21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

A2-209

CIGRE 2008

CONDITION ASSESSMENT OF MEDIUM-POWER TRANSFORMERS USING DIAGNOSTIC METHODS: PDC, FDS, FRA TO SUPPORT DECISION TO MODERNIZE OR REPLACE SERVICE-AGED UNITS

R. MALEWSKI* — Instytut Elektrotechniki
J. SUBOCZ — Politechnika Szczecińska
M. SZROT, J. PŁOWUCHA, R. ZALESKI — Energo-Complex

Poland

SUMMARY

Privatization of distribution companies induced the new owners to assess technical condition of their transformers, and to decide on modernization of older units or sending them to scrap. Such decision is based on an evaluation of the cost of modernization, and operating costs expressed in percents of a new transformer cost. Specific features of the transformers manufactured in Poland some thirty years ago, such as a generous safety margin of HV insulation and a relatively low load of many units, have been taken in consideration.

In general, transformers manufactured before 1965 have excessive no-load loss since the core was made of hot-rolled steel. Further operation of such units is not justified considering a high capitalized-cost of no-load loss. Cellulose insulation of some older units has lost its elasticity, and the reduced the initial winding compression. This has rendered the transformer prone to winding displacement by dynamic force of short-circuit current. Such deformation is detected by measurement and analysis of winding frequency response (FRA). Replacement of locally made on-load tap changer (OLTC) by a new one obtained from renommé manufacturer is recommended, but may not be justified in older units, since the old OLTC can be refurbished. The transformer condition assessment involves such factors as ageing of transformer solid insulation, water content in cellulose, as well as oil degradation and sludge in oil ducts. These are determined using dielectric polarization methods: polarization and depolarization current (PDC), frequency dielectric spectroscopy (FDS), recovery voltage measurements (RVM), as well as dissolved gas in oil analysis (DGA), complete physico-chemical oil-analysis and measurement of furans content.

Results of the condition assessment allow the utility to dress a ranking list of their transformers, and to plan replacement, modernization or scrapping of older units, depending on their critical importance to the network reliability and the scope of required modernization.

KEYWORDS

Medium-power transformer, condition assessment, cost of loss, insulation ageing, winding displacement, dielectric polarization, economic justification, transformer modernization.

---

*malewski@ieee.org

INTRODUCTION

Total population of medium-power (8 to 80 MVA, 110/15kV) transformers in Poland approaches seven thousands, and a large part of them has been in service for more than 30 years. Simultaneous replacement of service-aged units by new ones is not feasible, nor economically justified. To decide on modernization or replacement, their owners have to dress a ranking list based on each transformer technical condition and operational costs. An assessment of the no-load loss, winding mechanical integrity, cellulose and oil ageing, bushings, coolers, pumps, fans and on-load tap changer (OLTC) condition is complemented by an evaluation of the transformer critical importance to the distribution system reliability.

Such assessment starts with the manufacturing date, since hot-rolled steel was used for the core of units built before 1965, and a prohibitively high no-load loss does not justify expenditure in the repairs or modernization. Transformers manufactured between 1965 and 1975 were equipped with the core made of cold-rolled sheaths assembled at the right angle. Their no-load loss was considerably reduced, however still higher than that achieved in modern units with the step-lap assembled cores produced after 1995.

The older units were designed with fairly generous insulation safety-margin that was dictated by a lack of effective control of insulating materials, as well as by the centrally planned economy, which eliminated competition between the suppliers. These factors resulted in a relatively little thermal ageing of cellulose, and in a sufficient dielectric strength of the transformer, despite high moisture content and oil contamination. Soot was coming into the oil from the leaky chamber of OLTC diverter-switch, and from a common oil-conserver for the main tank and for the diverter-switch chamber. OLTC's produced by the local transformer manufacturer on license from ELIN have been of a rather low quality. They require frequent inspections and replacement of contacts, springs, drive elements, etc., but a number of small workshops has specialized in maintenance of these tap changers. Such services used to be inexpensive, but the shortage of qualified manpower, as well as the increased wages rendered the maintenance of old OLTC's too expensive, and replacement by modern, low-maintenance tap changers becomes economically justified in some cases. Such accessories as coolers, OLTC drives, bushings can be replaced at a reasonable cost, and the decision to modernize or to scrap the transformer, effectively hinges on the winding mechanical integrity.

