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Replacement of Power Transformers basis on Diagnostic Results and Load Forecasting

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***Abstract*—**This paper describes interconnection between technical and economical making decision. The reason of this dealing could be different: poor technical condition, change of substation (electrical network) regime, power transformer owner budget deficit and increasing of tariff on electricity. Establishing of recommended practice as well as to give general advice and guidance in economical sector, testing, diagnostic power transformers to establish its conditions, identify problems and provide potential remedies.

***Keywords*—**Diagnostic results, load forecasting, power supply system, replacement of power transformer.

I. INTRODUCTION

THE deregulation of wholesale electricity supply has led to a number of changes and new challenges for the global electric utility industry and the market participants. Increased equipment utilization, deferred capital expenditures and reduced maintenance expenses are all part of today’s strategies for transformer owners. The peak of high-voltage transformer building according to historical development has fallen 50th-60th and 80th years of the past century. Naturally today the most part of those transformers is in operation more than 25 years, i.e. the normative resource of transformers (t_{norm}) already is developed and this equipment requires replacement. The problem of increase in lifetime of transformers is very important and topical in many power companies. The simultaneous replacement of such plenty of transformers, which have worked out a normative resource, requires the large investments. The impossibility to provide them in necessary sizes carries on to some changes of the purposes and tasks of maintenance of the transformer equipment. One of tasks becomes a prolongation of real resource of transformers over normative terms (till 35-40 years) through diagnostics, modernization, repair and other measures. Other direction consists in refusal of carrying out periodic scheduled preventive works due to control the state of transformers by monitoring systems.

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Certainly, the decision on prolongation lifetime is accepted for each transformer separately. The solution about the prolongation of transformer resource should be accepted on the basis of careful inspection of a state of the equipment, estimation of aging of isolation, detection and elimination of imperfections. The experience of electrical networks confirms possibility of lifetime prolongation for transformers over normative term. However, it is necessary to note that prolongation lifetime of transformers is a provisional measure and only remove the replacement term [1].

Most power transformer will encounter emergency overloads on occasions, with subsequent loss of life. However, substantial benefits can be obtained by operating power transformer beyond current practices that are based on the name plate ratings. There is an increasing need for electrical utilities to employ transformers to the fullest while maintaining system reliability. Presently the load and the age of the power transformer is increasing and therefore the monitoring and diagnostic of power transformers becomes more and more important, whereby monitoring is the collection of relevant data during service (on-line) or during maintenance or test periods (off-line) and diagnostic the technical evaluation and Interpretation of the recorded data.

The urban power supply system (UPSS) is system of continuous development. The elements of such system are objectives of long-term or medium-term design. To solve the problems of development on such a prospect is not accurate background information and detailed guidelines projected subjects. It means that the challenges of development occur in conditions of incomplete and uncertain information.

The UPSS of a major city is, as rule, a component of the regional or the state power system. Every UPSS is formed historically with a certain hierarchy of voltages. There are the stages or subsystems of hierarchical structure: the external supply system of the city with voltage 330 kV or higher, the internal supply system with voltages 110-20-10-0.4 kV and the aggregate of urban consumers. Connections between subsystems are carried out through high-voltage transformer substations (TS) and networks of the corresponding levels of the voltage hierarchy.

For guaranteeing of viability of such large object as the major city should be the systems analysis and general approach to construction, formation of basic parameters of networks, the further development of separate subsystems and all UPSS as a whole. The voltage hierarchy of Latvian republic power supply system is shown in Fig.1 [8].

