terms, etc.;
- an economically feasible approach for selection of a new transformer supplier by tendering procedure was established, making basis for a rational use of investments in equipment renewal;
- the developed methods of feasibility assessment of the measures are applicable for different types of electrical equipment;
- a general quantitative analysis of a package of measures and the economic effectiveness assessment thereof have been developed as well as recommendations for energy companies, helping to choose the transformer base refreshment and upgrade manners principles have been made.

RESEARCH TOOLS AND METHODS

The results are obtained using the following research and development methods:

- mathematical modelling of the research object and the objective function implementation;
- modern methods of technical and economic analysis based on the total discounted annual costs (net present value of the costs) method for the entire life cycle of the equipment;
- determination of the optimum of objective function by making a comparison of a number of different options for the measures to be applied;
- calculations of the options are made using a specific calculation software developed in Microsoft Office Excel environment;
- for approximation of the objective function coefficients Mathcad software has been used.

PRACTICAL APPLICABILITY OF THE RESULTS

The results of this research can be used for evaluation and choice of measures for transformer base operational safety improvement in Latvenergo Joint-Stock

Company and other energy systems. The developed methodology for selection of technical measures contributes to the effective implementation of technical policy within the field of renovation and upgrade of transformer base. The range of use of the discounted total annual costs method for solution of technical problems has been extended in theoretical perspective. The reviewed objective functions for specific measures make it possible to carry out the analysis of a wide range of technical measures by changing concrete technical and economic indicators. The uniform approach to constructing technical and economic models offers a possibility to make a well-founded selection of technical measures based on the minimum of the total discounted annual costs criteria (not taking into account equal incomes from product sales for different options), and on the maximum of costs (including incomes from product sales for the options), taking into account losses from undelivered energy.

The results of the research are partly represented in:
A Contract made by Joint-Stock Company Latvenergo Nr. L7310 (Nr.010000/08-16) „Riga High-Voltage Circuit Diagram for the Period Until 2020" (adviser - prof. J.Rozenkrons), 2008 (collaboration).

APROBATION OF THE THESIS

The results of the research have been reported and discussed during 12 international conferences as follows:

1. 6-th International Conference on Electrical and Control Technologies, ECT-2011, 5-6 May, 2011, Kaunas, Lithuania (Paper).
2. The International Energy Forum 2010, 23-26 June, 2010, Varna, Bulgaria (2 papers).
3. XI International Scientific Conference „Problems of Present-day Electrotechnics, *PPE*-2010 ", 1– 3 June, 2010, Kiev, Ukraine (2 papers).
4. 5-th International Conference on Electrical and Control Technologies, ECT-2010, 6-7 May, 2010, Kaunas, Lithuania (paper).
5. 50-th International Scientific Conference „Power and Electrical Engineering", 14-16 October, 2009, RTU, Riga , Latvia (paper).
6. 49-th International Scientific Conference „Power and Electrical Engineering", section „Enerģētika", 13-15 October, 2008, RTU, Riga, Latvia (paper).
7. VI Международный Форум „Электротехника-2008", Петербургский энергетический институт повышения квалификации „ПЭИПК", 15-19 сентября, 2008, Санкт-Петербург, Россия (paper).
8. X Международная научная конференция „Проблемы современной электротехники - 2008", НАН Украины, Институт физико-технических проблем энергетики, 5-9 июня, 2008, Киев, Украина (paper).
9. 48-th International Scientific Conference „Power and Electrical Engineering", section „Enerģētika", 13-15 October , 2007, Riga, RTU, Latvia (paper).
10. 4-th International Scientific Symposium, Elektrenergetika EE, 19-21 September, 2007, High Tatry-Stara Lesna, Slovak Republic (paper).
11. XIII International Scientific Conference „Present-day Problems of Power Engineering, APE'07", 13-15 June, 2007, Gdansk - Jurata, Poland (paper).

12. 47-th International Scientific Conference „Power and Electrical Engineering”, section „Enerģētika”, 12-14 October, 2006, Rīga, RTU, Latvia (paper).

16 articles have been issued in international publications:

1. N. Breners, S.Guseva, N.Skobeļeva, O.Borscevskis. Directions to increase reliability of the maintained transformer equipment's functioning // Proceedings of 6-th International Conference on Electrical and Control Technologies, ECT-2011, 5-6 May, 2011, Kaunas, Lithuania. -175-178 p.
2. N.Breners, S.Guseva, N.Skobeļeva, O.Borscevskis**.** Choice and efficiency of measures for increase reliability functioning of power transformers // Proceedings of The International Energy Forum 2010, 23-26 June, 2010, Varna, Bulgaria. -269-279 p.
3. S.Guseva, N.Skobeļeva, O.Borscevskis, N.Breners. Rational approach to the formation of urban power supply system in solving of development problems // Proceedings of The International Energy Forum 2010, 23-26 June, 2010, Varna, Bulgaria. -280-289 p.
4. N.Breners, S.Guseva, O.Borscevskis, N.Skobeļeva. Применение мониторинга силовых трансформаторов для повышения эффективности функционирования систем электроснабжения. // XI International Scientific Conference „Problems of Present-day Electrotechnics, *PPE*-2010”, 1-3 June, 2010, Kyiv, Ukraine, 6 p. (digital format on CD).
5. S.Guseva, O.Borscevskis, N.Skobeļeva, N. Breners. The system approach to placement of transformer substations in the power supply system of the city // Proceedings of 5-th International Conference on Electrical and Control Technologies, *ECT-2010*, 6-7 May, 2010, Kaunas, Lithuania. -211-214 p.
6. S.Guseva, N.Skobeļeva, N. Breners, O.Borscevskis. Determination of service areas of urban transformer substations and distribution using geometrical templates // Latvian Journal of Physics and Technical Sciences, № 6 (Vol. 46), - Riga: FEI, 2009, Latvia. -16.-26. p.
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11. Гусева С.А., Бренерс Н.З., Махнитко А.Е., Скобелева Н.Н.. Оценка мероприятий по модернизации устройств регулирования напряжения под нагрузкой // Материалы X Международной научной конференции

„Проблемы современной электротехники-2008”, НАН Украины, Институт физико-технических проблем энергетики, 5-9 июня, 2008, Киев, Украина, с. 51-54.

12. Гусева С.А., Бренер Н.З., Скобелева Н.Н. Технико-экономическая модель оценки мероприятия по замене силовых высоковольтных трансформаторов // Сборник научных трудов „Методы и технические средства повышения эффективности применения электроэнергии в сельском хозяйстве”. - Ставрополь: Агрус, 2007, Россия, с. 209-215.
13. Svetlana Guseva, Anatoly Mahnitko, Nikolajs Breners. Evaluation of measures on reliability rise of power transformers by means of generalized mathematical model // Proceedings of IV International Scientific Symposium „Elektroenergetika 2007”, 19-21 September, 2007, Stara Lesna, Slovak Republic, 7 p. (digital format on CD).
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15. Guseva S., Breners N., Vindbergs H. Economic estimation of updating the bushing of high-voltage transformers // Enerģētika un elektrotehnika, Power and Electrical Engineering, 4. sērija, 20. sējums. –Rīga: RTU, 2007, Latvija. -66.-74. lpp.
16. Breners N., Guseva S., Kukļa N. Vienkaršots tehniski ekonomiskais modelis augstsprieguma transformatoru nomaiņas novērtējumam // Enerģētika un elektrotehnika, Power and Electrical Engineering, 4. sērija, 19. sējums. –Rīga: RTU, 2006, Latvija. -79.-84. lpp.

STRUCTURE AND CONTENTS OF THE THESIS

The Doctoral Thesis includes an introduction, a Conclusion, and 5 chapters. The thesis contains 115 bibliographical references, 53 figures, 26 tables, 1 appendix and consists of 126 pages in total.

1. ANALYSIS OF THE SITUATION WITH HIGH-VOLTAGE TRANSFORMERS' CONDITION IN LATVIA AND EQUIPMENT UPGRADE TENDENCIES

Production of power in the Latvian Power System

Latvian power system includes power plants, substations, transmission networks, heat supply networks and electricity consumers, which produce, transmit and distribute electrical and thermal energy to consumers.

The total installed capacity of the Latvenergo power generators in 2009 was approximately 2080 MW, including hydroelectric power plants of Daugava cascade (DHPP) – 1334.5 MW, thermal power plants in Riga TEC-1 and TEC-2 – 744 MW, Aiviekste HPP– 0.8 MW, Ainazi Wind Power Plant - 1.2 MW. Electricity is also produced at some minor private HPP (there are 149 of them in Latvia), cogeneration and wind power plants, but the amount of energy produced there is small [24,25].

In 2008, in Latvia 6555 GWh of electricity was sold to consumers, of which the Latvian power plants generated 4467 GWh, 637 GWh were purchased from independent power generators, and 2841 GWh of electricity have been purchased from Estonia, Lithuania and Russia.

Generating capacity deficit in the Latvian power system was 35% in 2006, 39.5% in 2007, in 2008 the deficit increased to 43%, and in 2009 it was 47%.

Latvenergo has been closely watching the electricity demand in order to meet the growing needs of consumers and reduce the dependence of Latvia on imported electricity, as the Latvian power system is deficient today.

Transmission system

The total length of the 330-110 kV lines comprising Latvenergo transmission system was 5270 km at the end of 2009, including 1258 km of 330 kV lines, 4012 km of 110 kV lines, of which 60 km were 110 kV cable lines, and 134 substations [1,24].

330-110 kV network throughput capacity is around 12-13 TWh/year, which is twice as large as the current demand – 6-7 TWh/year. Transmission network throughput capacity can cover electricity demand with a large reserve of capacity in normal regimes. High-voltage network connections with neighbouring countries have enough capacity to ensure power import and export. It is planned to use for power transmission the existing 330 kV and 110 kV voltages, which allows for the projected power flow through the next ten years. One of the power supply problems in Latvia is power supply reliability in Western part of the country – so far the power supply of this region is ensured by one 330 kV line. The power transmission network will be strengthened in Kurzeme in the years ahead by implementing the Kurzeme Circle Project.