To detect deformations of the winding its frequency response is measured, and the characteristic obtained on one phase is compared to that recorded on neighbor phases, as well as on a twin unit, since twin transformers were installed in many substations.

Moisture content in the insulation is assessed using dielectric polarization methods. Most frequently the polarization-depolarization current is recorded, but the frequency characteristic of the insulation capacitance and loss factor is also registered. Accuracy of these field measurements may be unacceptable for research purposes due to temperature gradient in the examined insulation, but in practice it is sufficient to determine that the water content in cellulose is less than 3%, 2% or 1%.

The process of transformer condition assessment has been implemented in Poland for a few years and wealth of measurement data was accumulated. Interpretation of the recorded characteristics often calls for an expert know-how of such subjects as damage location in the winding from its frequency response characteristic, but participation in activities of the relevant CIGRE Working Group A2 WG26 allows us to benefit from its collective knowledge. An interpretation of readings obtained from different instruments based on dielectric polarization methods, such as PDC, FDS or RVM, has been intensely studied in the frame of the dedicated European Union project lead by one of Polish Technical Universities, and their model studies support our findings.

These efforts have not always brought a positive answer in every particular case, but the practical experience gathered over a few years of work helps to resolve most of the practical questions.

The cost of complete assessment of the transformer condition does not exceed 5% of the modernization costs, and the cost of replacement by a new unit is approximately four times higher than the cost of modernization. Such modernization can extend the transformer technical life by 10 and sometimes even 15 years. This estimate does not account for the interest gained on funds saved by putting off the investment in the new transformer, and for the increased operational costs.

POLISH DISTRIBUTION COMPANIES COMPARED TO EU COUNTRIES

Polish distribution companies have been State-owned for 60 years, and they employ substantially more people per 1 MW of installed power than similar companies in “old” European Union countries.

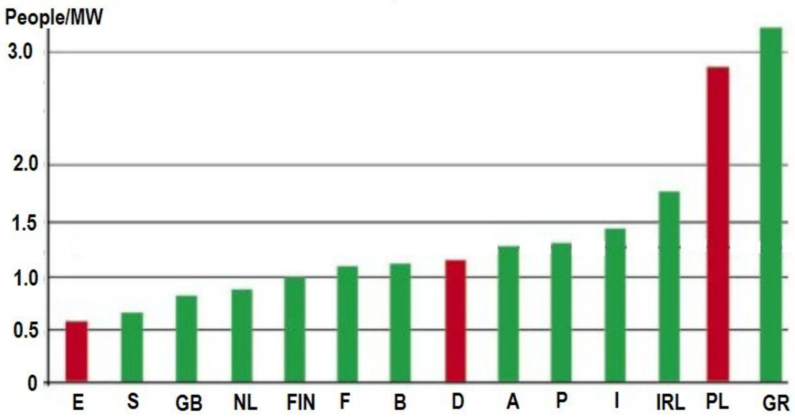

Fig. 1. (After [1]). Employment for 1 MW of installed power in EU countries.

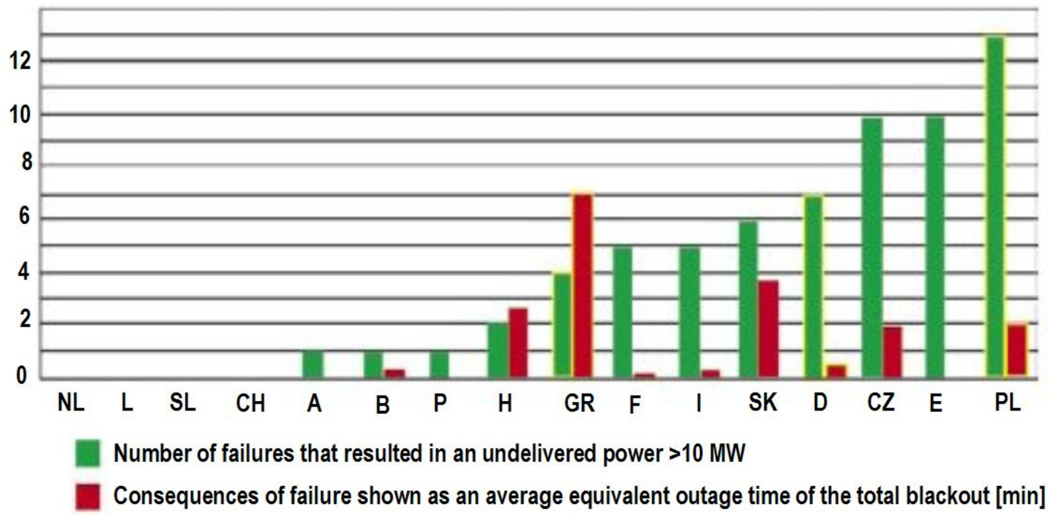

Fig. 2. (After [1]). Number of outages that caused a loss of delivered power >10 MW, and an equivalent time of their duration, in EU countries.