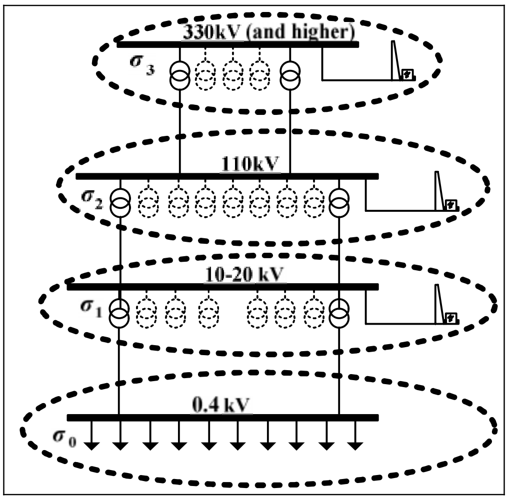

Fig. 1 The hierarchy of voltage levels and load densities in the urban networks

II. Power Transformer Diagnostic

A. Electrical measurements

The sequence in which the various tests are performed is also specified. An example of test sequence is as follows [2]:

(A) Tests before tanking: preliminary ratio, polarity and connection of the transformer windings, core insulation tests, ratio and polarity tests of bushing current transformers.

(B) Tests after tanking (final tests): final ratio, polarity and phase rotation, insulation capacitance and dissipation factor, insulation resistance, control wiring tests, lightning voltage impulse tests, applied potential tests, induced potential tests and partial discharge measurements, no-load loss and excitation current measurements, winding resistance measurements, load loss and impedance voltage measurements, temperature rise tests (heat runs), tests on gauges, accessories, LTCs, etc., sound level tests and other tests as required.

(C) Tests before shipment: Dew point of gas, core ground megger test, excitation frequency response test.

(D) Commissioning tests: ratio, polarity and phase rotation, capacitance, insulation dissipation factor and megger tests, LTC settings check, test on transformer oil, excitation frequency response test, space above the oil in the transformer tank.

Before mentioned tests are needed for to verify or measure the voltage ratio and proper connections, insulation condition, control devices and control wiring, dielectric withstand, performance characteristics.

B. Power transformer electrical tests separation by category

The manufactory may perform additional testing to ensure the quality of the transformer at various stages of the production cycle. For this discussion, test on power transformers are categorized as shown in Table I.

TABLE I
Electrical Tests By Category

Dielectric tests	Lightning impulse: • Full – wave • Chopped – wave • Steep – wave Switching impulse
Performance characteristics	No – load loss, excitation current, load loss, impedance, zero sequence impedance, ratio test, short circuit test
Thermal tests	Winding resistance, heat run test: • Oil rise • Winding rise • Hottest – spot rise Overload heat run, gas in oil, thermal scan
Other tests	Insulation, capacitance and dissipation factor, sound level tests, core ground, excitation current, electrical center, recurrent surge, dew point, core loss before impulse, control circuit test, LTC tests, ratio, bushings tests, oil preservation system
Dielectric tests /low (power) frequency	Applied voltage, single – phase induced, three – phase induced, partial discharge

Some of these tests are performed before the transformer core and coil assembly is placed in the tank, while other tests are performed after the transformer is completely assembled and ready for “final testing”. However, what are sometimes called “final tests” are not really final. Additional tests are performed just before transformer shipment and still others are carried out at the customer site during installation and commissioning [3].

There is described one example of transformer diagnostic of one transmission network company, as customer’s measurements before energizing. There are:

- Excitation current and load losses in low voltage winding;
- Insulation / megger measurements, capacitance and dielectric losses tests;
- Core insulation tests;
- Bushings tests;
- Winding resistance by DC;
- Turn ratio;
- Load losses and impedance voltage tests;
- Polarity tests;
- LTC tests;
- Thermal tests;
- Vibration tests;
- Oil tests;
- Dissolved gas analysis.

This quantity of measurements approved early, but nowadays receiving the new power transformers which are produced by IEC standards, the power transformers owner should be able make all necessary measurements. The technical, diagnostical specialists play the main role in introducing and initiation of new measuring methods. Owing to successfully chose optimal quantity of measurement, during power transformers maintenance, the technical problems found and solved. Necessary to note that majority electrical measurements are realized with de – energized power transformer. There is the advantage of monitoring systems

III. Monitoring systems

Theoretically, on-line application of these methods (dissolved gas analysis (DGA), partial discharge (PD) detection with acoustic localization of arcing source, frequency response analysis (FRA), acoustic monitoring of tap changer etc.) could provide detection of anomaly, identification of the problem and assessment of the severity of the condition. In practice, selection has to be made among the various methods available. Experience has shown that most transformers will spend their life without developing any problems and it would be unproductive to maintain a host of monitoring devices whose data would only show a flat line. Economic optimization therefore requires that a simple, broadband detection method be applied as a first line of defense or early warning and that diagnostic methods be applied only on those units that have shown to be developing a problem.