All the 330 kV substations, except for "Rigas TEC-1", "Imanta" and "Daugavpils", are double-ended. Most of the 110 kV substations have two transformers and are double ended, but there are 25 one-transformer substations.

Evaluation of the transformer base condition

Latvian power transmission networks include 330 and 110 kV substations. According to the data from 2010, 15 substations with 330 kV highest voltage and 119 substations with 110 kV voltages were operated. Characteristics of the substations depending on their service life are shown in Figure 1.1 [11].

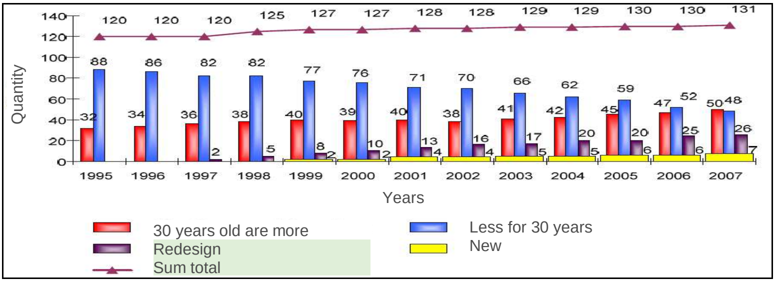

Fig. 1.1. Characteristics of 330-110 kV substations in 2007 based on their service life

The number of transformers at substations and their installed capacity are shown in Table 1.1, in parentheses – the number of transformers, which are not in use (not connected to voltage). There are 159 transformers with total capacity 3165 MVA in operation and 86 transformers with total capacity 1641 MVA in backup. It is obvious that the number of transformers is quite large for this relatively small power system. The total installed capacity of the transformers within the power system exceeds approximately five times the consumers' capacity and is sufficient for Latvian needs.

Table 1.1.

Characteristics of 330 and 110 kV substations

Voltage	Number of Substations	Number of Transformers	Installed capacity of the transformers, MVA
330 kV	15	21	3200
110 kV	119	245 (7)	4805.8
Total	134	266 (7)	8005.8

Although the transformers installed power is sufficient, there still is a problem – the equipment of power plants and substations is too old. Until the early nineties, mainly, new substations were constructed, but little was done to upgrade old equipment. Recently, much attention is paid to replacement of old equipment and, where possible, installation of modern, future compliant, systems. Distribution of 330-110 kV transformers by their operational lives, starting with 1995, is shown in Figure 1.7. Further 110 kV transformers condition is being analysed only.

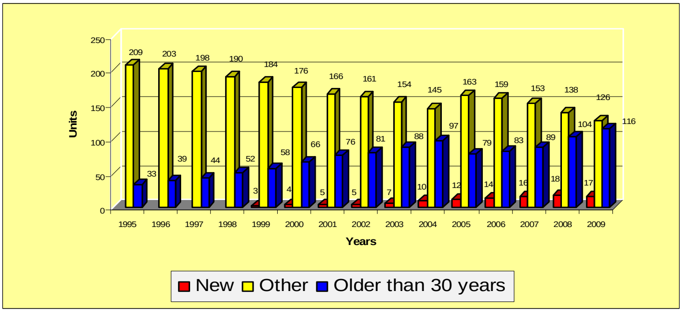

Fig.1.1. Distribution of the transformers by groups based on their service life

110 kV transformers are divided into four major groups depending to their age in 2009 (see Figure 1.8):
first – transformers, which have not reached their normative service life (25 years) – 35% of total number;
second - transformers aged from 25 to 30 years – 22%;
third - transformers aged from 30 to 40 years – 32% and
fourth, "historical", part – transformers aged over 40 years – 11%.
" Latvenergo " intends to purchase every year 4 – 5 new transformers, but there still remain a very large number of transformers that need serious decisions to be taken. 30 – 40 years of operation for a 110 kV transformer (as well as other high-voltage transformers) is considered to be a rather critical age.
Since the Latvian power system is based on the unstable 110 kV transformers (with expired normative service life), it is difficult to maintain safety of the power system under these circumstances.

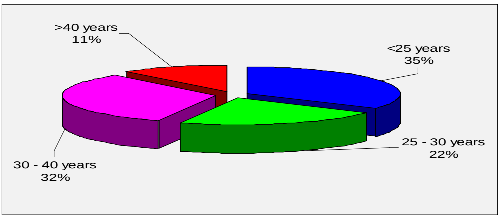

Fig.1.2. Distribution of transformers by their age in 2009

Making projections for the situation with transformer base in 2016 and assuming that the progress of transformers renovation at post-crisis period remains nearly the same, we can depict this situation as shown in Figure 1.3:

the first group – transformers, which have not reached the end of their nominal service life – 23% of the total number;
the second group – transformers aged from 25 to 30 years – 13%;
the third group – transformers aged from 30 to 40 years – 40%;
the fourth group – transformers older than 40 years – 24%.

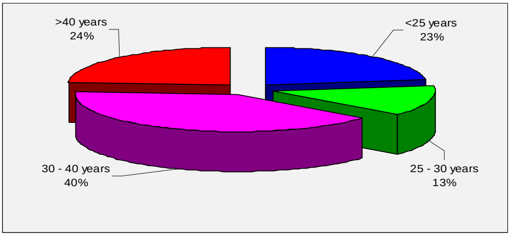

Fig.1.3. Distribution of transformers by their predicted age in 2016

To increase the power system reliability, ensure uninterrupted power supply of consumers and reduce operating costs, "Latvenergo" has elaborated a concept of development and reconstruction of transmission lines and substations for the time period until 2020, which is a part of "Latvenergo" development programme. This program provides for reconstruction of the oldest and the most worn out substations, replacement of all of the primary and secondary equipment, upgrade of transformers, as well as replacement of the damaged elements of transmission lines. For this approach to network development choosing a sound strategy for selection of technical measures is crucial [2].

Possible changes of operational tasks in power systems

Transformer equipment that is used for electricity generation, distribution and consumption, is one of the most expensive and responsible types of equipment. In recent years a number of new problems have appeared, and aging of the operated equipment is the main. There are two directions for solving the problem of equipment aging: replacement of old equipment with new, modern equipment, or extension of equipment physical resources beyond the normative service term. Due to the current economic situation energy companies can count on most of all on the transformer life prolongation and upgrade of existing equipment.

Thanks to changes in power system operation tasks a new operating policy should be developed: the going from preventive repairs of the transformers to the repairs depending on their actual condition with wide using of diagnostic and monitoring systems [2,4].

2. ANALYSIS OF CAUSES OF TRANSFORMER BREAKDOWNS AND WAYS OF IMPROVEMENT OF EQUIPMENT

Possible causes of high-power transformer breakdowns

Power transformer is one of the key elements that determine electricity supply reliability in a power system. Its ability to operate under a certain load depends on the condition of individual units and whether the defects that can result in transformer damages are eliminated in a timely manner. High-power transformer failures can lead to emergency situations in a power system with wide-ranging consequences. Transformer failures are closely related to the transformers' lifetime. Fault correlation with transformer's age is shown in Figure 2.1.

The transformers' failures can be divided into three groups:

- early failures, through approximately 3-5 years after installation;
- accidental failures until the end of the normative life at the 25th - 30th year;
- aging failure, starting with 25th-30th year of life.

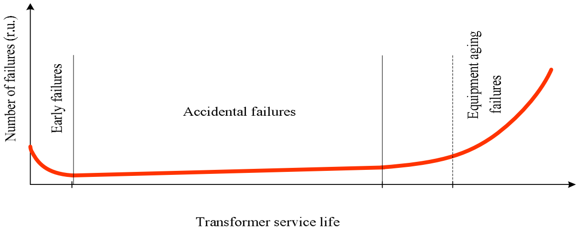

Fig.2.1. att. Transformer failure dynamics

During operations the power transformers are exposed to strong external factors and abnormal modes caused by the power system, such as:

- voltage surges and lightning discharges caused with commutations which can result in insulation winding damages;
- operating voltage increases due to the uncompensated capacitive power generated by high-voltage lines at the minimum load conditions (which rises magnetising current in the transformers and causes increased core heating);
- short-circuit current, which creates a mechanical shock in windings;
- faults in temperature regime that cause aging of insulation and damages of sealed high-voltage bushings[4,23].

Transformer technical condition diagnostics

According to the power transformer operating requirements the following operating parameters shall be monitored: currents, voltages and their compliance with the permissible values. Deviations from these values are to be continuously monitored by the relay protection, including gas relays. Monitoring of size and duration of power surges and over currents and, depending on the transformer requirements, surveys are carried out. Temperature measurements are also made at various points of the transformer, the oil level is taken in the conservator and inspections are performed on a regular basis to detect defects and damage by external features. None of these types of monitoring allow qualitative evaluation of the transformer condition.

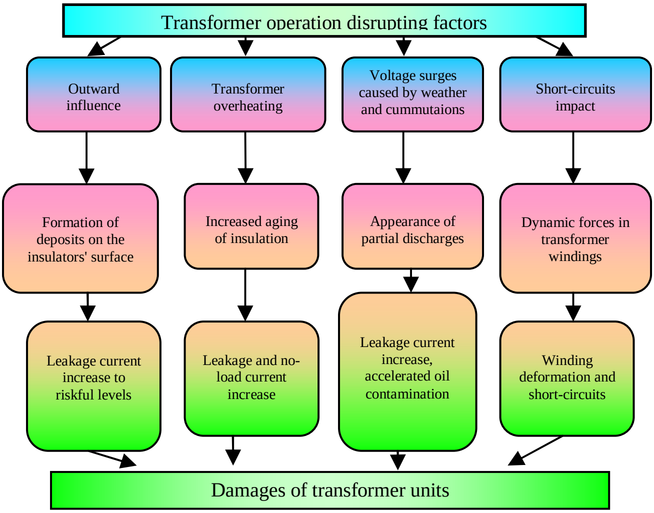

Fig. 2.2. Development of possible defects of the transformers

To perform high-level evaluation of condition can be achieved through the transformer diagnostics. Full diagnostics is carried out to a disconnected from the circuit transformer at the first stage and to the transformer under operating voltage at the second stage. The methods of diagnostics used to detect the above-mentioned defects are displayed in Figure 2.3.