Despite a relatively larger number of employees in Polish distribution companies, power failures are more frequent than in majority of European Union countries, as it is shown in Fig.1 and Fig.2. Inevitably, Polish utilities will have to reduce the number of employees, and at the same time to improve reliability of power delivery in the forthcoming years. Free, competitive energy-market forces these utilities to postpone major investments and to keep existing assets in operation as long as possible. Transformers are the most expensive elements of distribution network, and replacement of service-aged units is dictated by two factors: their critical importance to reliability of power delivery, and their technical condition.

A rational planning of investments requires a ranking list of transformers to be modernized or replaced. Relative importance of each transformer for system reliability, and the transformer technical condition is shown in Fig.3 [2, 3]. Besides, operational costs have to be considered, although some utilities prefer to keep older transformers in service despite their high loss and costly maintenance, just to postpone investment in modernization or replacement.

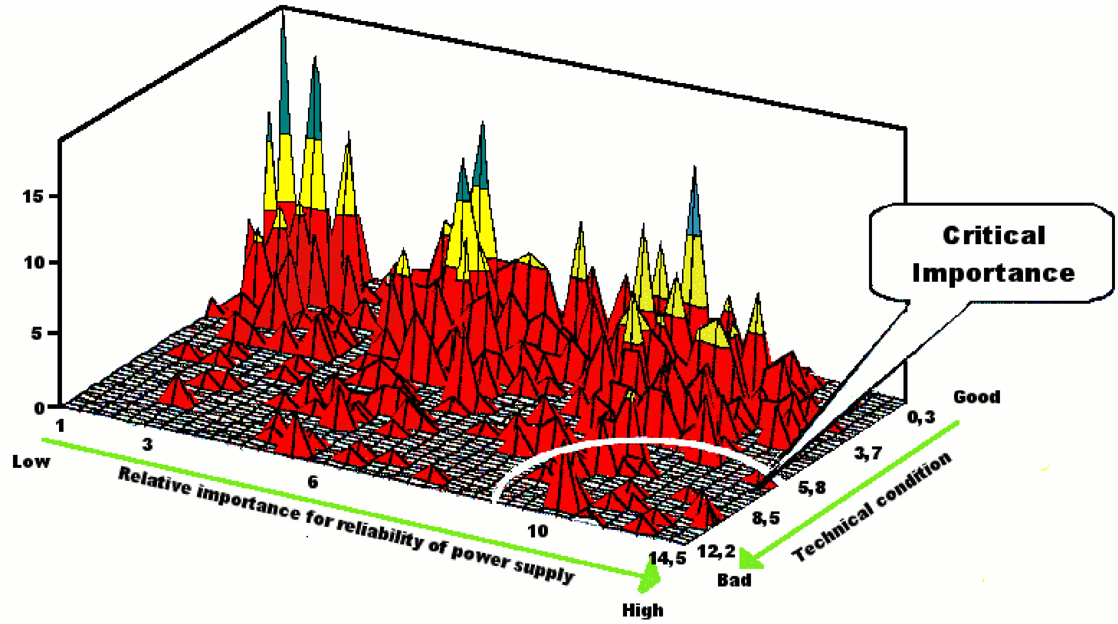

Fig. 3. (After [2, 3]). An example of 900 transformers with their relative importance for system reliability plotted against the transformer technical condition. Such graph forms the base of a ranking list of transformers to be modernized or replaced.

Operational costs become an important factor in taking decision to keep in service transformers older than 40 years, since their no-load loss may be 2.5 times higher than that of contemporary units. Polish Power Grid has determined the capitalized cost of loss in network transformers, as follows:

Capitalized cost of losses	Year	1997	1999	2001	2005
No-load loss	USD/W	3.5	6.0	5.0	5.0
Load loss	USD/W	1.3	3.8	3.0	2.5

The cost of losses is even higher in distribution transformers, since they dissipate loss-power that has already been charged with the cost of transmission loss [4, 5].