A.Monitoring cooperation with diagnostic

For correct selection of transformer on-line monitoring, it is required to distinguish between fault detection and fault diagnostic. In the recent CIGRE guide on transformer management this distinction is skillfully summarized with an analogy to the proper approach to human health problems: symptoms – diagnosis – cure.

The first step, which may be described as *monitoring* focus on detection of symptoms or evidence of abnormal condition. The fundamental question to be answered is whether the situation is normal or not. The techniques must be cost efficient and yet sufficiently sensitive and broadband to detect any potential problem at an early stage. Such monitoring techniques should be applied regularly and preferably continuously on-line [4].

The second step is the *diagnostic* where an abnormal situation is investigated to establish the type of fault, the severity of the problem and the corrective actions to be taken. The diagnostic step needs to be carried out only on those units that are deemed “abnormal” (usually less than 10% of the population). Tests that would be applied can be more expensive and off-line, and they need to be focused on individual attributes in an attempt to arrive at an unambiguous diagnosis. Beside the usual dissolved gas analysis (DGA), the diagnostic phase may imply a number of additional tests to assess the severity of the problem and the likely consequences if no action is taken. Examples of transformer tests that might be used include acoustic or electric partial discharge (PD), winding resistance, magnetizing currents, frequency response analysis (FRA), and polarization spectrum (recovery voltage) measurements. This reasoning is illustrated in the logic diagram in Fig. 2.

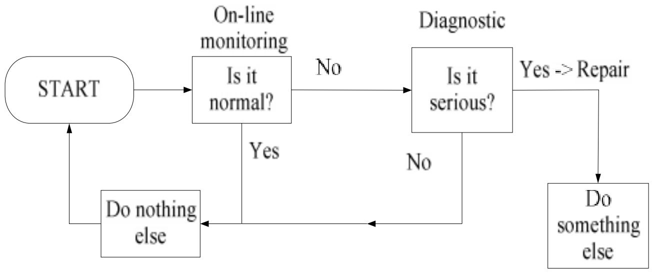

Fig. 2**.** Monitoring and diagnostic reciprocal logic diagram

This distinction between monitoring and diagnostic allows defining more accurately the requirements of the ideal monitoring and diagnostic systems: it must provide a wide coverage of faults detection but it does not have to cover the full range of diagnostic and condition assessment. It would be impractical to deploy on each power transformer all the methods of interest for condition assessment.

B.Monitoring system technology

A practical monitoring system should also be free of moving parts and ruggedized to provide years of service without any maintenance or recalibration. The technology has been developed to fulfill these requirements with a dependable and economic device, providing a wide coverage range of fault detection. The simplicity of this technology evolve from the use of a selectively permeable membrane that lows the key fault gases to come in contact with a miniature gas detector operating as a fuel cell.

The high sensitivity to hydrogen allows detection of minute change in the hydrogen gas concentration. The carbon monoxide is also detected, with attenuation to 18% thus leading to a value of the same order of magnitude as the typical hydrogen content. A composite value of the two gasses, with additional traces of acetylene and ethylene, ethane is provided. Accurate and dependable trending of the composite value of these gasses provides a wide coverage over any type of fault developing in the transformer tank. This technology does not require any consumable items such as helium gas, nor calibration gases for normal operation.

As hydrogen (H_2) is involved in nearly every fault of the insulation system of power transformers and carbon monoxide (CO) is a sign of an involvement of the cellulosic/paper insulation the presence and increase of acetylene (C_2H_2) and ethylene (C_2H_4) further classifies the nature of a fault as overheating, partial discharge or high energy arcing.