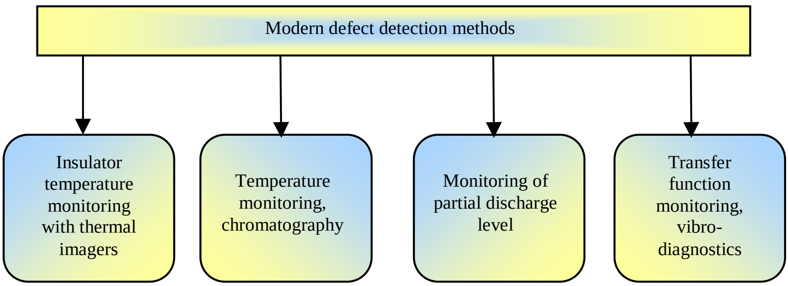

Fig. 2.3. Possible defect detection methods

When disconnected, the transformer is available for an in-depth inspection. In some cases it could be fully or partly disassembled. Transformer is surveyed during the overhaul, according to the schedule, or when the planned time of operations exceeds the prescripted limits.

In the case that maintenance is performed depending on the technical condition of the equipment, the transformer is inspection during operation using periodic or continuous monitoring methods. Inspection is carried also after emergency shutdowns of transformers. The inspection results make it possible to carry out

repairs in a timely manner in order to avoid accidental emergencies. The transformer inspection might also be carried out to find out the possibilities to upgrade the transformer for the purpose of reducing losses, increasing workload, etc. It might be necessary to increase a transformer's workload because the mains transformers are often underloaded and are able of more intense service.
Estimation of the transformer condition on the basis of the acquired data analysis is a very complex task that requires deep knowledge of the processes that are going on in transformers, experience in the diagnosis, and even some intuitive understanding during analysis of the measurement data. This stage of diagnostics is one of the hardest challenges. Even in relatively simple cases operating expertise sometimes appears to be insufficient to detect the equipment condition. In such cases, the rapidly developing equipment condition evaluation expert systems can be useful. The expert system's construction is shown in Figure 2.4.

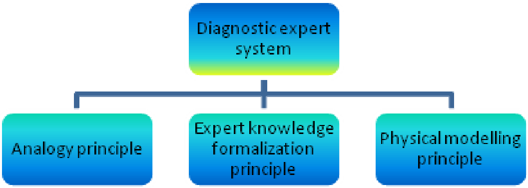

Fig. 2.4. Key principle of expert system's construction

The principle of analogy based on similarity of reference parameters in development of similar defects. Expert knowledge formalisation principle applies diagnosis algorithms developed by expert diagnosticians. Physical modelling principle is based on making of a machine model of the processes going on in the equipment and calculation of its basic reference parameters. More advanced systems make use of all three principles at the same time [1,4,23].

Key directions for improvement of the technical level and quality of a transformer

Transformer development and production takes place in the countries with highly developed electrical industry including the countries that produce materials for the manufacture of transformers. Integration of the world's countries today makes it possible to use the greatest achievements in both material development and manufacturing sector. Today, transformer manufacturers in these countries are developing new types of transformers that appear on the world's markets and are being recognized as the best quality products.
The directions of power transformers development are related to improvement of their performance standards. The directions determining the performance standards and quality improvement are the following:

- improvement of performance characteristics;
- power loss reductions;
- safety improvement;
- reduction of installation and operational costs.

3. BASIC PROVISIONS OF METHODS FOR SELECTION OF TECHNICAL MEASURES

Possible manipulations with transformers within the base

Analysis of time of operation of substations and transformers performed in Chapter 1.3 highlights some serious problems associated with massive aging of power transformer in Latvia. 66% of the transformers are at the end of the normative period (currently it is 25 years). Radical solution for refreshment of the transformer base 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 base refreshment and extending the transformers' physical resources beyond the normative lifetime 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 base upgrade measures should ensure maintained or risen capacity of the transformers at substations, in order to guarantee reliability of the power supply to consumers.

Along with the development of power system there are qualitative and quantitative changes taking place within transformer base[2,3,5,6,8,9,12]. Within the Latvian power transformer base the following activities with the power transformers could be undertaken (see Figure 3.1):

- purchasing of new transformers;
- repair and upgrade of the existing transformers;
- installation of new transformers at new substations;
- replacement of old transformers with new or renovated and upgraded ones at existing substations;
- installing additional new or repaired and upgraded transformers at substations during substations reconstruction;
- storage of the transformers temporarily withdrawn from exploitation in the reserve base;
- sale of transformers at a liquid price or their disposal.

Due to constant development of the energy system the changes in the transformer base must continue. To ensure rational utilisation of funds targeted to all the transformer capacity-building technical measures, reconstruction and upgrade thereof, the mentioned measures must be technically efficient and economically justified. Within this thesis a methods aimed at creating a theoretical and mathematical basis for the selection of technical measures by energy companies was developed.

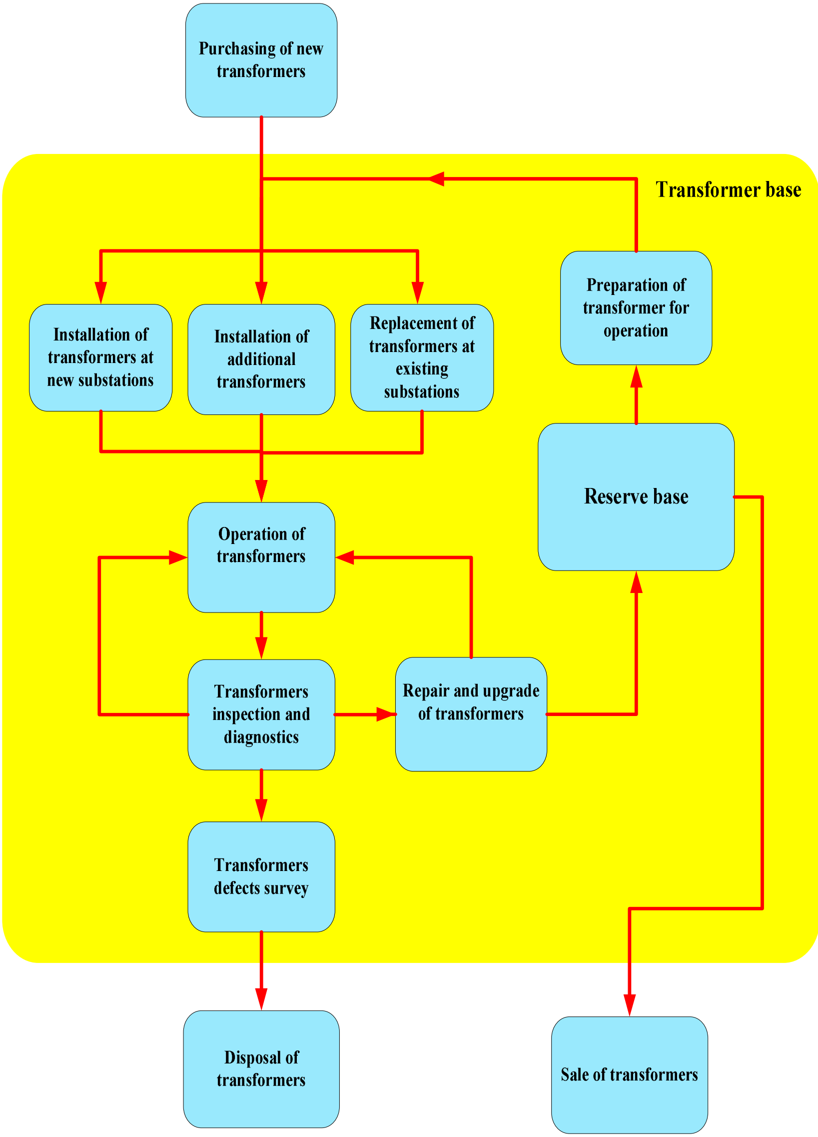

Fig.3.1. Possible manipulations with transformers within the base

General decision making procedure

As carrying out analysis of the technical condition of one or several transformers at one or more sites a number of technical measures providing for equipment upgrade or replacement could be set out in order to select the optimum solution. Decision-making procedure can generally be represented as follows.

Decision making is a choice of one solution option E_n from a variety of possible options E_m, i.e., $E_n \in E_m$. Each solution option E_n uniquely has some outcome e_n, which is a quantitative assessment, i.e., $E_n \Leftrightarrow e_n$.

According to the classical decision-making theory at the choice of an optimum alternative E_o to increase the reliability of the transformer equipment functionality can be ensured by such procedure:

$$E_o = \left\{ E_{no} \middle| \; E_n \in E_m \wedge e_{no} = opt\; e_n \right\} \quad , \tag{3.1}$$

i.e., the set of optimum alternatives of solution consists of the options E_{no}, which belong to the set of all variants E_m and their estimation e_{no} is optimum (minimum or maximum) among all estimations e_n.

The quantitative assessment e_n may take into account different conditions of the task, level of the available information, factor of risk, influence of the accepted solution upon different aspects of the activity etc., i.e., $e \in \{ e_n \}$. According to the requirements of task it is necessary to select the appropriate objective function

$$e_n = \underset{j}{oper} \; \{e_n\} \, , \tag{3.2}$$

which will be the most correct to mirror accepted solution in concrete conditions of development, reconstruction and upgrade of transformer base[7].

Structure of the technical measures selection methods

Developed methodology is divided into three main modules each meant for a relevant solution. The main tasks of each module are presented in Figure 3.2.

Module 1 – analysis of the condition of the transformer base 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 2 – 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. Detailed description of the diagnostic methods is presented in Chapter 2.3.

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 3.3.

Module 3 – 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 3.2). 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.