Capitalized cost Country	No-load loss [Euro/W]	Load-loss [Euro/W]
Germany	3.5 ↔ 4.0	0.7 ↔ 1.0
Sweden	3.5 ↔ 7.0	0.4 ↔ 0.8
Austria	4.0 ↔ 7.0	0.8 ↔ 1.8
Switzerland	7.5	1.9
Finland	3.5	0.3

In European countries there is a considerable spread of capitalized cost of losses in distribution network. However, the cost of no-load loss is always higher than twofold cost of load loss, since the transformer rated-capacity was selected to supply its average load. The practice in Poland was to install and operate two transformers in parallel, to ensure a high reliability of power supply. In consequence the load-loss is relatively low, but the no-load loss increases, since the two units are energized and dissipate their no-load loss. This practice will be revised, as the privatized distribution companies have to deduct the cost of losses from their profit.

To reduce operational cost Polish utilities will have to revise the practice of frequent inspections and maintenance required by on-load tap changers (OLTC) manufactured in Poland on license from ELIN. The time of transformer unavailability and cost of labor cannot be considered negligible any longer, and the modern, low-maintenance OLTCs will replace gradually the service-worn tap changers and their drives.

ASSESSMENT OF TRANSFORMER TECHNICAL CONDITION

Oil sample testing

Analysis of gas dissolved in oil (DGA) has been the basic technique of the transformer condition assessment, and the test of physical-chemical oil-properties complemented by determination of furan concentration provide valuable information on the state of paper-oil insulation. To interpret the concentration of gases in oil several codes can be used: Duval triangle, IEC, IEEE, Rogers and Doernenburg are the most popular. A specialized program to compare the findings obtained from the same oil sample by different codes has been developed by Łódź Technical University, Poland [6], and often reveals significant discrepancies between these diagnoses. Close collaboration with transformer-oil analysis division of Nynas-Naphtenics has been established, and their oil-testing laboratory shares the premises of Energo-Complex in Piekary Śląskie, Poland

Theoretically, water content in cellulose can be derived from oil samples using Oommen curves. However in practice, the temperature distribution inside a transformer in service is hard to determine.
Moreover, the relation between water content in cellulose (expressed in %) and water in oil (in ppm) has a very high steepness in the operating temperature range, which results in a large uncertainty of the obtained moisture-content in paper.

Solid insulation condition-assessment using polarization methods

More reliable and accurate assessment of cellulose ageing and water content is provided by diagnostic methods based on dielectric polarization: RVM, PDC, FDS. All these methods have been implemented in Poland, owing to the EU grant named "Rediatool" [7], lead by Poznań Technical University. Researchers of this University, in collaboration with the teams from Gothenburg and Stuttgart University, as well as with Polish and German utilities, acquired specialized instruments using the grant funds. Subsequently, they have developed reference data to calibrate these instruments using a large number of cellulose samples of a controlled water content and thermal ageing. Field measurements taken on a number of transformers in service were analyzed an interpreted by the joint team of research engineers from these three countries.
Following this research project, our service company Energo-Complex,, in collaboration with Szczecin Technical University, has implemented RVM, PDC and FDS techniques to condition assessment of a large number of medium-power transformers. In practice, the owner of a medium-power transformer has to decide on insulation drying, or continued operation. For this purpose it is sufficient to state that water content in cellulose is less than 1%, 2% or 3%, since a more accurate value does not change the transformer owner decision. However, such condition assessment has to be confirmed by more than one diagnostic technique. A typical record of moisture in solid insulation obtained using RVM and PDC is shown in Fig. 4.