Moisture ingress in transformers tends to collect in larger amount in the cooler parts of insulating barriers at the bottom of the transformer. The proximity of ends of the windings creates a high electric field on these components. Moisture reduces the dielectric strength and can promote the occurrence of tracking discharges on the pressboard barriers that can lead to a flashover. Electric discharge of low energy will generate predominantly hydrogen (H2) and some methane (CH4), there are typical gasses generated in case of wet insulation, Fig.3.

Fig. 3 Case of tracking discharge in wet insulation

The transformer core is normally insulated from tank and magnetic shields. Failure of this insulation may lead to circulating currents in the core and local overheating. These defect are known as "hot metal fault" and they produce predominantly ethylene (C2H4) and methane (CH4) but also significant amount of hydrogen (H2), there are typical gasses generated in case of current circulation in the core, Fig. 4.

Fig. 4 Case of current circulation in the core

There were only few cases of diagnostic and monitoring cooperation proof, because the diagnostic results showed the same problem making electrical tests: low insulation level, increasing of dielectric losses and excitation current. All that information validated by transformer oil testing and moisture representing in it.

The interpretation of condition assessment results are based on limits used by international standards, published literatures and recommendations from transformer as well as instrument manufacturers for in-service conditions [5].

The condition of some transformers demands the continuous control. The decision of this task will be helped by installation of systems of continuous monitoring.

As the rule, the final decision follows after this data processing and from the other side the load forecasting is taking into account too.

IV. Load Forecasting for Latvian Republic

The major part of the current electrical network of Latvian Republic has been built in the 1960th and 70th using old Russian technology. A lot of the electrical equipment in the network is reaching the end of its lifetime in the coming years. Therefore and due to the historical developments in the network structure, reliability is low compared to European standards. Also the operation of the network and detection of faults is difficult.

The decision about further development of separate subsystems of UPSS should be based on a forecast of long-term or medium-term consumption of electricity in the Latvian Power System (Latvenergo) and perspective total load of Latvian republic.

The forecasting of electrical load for Latvian Power System is fulfilled for the period from 2008 till 2020. The forecast is made in the light of the prevailing economic situation in the state in recent years. The analysis of measurements from 2000 to 2008 is made and subsequent forecast is fulfilled. The forecast of consumption of the Latvian Power System in graphical view for different scenarios of the economic development can be seen in Fig. 5.

For forecasting of Latvian Republic electrical load must take into account:

- the actual load of 110 kV transformer substations by measurements from 2000 to 2008;
- load of consumers growing by years;
- marketable power of new objects;
- technical possibilities to cover new declared powers and another factors.

The variants of forecast are taken for:

- 3% -percent year load growing, beginning from 2008 till 2020 in favorable scenario of the economic development (AS Latvenergo forecast till beginning of crisis of the economics);
- 2%, 1.7%, 1.3% and 1.1%-percent year load growing in disadvantaged scenario of the economic development, without excluding the period of recession in the economy;
- 2%, 1.7%, 1.3% and 1.1%-percent year load growing in disadvantaged scenario of the economic development with the period of recession from 2008 till 2012 without load growing and with improvement of economic situation since 2012.

The deteriorating economic situation leads to the need to periodically adjust the previously made predictions [6].