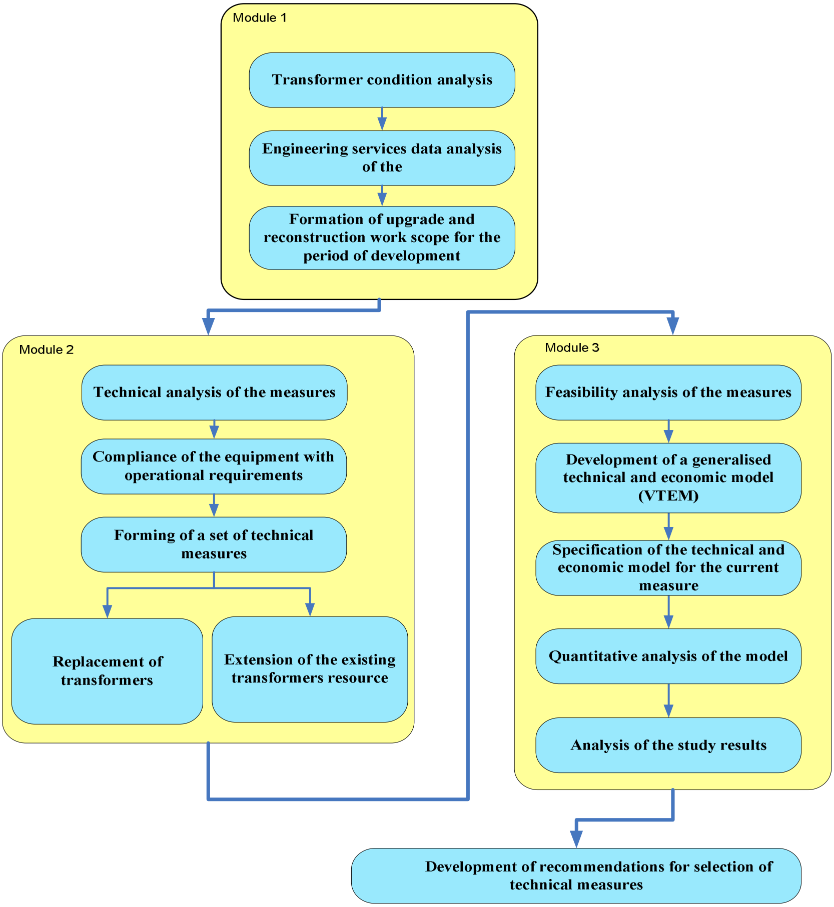

Fig. 3.2. Structure of the technical measures selection methods

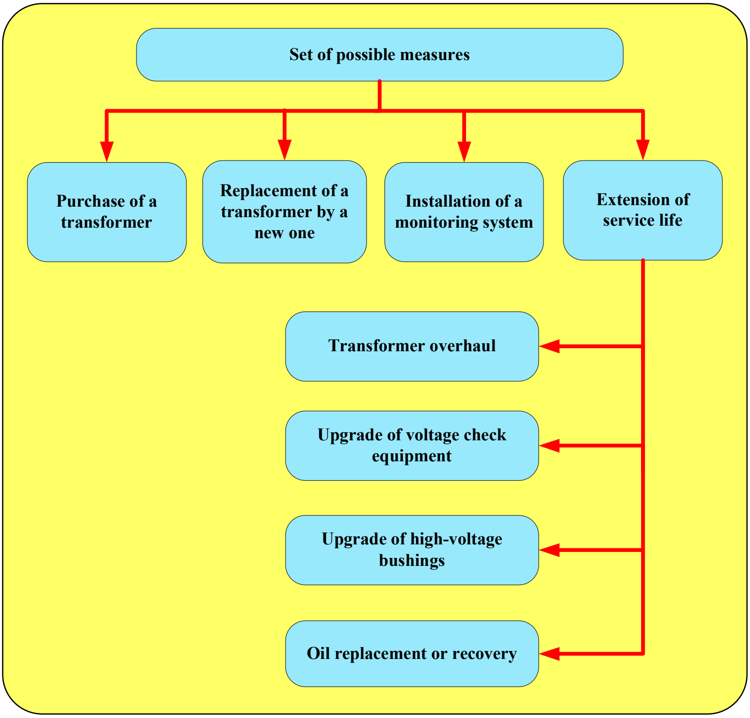

Fig.3.3. Technical measures aimed at increasing a transformer operational reliability

Technical analysis of the specific measures mentioned in Figure 3.3 is performed in Chapter 4 and 5.

Methods of economic analysis of technical measures to increase transformer operational reliability

Unit 3 in Figure 3.2 displays the main phases of the economic analysis of the possible technical measures. For realization of these phases the technical and economic 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. 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 Thesis the method of total discounted annual costs is applied.

Generalised technical and economic model of 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 modern 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 increase 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) (see Figure 3.3) aimed at ensuring qualitative assessment of feasibility of the measures and quantitative assessment of an appropriate objective function have been developed within this Thesis. Appropriate objective functions are based on the Net Present Value (*NPV*) of the transformer user's total discounted annual costs through the entire estimated period (the equipment life cycle) [15,17,21,22].

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 uniform generalized technical and economic model. For quantitative evaluation of the technical measures intended to achieve the purposes displayed in Unit 3 at Figure 3.2 the following objective function has been developed on the basis of NPV_n:

$$NPV_n = \sum_{t=0}^{T} C_{nT,t} \cdot \frac{1}{(1+i_d)^t} = C_{n0} + \sum_{t=1}^{T} C_{nT,t} \cdot d_t \quad , \tag{3.8}$$

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

Total annual costs of the operator of the transformer $C_{nT,t}$ of the *t-th* year for realization of measure n in expression (3.8) include several components:

$$C_{nT,t} = C_{nK,t} + C_{nOp.c,t} + C_{nOp.v,t} + C_{nR} \quad , \tag{3.9}$$

in addition:

$$C_{nK,t} = \frac{i}{100} \cdot K_{nT\Sigma,t};$$ (3.10)

$$C_{nOp.c,t} = \frac{p_{na} + k_{r,t}\, p_{nr}}{100} \cdot K_{nT\Sigma,t};$$

$$C_{nOp.v,t} = k_{E,t}\,(\Delta P_{nnl} \cdot T_d + \beta_T^2 \cdot \Delta P_{nsc} \cdot \tau) \cdot \beta' + (\Delta P_{nnl} + \beta_T^2 \cdot \Delta P_{nsc}) \cdot \beta'';$$

$$C_{nR} = c_{nR} \cdot A_n = c_{nR} \cdot \chi_n \cdot A_{n,\max} \quad ,$$

where $C_{nK,t}$ - 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); $C_{nOp.c,t}$ - constant operating costs on amortization, maintenance and repair, including corresponding percentage p_{na} and p_{nr}; $C_{nOp.v,t}$ - variable costs for compensation of losses of the electric power in the transformer; $\Delta P_{n\,nl}$, $\Delta P_{n\,sc}$ – no-load and short-circuit losses of the transformer; T_d - the utilization time of the transformer per year; τ - the utilization time of maximum losses per year time of the maximal losses; β_T – expected loading factor of the transformer; β' - the cost of 1 kWh losses of the electric power; β'' - the cost of 1 kW capacity during the maximal load of power supply system; C_{nR} - loss related to the electricity undelivered to the consumers*;* c_{nR} - probable losses for a consumer because of power shortage; A_n - quantity of undelivered power per year; χ_n - probable duration of emergency switching-off of the transformer per year; $A_{n,\max}$ - maximum transferable power through the transformer per year.

Weighted average rate of return on capital *i*:

$$i = i_p \frac{K_p}{K_p + K_{kr}} + i_{kr} \frac{K_{kr}}{K_p + K_{kr}} \,,$$ (3.11)

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

Regarding the above mentioned and the total annual cost of components, the generalized objective function shall be as follows:

$$NPV_n = C_{n\,0} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \sum\limits_{j=1}^{m} \left[\begin{array}{l} \left(\dfrac{i}{100} \cdot K_{n\,T\Sigma,\,t\,j} \right) + \\ + \left(\dfrac{1}{100} \cdot (p_{n\,a} + k_{nr,t}\, p_{n\,r}) \cdot K_{n\,T\Sigma,\,t\,j} \right) \end{array} \right] + \\ + k_{E,t} \cdot \left[\begin{array}{l} \left(\Delta P_{n\,n\,l} \cdot T_d + \beta_T^2 \cdot \Delta P_{n\,sc} \cdot \tau \right) \cdot \beta' + \\ + \left(\Delta P_{n\,n\,l} + \beta_T^2 \cdot \Delta P_{n\,sc} \right) \cdot \beta'' \end{array} \right] + k_{E,t} \cdot k_{nr,t} \cdot C_{nR} \end{array} \right\} \cdot \frac{1}{(1 + i_d)^t} \,,$$ (3.12)

where j – current investment in realization of a measure, moreover $j = 1, ..., m$; $k_{nr,t}$ - 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 got by approximation of statistical data and taking into account the energy loss value increase in recent years and b=0,03; $k_{E,0}$ – initial costs of the energy loss of the calculated period.

Factor $k_{nr,t}$ is a time function too. It is got by approximation of statistical data and taking into account the transformer operating expenses increase due to aging and the growing risk of failure during operation (according to the functional dependency in Figure 2.1). Factor $k_{nr,t}$ is determined for two time intervals: for the first interval, 0…25 years of operation, – $k_{nr,t}(t) = 1+bt$, where $b = 0{,}02$; for the second interval, 25...40 years of operation, – $k_{nr,t}(t) = at^2+bt+c$, where $a=0.01$, $b=0{,}02$, $c=1{,}3$.

Minimum total discounted annual costs (3.12) (*min* NPV_n) under the calculated period (*min* NPV_n) are the optimum measure selection criterion, disregarding of the income from sales of production (electricity), in case that these are identical in all options. In this event, the costs are assumed with the "+" sign.

The TEM (3.12) does not take into consideration the income from the sale of electricity and power supply services, considering that they are the same for all options. Expected income can be calculated using the formula:

$$I_n = \sum_{t=1}^{T} \left[\beta_E \cdot P_T \cdot \beta_T \cdot T_m + \beta_R \cdot P_T \cdot (1-\beta_T) \right] \cdot k_{E,t} \cdot k_p \ , \tag{3.13}$$

where I – total annual income from the sale of electricity and power supply services; P_T – transformer active rated capacity; T_m – the utilization time of the power system per year; β_E –transmission tariff for 1kWh of electricity; β_R – cost of reserve capacity in power system; k_p - income ratio showing the proportion of the income after all tax payments.