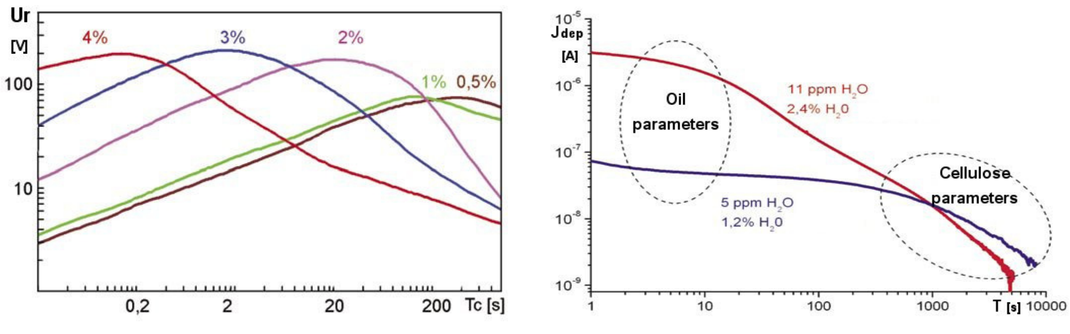

Fig. 4. Water content in cellulose [%] revealed by the Recovery Voltage curves for five different insulation samples – left graph. Water content in oil [ppm] and in cellulose [%] derived from Depolarization Current characteristic measured on insulation of two transformers – right graph.

Historically, the first insulation diagnostic-method consisted in measurement of capacitance at 2 Hz and at 50 Hz. A ratio of these readings C_2/C_{50} indicated excessive water content in solid insulation. Introduction of modern transformer oils with very high resistivity precluded further use of C_2/C_{50} ratio, which was employed as water-in-transformer indicator in Poland 50 years ago. Recovery Voltage Measurement was initially used to determine water content in cellulose insulation of HV capacitors and cables. Subsequently, this technique was extended to transformer paper-oil insulation, and excessive water content was indicated in new, factory-dried transformers. With special signal-processing software that corrects the effect of insulation temperature, and reduces influence of oil resistivity, the RVM readings provide useful assessment of moisture content in solid insulation. However, an uncertainty of ±0.5% is not uncommon.

Polarization and depolarization current is recorded for couple of hours after application or short-circuiting a direct voltage. Certain sections of this current decay characteristic reveal water content in oil and in cellulose. The characteristic is analyzed by decomposition into a straight line that reflects oil resistivity, and a few exponential components with different decay time-constants. These time-constants, derived from for instance depolarization current plot, correspond to certain water content in cellulose. Again, this analysis requires reference values obtained by examination of cellulose samples with controlled and known water content. Once calibrated, the depolarization current plot provides water content in oil and in cellulose with accuracy sufficient for transformer condition assessment.

Frequency Domain Spectroscopy of paper-oil insulation yields the dielectric loss factor tgδ and capacitance frequency-characteristic in very low frequency range. To determine water content in solid insulation these characteristics are analyzed using X-Y model of barrier insulation between the high and low voltage winding [8]. Reference characteristics derived from controlled moisture-content cellulose-samples are required to calibrate the model. Water content in the main insulation of three GSU transformers rated at 75 MVA, 115/10.5 kV is as follows: TR1 – 1.2%, TR2 – 3.2%, TR3 – 1.4% and the reserve unit T_{REZ} – 3.1%. A quick, visual inspection of characteristics shown in Fig. 5 reveals a marked difference between the dry insulation of TR1 and TR3, as compared to rather wet cellulose insulation of TR2 and T_{REZ}.

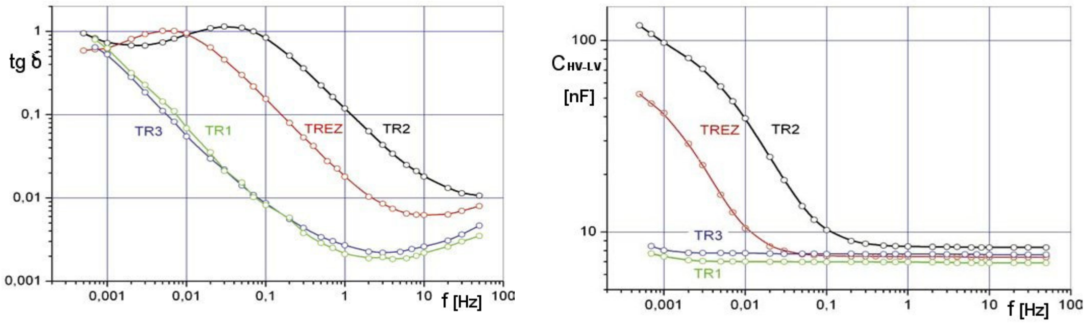

Fig. 5. Dielectric loss factor tgδ of main insulation of four GSU transformer plotted as a function of frequency from 0.6 mHz to 60 Hz (left graph). Capacitance of main insulation of the same transformers plotted in the same frequency range (right graph).