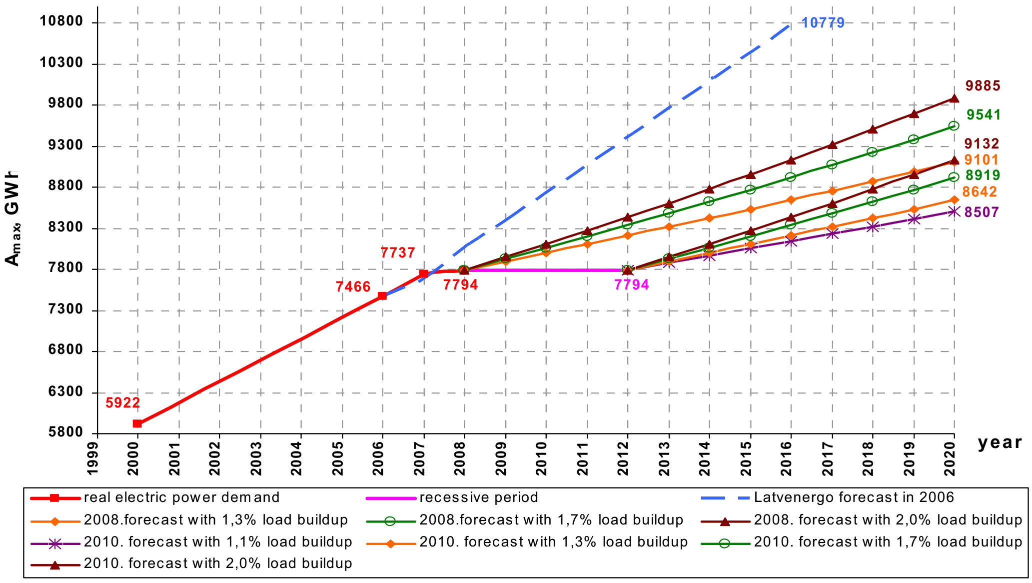

Fig. 5 The forecast of Latvian Power System consumption of electricity

V. Load Definition of Transformer Substation for The Period till 2020

The maximal active electrical load of each existing transformer substations can be found with the help of expression:

$$P_{2020} = P_{2008} \cdot \left(1 + \frac{\alpha}{100}\right)^{t_2 - t_1} + k_1 \cdot k_2 \cdot P_p \qquad (1)$$

where α is the medium growing of consumers' load per year;
t_2 is the final year of calculation period (t_2=2020);
t_1 is the beginning year of load growing (t_1=2008 or t_1=2012 in accordance with accepted calculation variant);
P_p is the marketable power of consumer;
k_1 is the factor of simultaneity of load maximum (k_1=0.8);
k_2 is the correction factor, which depends on marketable power of consumer and on uncertainty of connection term (k_2=0.7) [6].

VI. Theoretical Prognosis Transformer Substations` Capital Investments

For rational construction of power system it is necessary to determine the optimal power of substations for each voltage level. This is a complex and laborious task. In paper the choice of TS optimum power for the 110kV network on basis of variants` comparison is made [7].

Total investments of variants K_Σ can be found by expression:

$$K_\Sigma = K_{TS\Sigma} + K_{TP\Sigma} + K_{AL\Sigma} + K_{VL\Sigma} \qquad (2)$$

where $K_{TS\Sigma}$ are capital investments for 110/10 kV TS construction;
$K_{AL\Sigma}$ are capital investments of 110 kV cable line for 110/10kV TS connection;
$K_{TP\Sigma}$ are capital investments for 10/0.4 kV TS construction;
$K_{VL\Sigma}$ are 10 kV cable line capital investments for 10/0.4kV TS connection.

Certain functions of the components can be calculated as follows:

$$K_{TS\Sigma} = n_{TS} \cdot K_{TS} \qquad (3)$$

where n_{TS} is the number of 110/10kV TS;

$$\begin{aligned} K_{AL\Sigma} &= \lambda_A \cdot A \cdot n_{TS} \cdot K_{ipAL} = \\ &= 1.7 \cdot 1.1\sqrt{\Pi_{TS}} \cdot n_{TS} \cdot K_{ipAL} = \\ &= 1.9\sqrt{\Pi_{TS}} \cdot n_{TS} \cdot K_{ipAL} \end{aligned} \qquad (4)$$

where λ_A is 110kV network configuration factor (loop-through scheme adopted $\lambda_A = 1.7$);
A is the theoretical distance between the 110/10 kV substation adjacent;
K_{ipAL} is 1 km of 110kV cable line construction costs;

$$K_{TP\Sigma} = n_{TP} \cdot K_{TP} \cdot n_{TS} \qquad (5)$$

where n_{TP} is 10/0.4kV TS quantity in one 110/10kV TS service area;

K_{TP} is 10/0.4kV TS cost.