When income is introduced the event selection criterion is changing for the objective function. Now, the maximum total discounted annual costs (max NPV_n) for the calculated period is the criterion for selection of the optimum measure. In addition, assessment of the measures based on the payback period criterion taking income into account is available. 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.

The maximum total discounted costs (3.14) under the calculated period (*max* NPV_n) are the optimum measure selection criterion, subject to the income from sales of production (electricity). In this case, expenditures are assumed with the "-" sign, and income with the "+" sign.

Combining the costs and income in one formula we obtain:

$$NPV_n = -C_{n0} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \left[P_T \cdot \beta_T \cdot \beta_E \cdot T_m + P_T \cdot (1-\beta_T) \cdot \beta_R\right] \cdot k_{E,t} \cdot k_p - \\ -\left[\frac{i}{100} \cdot K_{n\,T\Sigma,tj} + \frac{1}{100} \cdot (p_{na} + k_{nr,t}\, p_{n\,r}) \cdot K_{n\,T\Sigma,\,t\,j}\right] - \\ -k_{E,t} \cdot \left[\begin{array}{l} \left(\Delta P_{n\,n\,l} \cdot T_d + \beta_T^2 \cdot \Delta P_{n\,sc} \cdot \tau\right) \cdot \beta^{/} + \\ +\left(\Delta P_{n\,n\,l} + \beta_T^2 \cdot \Delta P_{n\,sc}\right) \cdot \beta^{//} \end{array}\right] - k_{E,t}\, k_{nr,t} \cdot C_{nR} \end{array} \right\} \cdot \frac{1}{\left(1+i_d\right)^t}, \tag{3.14}$$

The algorithm for evaluation of the technical measures feasibility is shown in Figure 3.4. The algorithm is implemented by a calculation program in Excel environment. The economic analysis of the specific measures is carried out in Chapter 4 and 5.

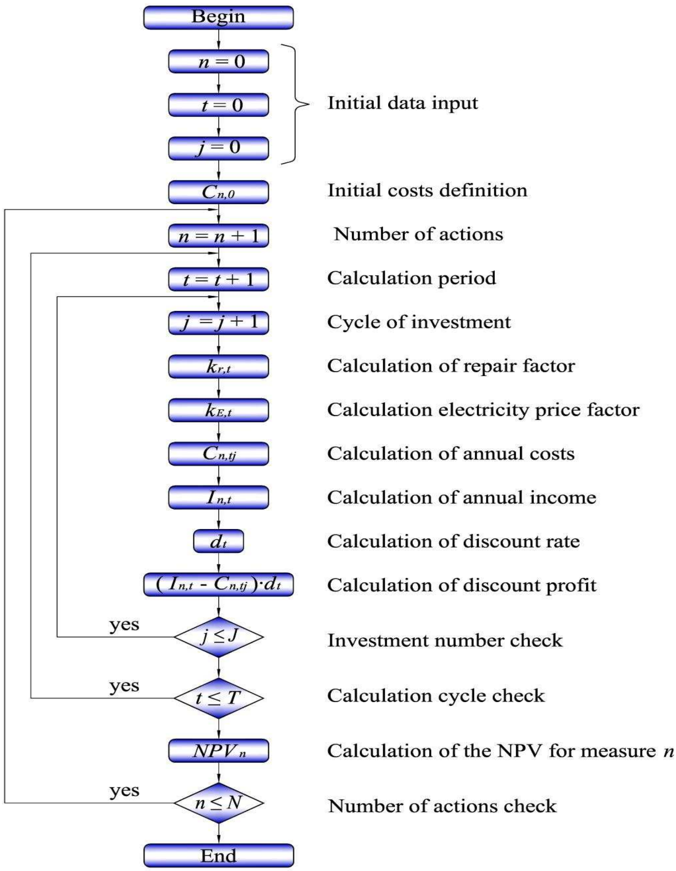

Fig. 3.4. Algorithm of technical measures feasibility evaluation

4. PURCHASING AND REPLACEMENT OF TRANSFORMERS

Comparison of technical data of the modern transformers installed in Latvia

As the power system develops constantly, the measures aimed at maintenance of operational reliability and improvement of technical condition of transformer base shall be planned. Some of these measures are related to purchasing of new transformers.

When purchasing a new transformer it should be ensured that the transformer has improved performance data. Leading transformer manufacturers make use of similar technological processes, therefore technical characteristics of the transformers do not differ much. The most important data should be taken into account when selecting a new transformer are no-load losses, short circuit (load) losses, short-circuit voltage, idle current, noise level, weight, oil volume and others.

There are different companies operating in Latvia that are transformer equipment manufacturers' representatives. Further a comparison of the technical data and parameters of the equipment supplied by the above-mentioned companies is given. No-load and load losses determine the aggregate losses of power in the transformer. These are calculated as follows:

$$\Delta P_T = \Delta P_{nl} + \left(\frac{S_T}{S_{nom}}\right)^2 \cdot \Delta P_{sc} = \Delta P_{nl} + \beta^2 \cdot \Delta P_{sc}, \qquad (4.1.)$$

where S_T, S_{nom} – demand and rated load of the transformer; β – transformer loading factor; ΔP_{nl} , ΔP_{sc} – transformer no-load and short-circuit losses.

The aggregates power losses at different loads of the transformers offered by the major Latvian suppliers are shown in Figure 4.1- 4.3.

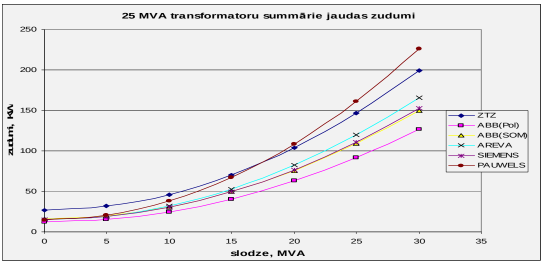

Fig.4.1. Aggregate power loss of the 25 MVA transformers

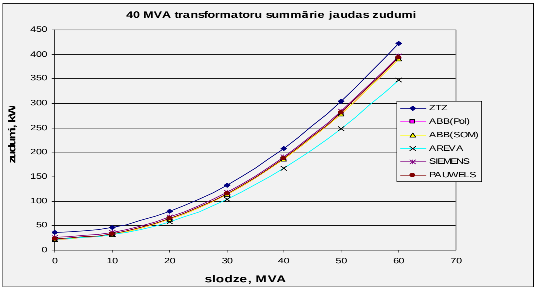

Fig.4.2. Aggregate power loss of the 40 MVA transformers

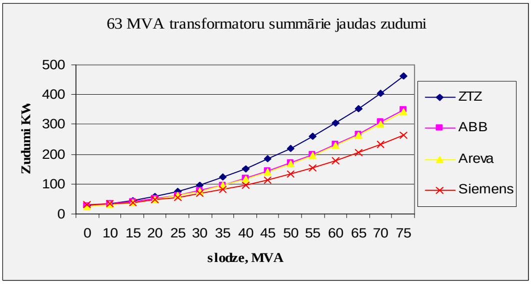

Fig. 4.3. Aggregate power loss of the 63 MVA transformers

Practical calculations for evaluation of the measure involving purchasing of a new transformer

Technical analysis of the measure

Transformer base renewal in Latvia (see statistical data in 3.1) is carried out by replacing the old transformers by the new and modern ones, which has to be done also in the future. Purchasing of transformers for new and existing facilities is performed through a tendering procedure [13,15,16,20,22]. Before the start of the bidding, the site owner identifies engineering requirements for the equipment. Usually technical requirements include preferred equipment specifications and dimensions. It should be noted that nowadays transformers are manufactured on a by-order basis. At the last stage of the tendering procedure the customer has to make a decision: which bidder and which offer are the best. Selection of the optimum option for purchasing of a power transformer is being viewed as tender award to one of the different transformer supplier or manufacturer companies. Firstly, all the applicants should meet the technical requirements set out by the customer. However, if the technical data of different transformer versions are compared only, it would be difficult to give priority to some applicant because the technical data are different for each supplier. Selection of the transformer supplier also depends on:

- social and political relationship with the supplier's country, factory or business reputation etc.;
- product data – quality of manufacture, number of failures, service life, opportunities to renovate or replace separate units, capacity and power losses and other data;
- economic data – current price of the equipment, spare parts, expected operating expenses, etc.

During technical analysis of the bidders' offers (as noted in Fig. 3.2, Unit 2), some options may be eliminated. The remaining options, which meet all the technical requirements, are to be subject to economic analysis (as noted in Fig. 3.2 Unit 3).

Economic analysis of the measure

The technical and economic model (TEM1) of a measure involving purchase of a transformer, n = 1, can be obtained from a generalized economic model VTEM and appropriate objective function (3.14) by specifying the individual components and indicators. The corresponding objective function NPV_1 for this measure is based on the total discounted annual costs of the purchase of the transformer and its further operation throughout the lifetime.