DETECTION OF DEFORMED TRANSFORMER WINDINGS

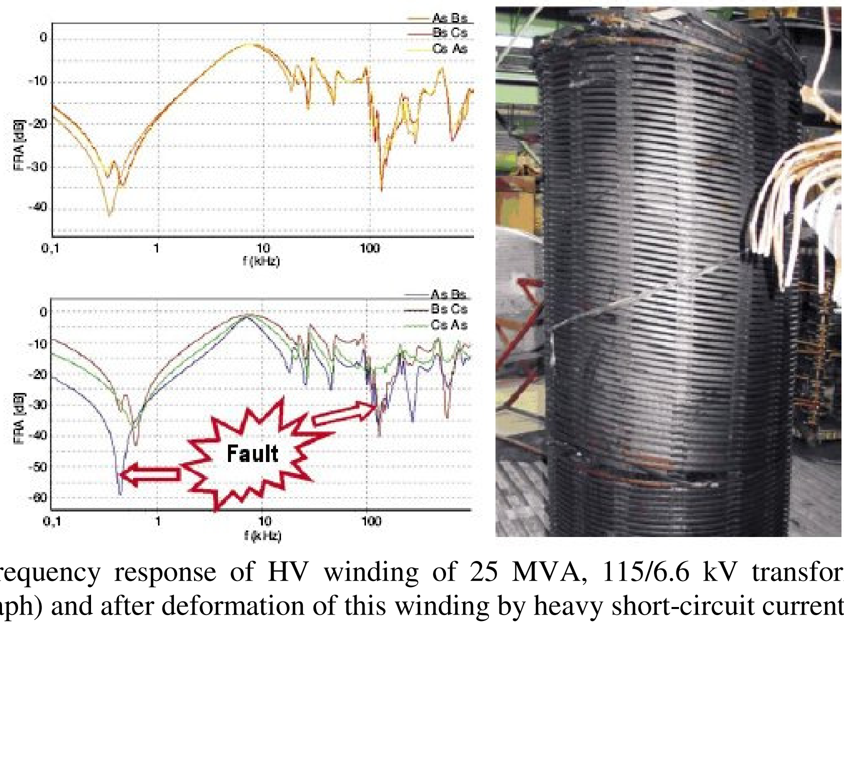

Fig. 6. Frequency response of HV winding of 25 MVA, 115/6.6 kV transformer recorded before (upper graph) and after deformation of this winding by heavy short-circuit current (lower graph).

Transformer windings have been designed to withstand the dynamic forces induced by short-circuit current in the network. The windings have been pressed in the factory, and the compression force was chosen to exceed the axial dynamic force and to prevent loose winding movement. However, the compressed cellulose has lost its initial elasticity during the years of service at high temperature, and the initial winding-compression has disappeared. Service-aged winding is then prone to coil displacement or deformation by the dynamic force, which is proportional to the square of short-circuit current magnitude. A small deformation does not always result in an immediate short-circuit, but a displacement of some coils decreases the oil-gaps size, crushes the brittle, service-aged paper insulation, and reduces the winding dielectric strength. Next lightning or switching over voltage may break such weakened insulation. A major failure of the transformer in service may develop, if the protection is not fast enough to clear the fault caused by an internal short-circuit inside the windings.

An early detection of deformed windings provides an early warning, and allows the utility to plan the transformer repairs, rather than wait for an unexpected and costly in-service failure.

Polish engineers Lech and Tyminski [9] have been first to reveal the winding displacement in transformers in service. They recorded the winding response to a repetitive steep-front low-voltage impulse, and compared records taken on three-phase windings. The comparison of winding response presented as a function of frequency, rather than time [10], has facilitated interpretation of the recorded characteristics.

Specialized instruments have been designed and commercialized for Frequency Response measurements and Analysis (FRA). This diagnostic method has gained general acceptance, and has been implemented by utilities in all industrialized countries. CIGRE and IEEE have set up working groups to determine a standard format of the winding frequency response presentation, to ensure reproducibility of records taken by different FRA instruments, and to provide guidance on interpretation of the recorded response traces.

Energo-Complex has pioneered the FRA method in Poland. Hundreds of medium and large power transformers have been examined for winding displacement and assessed using this technique [11]. As in other diagnostic techniques based on comparison of characteristics taken at certain time intervals, the FRA interpretation suffers from lack of reference response records taken on a new transformer in the factory. No such reference is available for older units that may have loose windings and are vulnerable to winding displacements. To detect a displacement of such winding their frequency response is compared to that of other phase windings, or to the response of the twin transformer windings. An interpretation of the recorded characteristics requires special skills, and an active participation of Energo-Complex engineers in CIGRE WG A2-26 provides access to the collective know-how gathered by this working group members [12].