In addition:

$$n_{TP} = \frac{\Pi_{TS}}{\Pi_{TP}} = \frac{S_{r,TS}}{k_{o,TP} \cdot S_{r,TP}} \qquad (6)$$

where Π_{TP} is 10/0.4kV TS service area;

$S_{r,TP}$ is 10/0.4kV TS rated power;

$k_{o,TP}$ is factor of simultaneity at transformers' load maximum, depending of 10/0.4kV TP quantity;

$$K_{VL\Sigma} = n_{TP} \cdot K_{ipVL} \cdot L_{VL} = \\ = n_{TP}(K_{ipVL} \cdot \lambda_V \cdot 1.1\sqrt{\Pi_{TP}} \cdot n_{fid}) = \\ = n_{TP} \cdot K_{ipVL} \cdot 3.3\sqrt{\Pi_{TP}} \cdot \frac{n \cdot \beta \cdot S_{TS}}{S_{fid}} \qquad (7)$$

where K_{ipVL} is 1 km of 10kV cable line construction costs.;

L_{VL} is length of new 10kV cable lines to connect TP;

λ_V is 10kV network configuration factor (loop-through scheme adopted $\lambda_A = 2.5$);

Π_{TP} is TS service area;

n_{fid} is 10 kV feeder average number from TS;

S_{fid} is 10 kV feeder medium permeability ($S_{fid} = 2.5MVA$).

The optimum solution of function (2) is equal with the minimum of total investments of variants` comparison. The results of calculations are shown in Fig. 6.

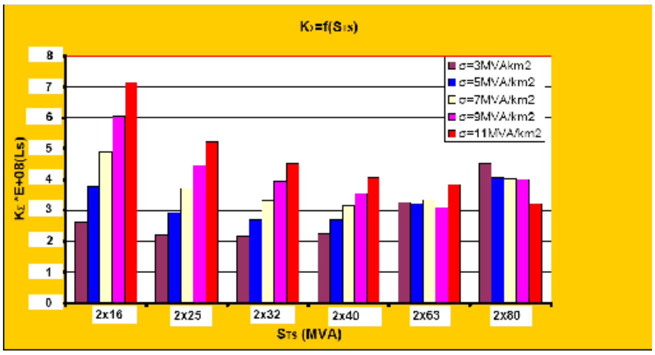

Fig. 6 Total capital investments depending on the transformer substations' power $K_{\Sigma}=f\ (S_{TS})$

On the basis of the results (Fig. 6) followed that cities with a load density σ = 3-5 MVA/km^2 is economically to use the TS with power in 2x32 MVA, with a load density σ = 5-9 MVA/km^2 - 2x40 MVA substation, with load density σ = 9 MVA/km^2 - 2x63 MVA substation, σ > 11 MVA/km^2 - 2x80 MVA substation [7].

VII. Conclusion

Electrical tests of power transformers and monitoring system in the result gives in general the diagnostic of power transformer.

On-line monitoring of power transformers provides a clear indication of their operational status and ageing behavior. If more detailed monitoring information is transmitted on-line to the power system control center, maximal and admissible overload operation time under given operating conditions can appropriately be assessed and the results can be displayed in the form of line flow diagrams. Thus, reliable decision making support is given to the operators. This information helps to counteract with the threatening failures in time.

All in the paper mentioned information gives possibility to make correct technical and economical decision about furthers procedures. It is very actual moment in technical maintenance of expensive electrical equipment, such power transformers.

Forecasting is made for all existing and 28 two-transformer virtual perspective 110 kV transformer substations. The perspective transformer substations can appear with irregular growing of load in different districts of state or if the load of existing transformer substations is not enough due to big load compactness in these districts. For each possible transformer substation place in the territory of Latvian republic and in the developed power supply system must be reserved [9].

Taking into account those two strategies: diagnostic (determination of technical condition) and load forecasting in substation points ensures rational disposition of the funds, but connectivity between technical specialists and financial specialists must be co-ordinate, therefore avoid the transformer owner from unnecessary cash expenditure.

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