Total discounted annual costs NPV_1 of the measure involving buying a transformer, n = 1, considering certain cost components, can be represented as follows:

$$NPV_1 = -C_{10} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \left[P_{nom} \cdot \beta_T \cdot \beta_E \cdot T_m + P_{nom} \cdot (1-\beta_T) \cdot \beta_R\right] \cdot k_p - \\ -\left[\frac{i}{100} \cdot K_{1\,T\Sigma,\,t} + \frac{1}{100} \cdot (p_{1a} + k_{1r,t}\, p_{1r}) \cdot K_{1\,T\Sigma,\,t}\right] - \\ -k_{E,t} \cdot \left[\begin{array}{l} \left(\Delta P_{1\,nl} \cdot T_d + \beta_T^2 \cdot \Delta P_{1\,sc} \cdot \tau\right) \cdot \beta^{/} + \\ \quad + \left(\Delta P_{1\,nl} + \beta_T^2 \cdot \Delta P_{1\,sc}\right) \cdot \beta^{//} - k_{E,t} \cdot k_{1r,t} \cdot C_{1R} \end{array} \right] \end{array} \right\} \cdot \frac{1}{(1+i_d)^t}, \tag{4.2}$$

where C_{10} – costs of the measure involving purchase of a new transformer at the beginning of the calculated period t=0, which are equal to the total capital investment $K_{1T\Sigma}$, i.e., $C_{10} = K_{1T\Sigma}$; $K_{1T\Sigma,\,t}$ – total capitals investment in the measure n=1 under the calculated year t; p_{1a} , p_{1r} - percentage deductions for depreciation, repair and maintenance; $\Delta P_{1\,nl}$, $\Delta P_{1\,sc}$ – no-load and short-circuit losses of the transformer; C_{1R} – eventual loss related to the electricity undelivered to the consumers for measure n=1[21].

Total capital investment $K_{1T\Sigma}$, in the purchase of a transformer include several components, e.g.: cost of the transformer K_T; shipment costs from the manufacturer to the installation site K_{tr}; new transformer installation costs K_i; spare parts costs K_{sp} (to ensure operation during a 5-year period upon purchasing); custom fees for the manufacturer's products K_{cd}; overhead expenses K_{add} (e.g. acceptance test costs, etc.), i.e.,

$$K_{1T\Sigma} = K_T + K_{tr} + K_i + K_{sp} + K_{cd} + K_{add} \quad . \tag{4.3}$$

The maximum total discounted annual costs (*max* NPV_1) to be covered by the power transformer operator through the whole operating cycle of the transformer *T* is the main criterion for the tender award and the optimum solution of the set problem.
Using the optimality criterion $NPV_1 = max$ for the objective function (4.2) an assessment for the purchase of 110 kV 63, 40, 32, 25, 16 MVA transformers from various manufacturers and suppliers has been made.
An example of practical calculation for objective function NPV_1 for the purchase of new 110 kV, 63 MVA transformers is shown in Figure 4.2. Calculations are made according to (4.2) 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.

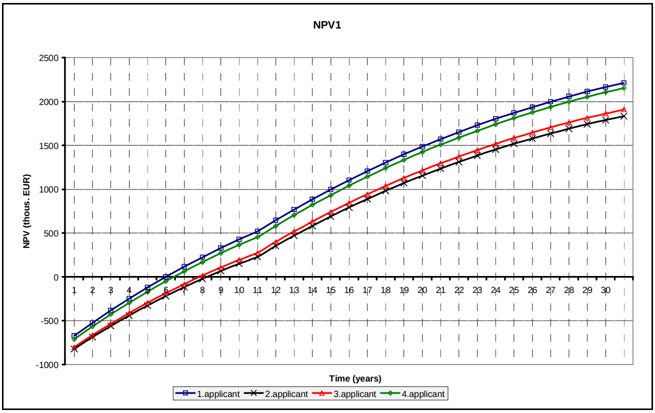

Fig.4.2. Practical implementation of calculations for measure n=1

Having analysed the results 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 supplier who offered the first option.

Technical measure involving replacement of out-of-date transformers

There can be several reasons for the need to replace the existing power transformers by new ones having improved technical data (lower idle and short-circuit losses, lower steel weight, etc.). These could be the need to change the physically worn or outdated equipment, breakdowns due to emergencies with no possibility to restore availability of the transformer, inadequacy to consumer demand, etc. The replacement measure encompasses such components as purchasing, delivery and installation of a new transformer, dismantling and sale of the old transformer. By comparing the technical parameters only it is difficult to choose which manufacturer shall be selected, for the technical data varies from manufacturer to manufacturer quite significantly. Optimum total discounted annual costs NPV_n for the purchase of the transformer make up a part of the overall measure activities.

Unlike the previously considered measure n=1, additional income is introduced in the formula (4.2) – the liquid value of the old transformer K_{likv} and dismantling costs K_d. Assuming the liquid value equivalent to the old transformer dismantling costs the function does not differ fundamentally from the function (4.2) for the purchase of a transformer. The maximum total annual discounted costs (*max* NPV_2) through the calculated period are the optimum solution of the set problem [20].

5. REPAIR AND UPGRADE OF THE TRANSFORMERS

Extension of a transformer's service life beyond the normative term

The peak of high-voltage transformer building according to historical development has fallen in the 50th-60th and 80th years of the past century. Therefore a large number of the transformers have been working beyond their normative service life already. The simultaneous replacement of such a large number of transformers requires massive investments and is difficult from the technical and economic point of view. This problem might be solved by extending the service life of the existing transformers upon their diagnostic tests, carrying out defect prevention, upgrades and repairs. A significant proportion of the transformers' failures is related with their accessory equipment.

Further 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 (TEM) and appropriate objective functions created for the specific measures on the basis of the generalized objective function (3.12) or (3.14) are used.

If the measures are intended to extend the useful life of transformers, the appropriate objective function calculated period begins from the end of the transformer's normative term t_{norm} and this year is accepted as $t=t'=0$. The calculated period for the beyond-normative time (the prolongation period) is $t'_{pag} = T_{vnorm}$ = 15 – 20 years (see Figure 5.1).

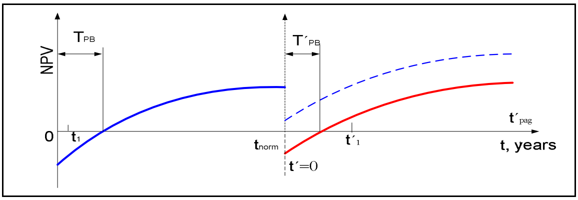

Fig. 5.1. Assumption of calculated period for different measures

Further technical analysis and economic evaluation of the measure involving extension of a transformer's service life is done [1].

Objective function components and coefficients or specific technical measures are shown in Table 5.1

Table 5.1.

Objective function components and coefficients for specific technical measures

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

Technical analysis and economic evaluation of the measure involving transformer overhaul repair

Power transformer is one of the key elements of a power system that determines reliability of power supply. A failure of base and large transformer can lead to accidents with large-scale consequences in the power system. To maintain the power supply reliability it is necessary to ensure proper operation of the transformer. It is also important to eliminate the defects that can result in the transformer failures in a timely manner. Speaking of the work scope maintenance and overhaul repair is distinguished. Maintenance repair of a substation's main power transformers are carried out once a year. Overhaul repairs are scheduled as necessary, taking into account the results of the diagnostics and inspection. As regards the volume of work current (operational) and overhaul repair are distinguished. Overhaul repair may include replacement of winding without repair of the core and replacement of winding with partial or full repair of magnetic system. Any repair related to the oil tank opening is to be considered as an overhaul.

Transformer overhaul requires relatively large funds. In order to evaluate the measure on the basis on the VTEM a feasibility model TEM3 and appropriate objective function NPV_3 were obtained. For the NPV_3 objective function individual component were specified in (3.14). For extension of the transformer life time t' has been introduced into the function, moreover, the time t' starts at the end the transformer's normative life and varies between $t'=0$ to $t'=t'_{pag}$. The objective function NPV_3 for evaluation of the measure n=3 involving transformer overhaul is as follows:

$$NPV_3=-C_{3\,0}+\sum_{t'=0}^{t'_{pag}}\left\{\begin{array}{l}\left[P_{nom}\cdot\beta_T\cdot\beta_E\cdot T_m+P_T\cdot(1-\beta_T)\cdot\beta_R\right]\cdot k_p\cdot k_{E,t}-\\ -\left[\frac{i}{100}\cdot K_{3\,T\Sigma,t'}+\frac{1}{100}\cdot(p_{3a}+k_{3r,t}\,p_{3r})\cdot K_{3\,T\Sigma,t'}\right]-\\ -k_{E,t}\cdot\left[\begin{array}{l}\left(\Delta P_{3\,nl}\cdot T_d+\beta_T^2\cdot\Delta P_{3\,sc}\cdot\tau\right)\cdot\beta'+\\ +\left(\Delta P_{3\,nl}+\beta_T^2\cdot\Delta P_{3\,sc}\right)\cdot\beta''\end{array}\right]-k_{E,t}\cdot k_{3r,t}C_{3R}\end{array}\right\}\cdot\frac{1}{(1+i_d)^{t'}},\qquad(5.1)$$

where C_{30} is equal to total capital investment $K_{3T\Sigma}$ in the transformer overhaul; $k_{3r,t}=at'^2+bt'+c$, un $a=0{,}01$, $b=0{,}02$, $c=1{,}3$; $k_{E,t}=1+bt'$ un $b=0{,}02$. In case that the requirement $NPV_3\leq NPV_2$ is met, the measure n=3 involving overhaul repair should be considered as feasible. The measure involving the overhaul of 110 kV 32 MVA transformer was supplied with the calculation for three repair cost options: 80%, 65%, 50% of the cost of new transformer and for replacement of the transformer at the year 15 of the transformer's extended life. The calculations were made based on the NPV_3 formula (5.1). For one repair option with the price amounting to 65% of the cost of new transformer the calculation according to the formula (5.1) was made for the whole calculated period from $t'=0$ to T' and without replacement of the transformer. For comparison objective function NPV_2 for replacement of out-of-date transformer at the beginning of the calculated period $t'=0$ and its further operation until the end of the calculation term T' was evaluated. The results are compared in Figure 5.2.

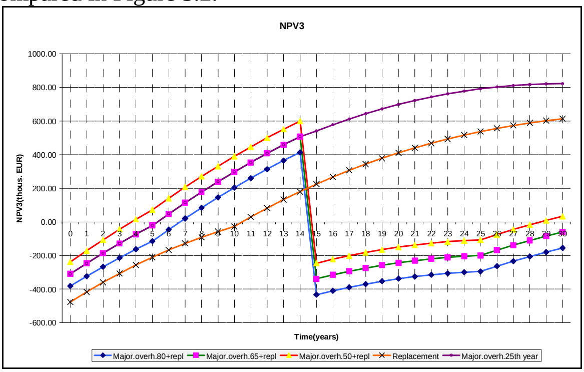

Fig. 5.2. Comparison of the NPV_3 options for the overhaul repair of 110 kV 32 MVA transformer

Overhaul repair during the normative life of the equipment is not effective in the long-term prospective in comparison with total costs for replacement of out-of-date transformer at the beginning of the calculated period $t'=0$ and its further operation.