COSTS OF A MEDIUM-POWER TRANSFORMER MODERNIZATION

In paper-oil insulation cellulose accumulates all the moisture, and only its very small part is transported to and from oil during the cyclic changes of the transformer load and temperature. Drying of transformer oil cannot remove water absorbed by cellulose. Such water can be extracted under vacuum, when the winding is heated up by hot oil spray, and by e.g. a low-frequency current. The windings have to be pressed after drying, since the cellulose insulation may shrink and the winding may lose its initial compression. At the occasion pressboard barriers as well as accessible parts of insulating system are cleaned from soot deposits, and sludge is removed from accessible oil ducts.

Such operations can be performed by a repair facility that can also replace worn contacts, springs and drive of the on-load tap changer (OLTC), as well as install new bushings and radiators, if need arises.

Modernization of an older transformer is economically justified if the cost of drying, cleaning and pressing of the windings, replacement of radiators, filling transformer with new oil, overhaul of OLTC, and transport to the repair facility represents an acceptable fraction of the new transformer cost. The modernized unit may serve for another 10 to 15 years, and the investment in the new transformer is postponed. With the sharply increased price of transformer steel and copper, cost of a new unit represents a substantially larger expenditure than modernization that preserves at least the core, windings and tank. The cost of condition assessment is negligible in comparison to the cost of modernization, which is presented in Fig. 7 for a typical transformer rated at 25 MVA, 115/15 kV.