Technical analysis and economic evaluation of the measure involving replacement of voltage regulation devices

Voltage in powerful power transformers is regulated by changing the number of turns of the primary winding. To this end, switchable winding taps are made. For powerful 110 kV transformers voltage regulating device, which makes it possible to switch the winding taps in the operation mode, is used. A voltage regulation device is one of the most unreliable elements of a power transformer. Approximately 40% of transformer accidents are associated with regulation devices[14]. Transformer breakdown, which is related to a voltage regulation device, may lead to serious consequences requiring repair of the transformer at the factory. For this reason, special attention must be paid to the voltage regulation facilities.

To assess the measures, which include voltage regulation equipment replacement and upgrade, technical and economic model TEM4 with appropriate objective function NPV_4 has been developed on the basis of VTEM. For the NPV_4 objective function individual component were specified in (3.14). Implementation of the measure did not require any bank loan – the funding was provided from the company's own resources. The objective function for evaluation of the measure n=4 involving replacement and upgrade of the voltage regulation device of the transformer is as follows:

$$NPV_4 = -C_{40} + \sum_{t=0}^{t'_{pag}} \left\{ \begin{array}{l} \left[P_{nom} \cdot \beta_T \cdot \beta_E \cdot T_m + P_{nom} \cdot (1-\beta_T) \cdot \beta_R\right] \cdot k_p \cdot k_{E,t} - \\ -\left[\frac{1}{100} \cdot k_{4r,t'} p_{4r} \cdot K_{4\,T\Sigma,\,t'}\right] - \\ -k_{E,t} \cdot \left[\begin{array}{l} \left(\Delta P_{4\,nl} \cdot T_d + \beta_T^2 \cdot \Delta P_{4\,sc} \cdot \tau\right) \cdot \beta' + \\ + \left(\Delta P_{4\,nl} + \beta_T^2 \cdot \Delta P_{4\,sc}\right) \cdot \beta'' \end{array}\right] - k_{E,t} \cdot k_{4r,t'} \cdot C_{4R} \end{array} \right\} \cdot \frac{1}{(1+i_d)^{t'}} + NPV_2 \,, \quad (5.2)$$

For the objective function NPV_4 calculations are made for replacement and upgrade of 110 kV 32 MVA transformer's voltage regulation device. There are three options discussed for measure n=4, which include replacement and upgrade of the voltage regulation devices upon reaching the end of the normative life of the transformer (t=t_{norm} or t'=0) and subsequent replacement of the transformer with a new one at the year 5, 10, or 15 of the transformer's extended life. In all the three options no bank loan was necessary for purchasing a new transformer. Funding is provided from the savings made during the extended period of operation of the equipment. For comparison, replacement of an old transformer with a new one at the beginning of the calculated period t'=0 was evaluated. Calculations were made using the formula (5.2). Replacement of the voltage regulation devices will take place at the end of the transformer's normative life. The chart also shows the measure NPV_2 to facilitate the comparison of the options. Comparison of the results is shown in Figure 5.2.

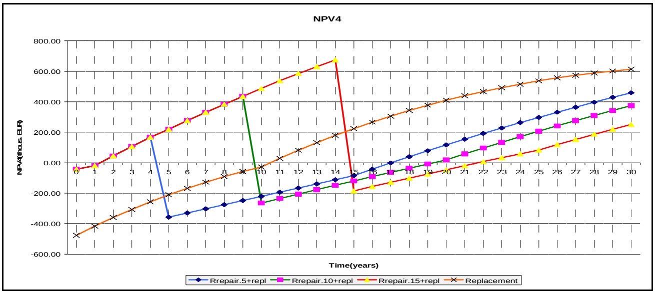

Fig. 5.3. Comparison of the NPV_4 options involving upgrade of 110 kV 32 MVA transformer's voltage regulation devices

Having analysed the results we can conclude:

- replacement of a transformer upon reaching the end of the normative service life ($t=t_{norm}$ or $t'=0$) is feasible due to higher reliability of the new transformer;
- replacement of voltage regulation devices has short-term economic effect at the beginning of the extended life of the transformer, until it is replaced by a new one;
- replacement of a transformer with a new one should be carried out in the early years of its extended service life, even if the voltage regulation devices have been replaced, because later the transformer price is going to increase due to inflation.

Technical analysis and economic evaluation of the measure involving upgrade of a transformer's high-voltage bushings

High-voltage bushings are considered to be the most unsafe units of a transformer.

Faults in high-voltage bushings may bring about severe effects: explosions, fires, oil leakage from the transformer, damage of the transformer windings. Most bushings operated in Latvia are manufactured at the Moscow factory "Mosizolator." There are constructive modifications in the new, upgraded GTT, GTD, GMTB type bushings and gas-filled bushings, which increases the operational reliability. The upgraded GBMT type bushings have a new type of insulation and the oil in these bushings serves only for cooling therefore no monitoring of electrical parameters is needed. Gas-filled bushings have a number of advantages that are associated with the nature of the insulative gas used in them: fire and explosion safety, ecological purity and no need to change it throughout the lifetime. New bushings can be installed in place of the old-type bushings because the termination point dimensions and the bottom part length have been preserved the same [13,18].

In order to evaluate the measure on the basis on the VTEM a feasibility model TEM5 and appropriate objective function NPV_5 were obtained. For the prospective measure involving replacement and upgrade of bushings two options are available: replacement of bushings before and upon the end of the transformer's service life. Implementation of the measure did not require any bank loan – the funding was provided from the company's own resources.

Option two has been reviewed as a complex measure comprising two simple measures: replacement of bushings in the year $t=t'=0$ in order to extend the transformer's service life and replacement of the old transformer with a new one in the year 5, 10 or 15 of the extended transformer's life. The objective function for the complex measure $n=5$ is as follows:

$$NPV_5 = -C_{50} + \sum_{t'=0}^{t'_{pag}} \left\{ \begin{array}{l} \left[P_{nom} \cdot \beta_T \cdot \beta_E \cdot T_m + P_{nom} \cdot (1-\beta_T) \cdot \beta_R\right] \cdot k_p \cdot k_{E,t} - \\ -\left[\dfrac{1}{100} \cdot (p_{5a} + k_{5r,t'} p_{5r}) \cdot K_{5T\Sigma,t}\right] - \\ -k_{E,t} \cdot \left[\begin{array}{c} \left(\Delta P_{5nl} \cdot T_d + \beta_T^2 \cdot \Delta P_{5sc} \cdot \tau\right) \cdot \beta' + \\ +\left(\Delta P_{5nl} + \beta_T^2 \cdot \Delta P_{5sc}\right) \cdot \beta'' \end{array}\right] - k_{E,t} \cdot k_{5r,t'} \cdot C_{5R} \end{array} \right\} \cdot \frac{1}{(1+i_d)^{t'}} + NPV_2, \tag{5.3}$$

For the objective function NPV_5 the calculation for three options were done: replacement and upgrade of high-voltage bushings of out-of-date 32 MVA capacity transformer at the end of the transformer's normative life ($t=t_{norm}$ or $t'=0$) and further replacement of the transformer in the year 5, 10 and 15 of the extended life. For none of the three options for the purchase of new transformer a bank loan is needed. Funding is provided from the savings made during the extended period of operation of the equipment. For comparison objective function for replacement of out-of-date transformer at the beginning of the calculated period t´=0 and its further operation until the end of the calculation term T' was evaluated. The calculations were made using the formula (5.3).

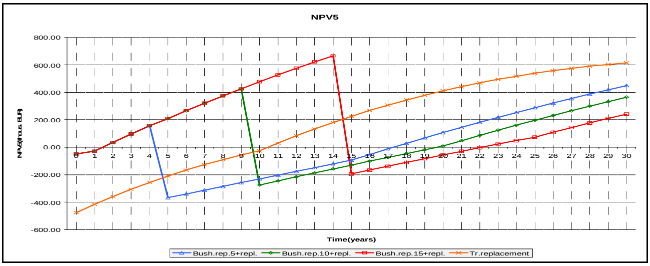

Fig. 5.4. Comparison of the NPV_5 options for replacement of 110 kV 32 MVA transformer's high-voltage bushings

Having analysed the results we can conclude:

- replacement of a transformer at the end of the normative service life ($t=t_{norm}$ or $t'=0$) is feasible due to higher reliability of the new transformer;
- replacement of high-voltage bushings has short-term economic effect at the beginning of the extended life of the transformer, until it is replaced by a new one;
- replacement of a transformer with a new one should be carried out in the early years of its extended service life, even if the high-voltage bushings have been replaced, because later the transformer price is going to increase due to inflation.

Technical analysis and economic evaluation of the measure involving transformer oil recovery or replacement

Relatively large number of defects occurs not only due to deterioration of windings and magnetic core system or accumulation of dirt and moisture on the solid insulation, but also due to accumulation of dirt in oil owing to aging. Key events and factors that significantly affect the operational capacity of the transformer are dampening and aging of the insulation, which largely determine the whole transformer's life span. Water content in insulation impacts seriously electrical insulation strength and durability. Moisture comes into the oil from the ambient air and then diffuses into the solid insulation. As the winding and oil temperature changes, moisture exchange occurs between the oil and paper insulation. Oil contamination and dampening causes electrical strength decrease. Contamination is ingress of different particles, foreign bodies and contaminants into the oil. As the transformer's operation time increases the oil ages. The oil is exposed to temperature, electric field, atmospheric oxygen and the transformer's construction materials. If oil contact with atmospheric air were prevented, a significant reduction in acid formation process in the operating transformer's oil would be achieved. Oil recovery and, especially oil replacement, significantly reduces the moisture content in solid insulation [10].