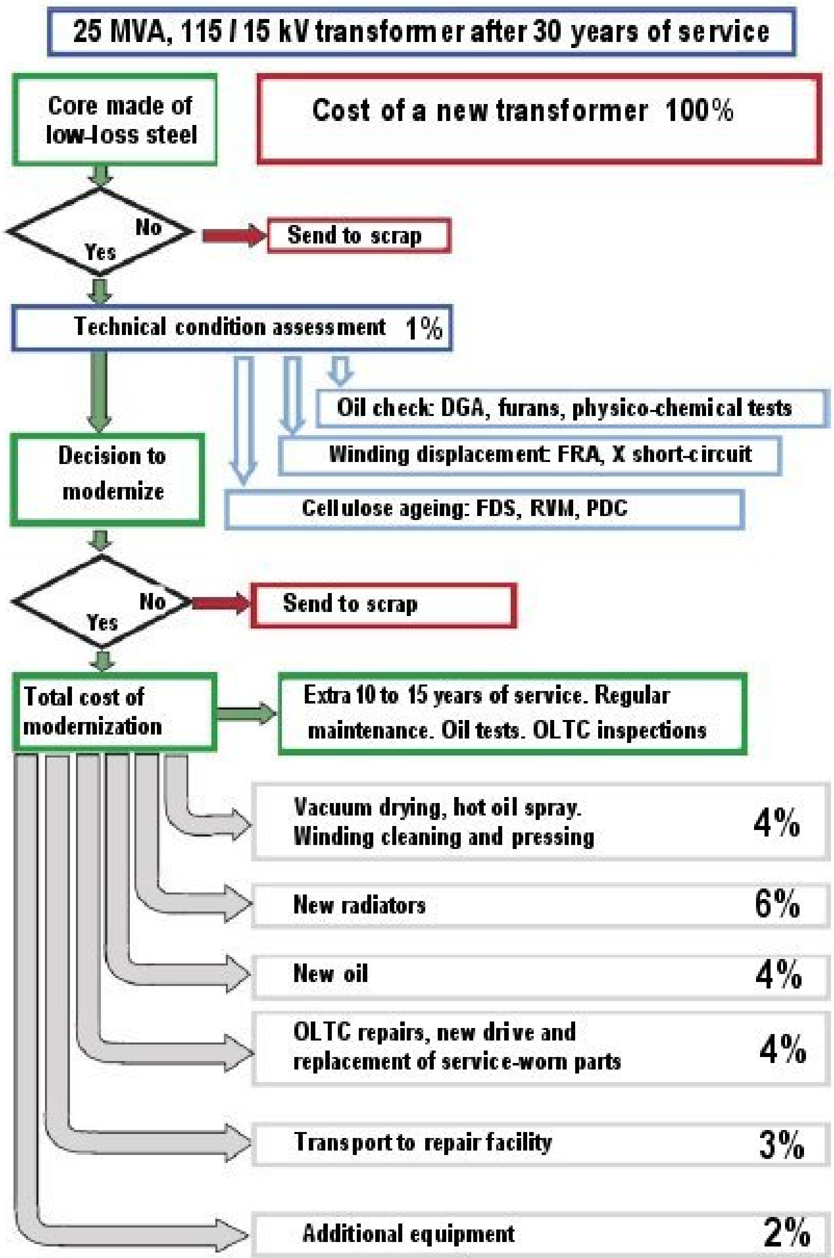

Fig. 7. Core loss evaluation, assessment of winding integrity and cellulose ageing are required to take a decision on sending an older transformer to a repair facility or to scrap. Cost of components and labor involved in modernization of a typical medium-power transformer at a repair facility amounts to 24% of the new transformer cost, including the cost of condition assessment.

CONCLUSIONS

- Distribution utilities in Poland have to face an oncoming end of the technical-life of a large number of medium-power transformers. A simultaneous replacement of all service-worn units is not feasible, and cannot be economically justified. Some of these transformers can be modernized and their life can be extended by 10 or even 15 years. The decision to modernize, or send to scrap, has to be based on an assessment of transformer technical condition. A ranking list has to be dressed to determine a sequence of replacements and repairs.
- The assessment of transformer technical-condition involves a review of its operational history, design and materials used, as well as: mechanical winding integrity, ageing and water content in solid insulation and oil, technical condition of the on-load tap changer and its drive, bushings,

radiators and auxiliary equipment. Modern methods and instruments can detect winding deformation (FRA), excessive water content and advanced ageing of cellulose (RVM, FSD, PDC). Specialized companies offer such condition assessment at the reasonable cost as compared to the cost of transformer modernization.

- Modernization of older transformers postpones the investment in a new unit, but requires a careful maintenance, regular inspections and checks. These are included in the operational costs, but the cost of loss, and in particular the no-load loss is the main component of the cost of operation. The increased operational cost has to be taken into account in an economic justification of keeping the modernized transformer in service for next 10 to 15 years.

BIBLIOGRAPHY

1. Miśkiewicz, M., "European Electric-Power Systems, comparison of basic data", Elektroenergetyka, vol. 53, nr. 2, p. 11-43, (*in Polish*).
2. CIGRE SC A2 Transformers, WG 20: Economics of Transformer Management, ELECTRA, nr 214, 2004, p. 51-59.
3. CIGRE Technical Brochure Nr. 227: Guide for Life Management for Power Transformers, Paris 2003.
4. Dziura, J., Spałek, D., "Particular features of optimum design transformers", VI Conference "Power and special transformers", Kazimierz Dolny, 2006, p. 95-112, (*in Polish*).
5. Gadula, A., "Repairs, modernization, or acquisition of new transformers", ibid. p. 195-204, (in Polish).
6. Piotrowski, T., Mosiński, F., :Multistage Methods fo DGA", International Conference "Transformer '03", Pieczyska, May 18-23, 2003, p. 56-81.
7. Feser, K., Neumann, C., Tenbohlen, S., Filipowski, A., Mościcka, H., Tatarski L., Gubański, S., Karlsson, L., "Reliable Diagnostics of HV Insulation for Safety Assurance of Power Transmission System, REDIATOOL- European Commission Research Project", CIGRE, Paris 2006, paper D1-207.

8, CIGRE Technical Brochure Nr. 254: Dielectric Response for Diagnostics of Power Transformers", Paris 2004.

9. Lech, W. Tyminski, L., "Detecting transformer winding damage by the Low Voltage Impulse method," Electrical Review, No. 21, vol 179, November 1966, pp 768-772.
10. Malewski, R., Poulin, B., "Impulse Testing of Power Transformers using the Transfer Function Method", IEEE Trans. Vol. PWRD-3, No. 2, April, 1988.
11. Malewski, R., Szrot, M., Płowucha, J., "Detection of Transformer Winding Deformation using Frequency Response Analysis and Evaluation of Results", Energetyka, No. 6, 2004, p. 341-345.
12. CIGRE Technical Brochure: Mechanical-Condition Assessment of Transformer Windings using Frequency Response Analysis (FRA)", in print, 2007.