In order to evaluate the measure on the basis on the VTEM a feasibility model TEM6 and appropriate objective function NPV_6 were obtained For the NPV_6 objective function individual component were specified in (3.14). Implementation of the measure did not require any bank loan – the funding was provided from the company's own resources.

The objective function NPV_6 for evaluation of the measure n=6 involving oil recovery or replacement is as follows:

$$NPV_6 = -C_{60} + \sum_{t'=1}^{t'_{pag}} \left\{ \begin{array}{l} \left[P_{nom}\cdot\beta_T\cdot\beta_E\cdot T_m + P_{nom}\cdot(1-\beta_T)\cdot\beta_R\right]\cdot k_p\cdot k_{E,t} - \\ -\left[\frac{1}{100}\cdot(p_{6a}+k_{6r,t}\,p_{6r})\cdot K_{6\,T\Sigma,\,t'}\right] - \\ -k_{E,t}\cdot\left[\begin{array}{l}\left(\Delta P_{6\,nl}\cdot T_d+\beta_T^2\cdot\Delta P_{6\,sc}\cdot\tau\right)\cdot\beta^{/}+\\ +\left(\Delta P_{6\,nl}+\beta_T^2\cdot\Delta P_{6\,sc}\right)\cdot\beta^{//}\end{array}\right] - k_{E,t}\cdot k_{6r,t'}\cdot C_{6R} \end{array} \right\} \cdot \frac{1}{\left(1+i_d\right)^{t'}} + NPV_2 \qquad (5.4)$$

For the objective function NPV_6 calculation for three options were done: recovery or replacement of the oil of out-of-date 32 MVA capacity transformer at the end of the transformer's normative life (t=t_{norm} or t'=0) and further replacement of the transformer in the year 5, 10 and 15 of the extended life. For none of the three options for the purchase of new transformer a bank loan is needed. Funding is provided from the savings made during the extended period of operation of the equipment. For comparison objective function for replacement of out-of-date transformer at the beginning of the calculated period t′=0 was evaluated. The calculations were made using the formula (5.4). Comparison of the results is shown in Figure 5.5.

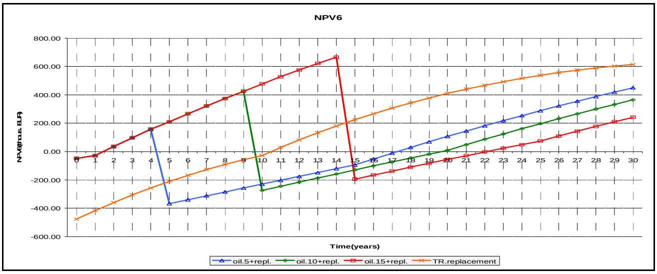

Fig. 5.5. Comparison of the NPV_6 options for 110 kV 32 MVA transformer's oil replacement

Having analysed the results we can conclude:

- replacement of a transformer upon reaching the end of the normative service life ($t=t_{norm}$ or $t'=0$) is feasible;
- replacement or recovery of transformer oil has short-term economic effect at the beginning of the extended life of the transformer, until it is replaced by a new one;
- replacement of a transformer with a new one should be carried out in the early years of its extended service life, even if the transformer oil has been replaced or recovered because later the transformer price is going to increase due to inflation.

Technical analysis and economic evaluation of the monitoring system use

Most effective for transformer accident prevention could be an uninterrupted monitoring system with a set of sensors responding to the maximum number of eventual defects.

Parameter measurement results in such systems are transformed into user-friendly form and stored for analysis and trend detection. Apart from the data obtained from direct measurements the data of the previous operating conditions are entered. Uninterrupted monitoring data forming an online database are used as a basis for diagnosis. Previous measurements of the parameters and information on operation modes allow better evaluation of the transformer condition and predictions making regarding development of processes [4].

The common goal for all the uninterrupted monitoring systems is detection of transformer faults at the early stage. All of the systems ensure parameters and other data processing, analysis and conversion in a way that facilitates usage of the data by the maintenance personnel. Something that is different there are the sensors responding to various faults, as well as methods for detection of unsafe condition of a transformer. If monitoring systems are used it is possible to shift from preventive equipment repairs to repairs depending on the actual condition of the equipment. This measure enables the transformer operator to reduce costs.

In order to evaluate the measure involving installation of a monitoring system an appropriate objective function NPV_7 was obtained:

$$NPV_7 = C_{70} + \sum_{t=1}^{T} \left\{ \begin{array}{l} \sum_{j=1}^{m} \left[\frac{i}{100} \cdot K_{7\,T\Sigma,tj} + \frac{1}{100} \cdot (p_{7\,a} + k_{7r,t} \cdot p_{7\,r}) \cdot K_{7\,T\Sigma,\,t\,j} \right] + \\ + k_{E,t} \cdot \left[\begin{array}{l} \left(\Delta P_{7\,nl} \cdot T_d + \beta_T^2 \cdot \Delta P_{7\,sc} \cdot \tau \right) \cdot \beta' + \\ + \left(\Delta P_{7\,nl} + \beta_T^2 \cdot \Delta P_{7\,sc} \right) \cdot \beta'' \end{array} \right] + k_{E,t}\, k_{7r,t} \cdot C_{7R} \end{array} \right\} \cdot \frac{1}{(1+i_d)^t} \quad (5.5)$$

The optimum of function is $NPV_7 = \min$ for the whole period of calculation, because income from sale of production which is similar for all the options is not taken into account.

For the objective function NPV_7 calculation for three options for procurement of new 110 kV 63 MVA transformer: transformer without a monitoring system, transformer with a monitoring systems, the prices of which make up 5% and 7% of the new transformer's price. The income from production (electricity) sale is not taken into account as it is similar for all the options. Condition $NPV_7 = \min$ is taken as an optimum option. Calculations are made using the formula (5.5). Comparison of the results is shown in Figure 5.6.

Having analysed the results we can conclude:

- increasing the number of parameters to be monitored worsen slightly the economic efficiency.
- usage of monitoring system makes it possible to reduce operating costs and is more cost-effective than the operating of a transformer without a monitoring system.

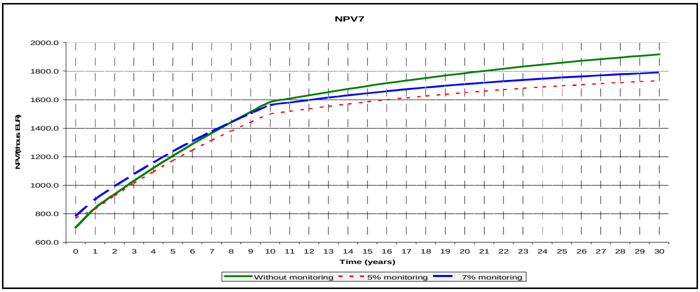

Fig. 5.6. Comparison of the NPV_7 options for purchasing of 110 kV 32 MVA with a monitoring system

Comparison of results for different technical measures

Comparison of the calculation results for different technical measures for 110 kV 32 MVA transformer is shown in Figure 5.7. 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_5 – replacement of high-voltage bushings, NPV_6 – recovery or replacement of insulation oil [2,8].

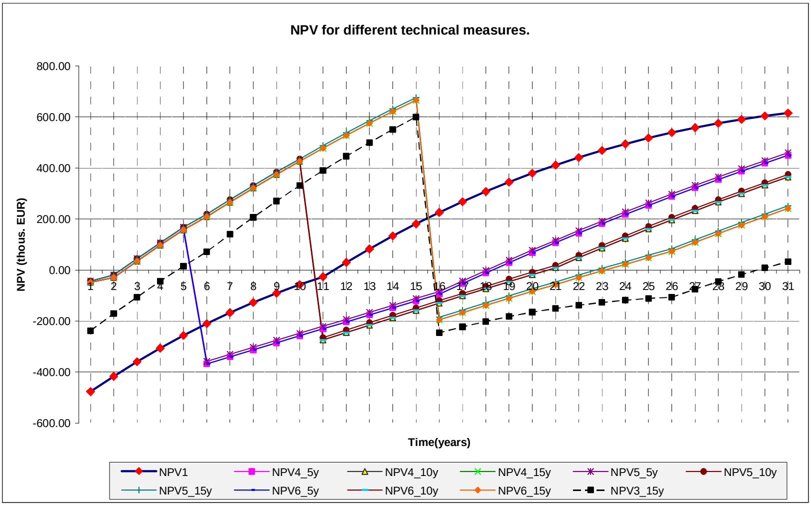

Fig. 5.7. Comparison of different technical measures for 110 kV 32 MVA transformer

Comparison of different technical measures shows that technical measures for prolongation of 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.

GENERAL CONCLUSIONS

1. Analysis of the 110 kV transformer base conditions in Latvia and other countries reveals that there is a clear transformer equipment aging problem.
2. Due to economic situation in Latvia and in the world the energy companies have to focus both on the replacement of out-of-date transformers by new, modern ones and extension of the service life of the existing transformers.
3. Due to the changed operational tasks in the energy systems it is desirable to develop a new operating policy: a transition from the transformer preventive repairs to the repairs depending on the actual condition should be made.
4. A comprehensive methodology for selection of the measures aimed at improvement of the transformer base operational reliability was developed. The methodology includes technical and economic analysis of each measure.
5. The developed generalized technical and mathematical model and specific models for particular 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.

6. For evaluation of the technical measures total discounted annual costs through the whole life cycle of the equipment criterion should be used for implementation of the method with the optimum *NPV* value.
7. A method of tender award for procurement of transformers based on the maximum NPV_1 value (maximum profit) and the minimum payback period.
8. Overhaul repairs during the lifetime of transformer is not effective in the long-term prospective because of deterioration of total economic indicators.
9. Usage of a monitoring system for a transformer is technically and economically effective, for it allows diminishing of the operating costs thanks to transition to the transformers' maintenance procedure which is based on their actual condition.
10. Replacement of separate transformer units for extension of the transformer's service life beyond the normative term is effective in terms of saving invested funds only, but it does not solve the transformer aging problem in its essence.
11. The developed methodology is applicable for evaluation of replacement and upgrade of various electrical equipment.
12. The offered methodology provide a means for a more rational and effective use of the investments in the energy companies.

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