Power transformers management in the power system of Crete

Kiriakos Siderakis, Dionisios Pylarinos and Emmanuel Thalassinakis

Abstract-- **A power transformer is probably the most critical component of a substation, since a possible failure may result to a long term power outage and the necessary repairs require significant time and budget and in some cases cannot even take place on site. The resulting overall cost makes power transformer maintenance a critical procedure. Consequently, it is necessary to formulate an optimum strategy for performing evaluation measurements, in order to be able to detect equipment deterioration, estimate the possibility of a failure and proceed to preventive maintenance actions to maintain the desired levels of system reliability. In this paper, the investigation and evaluation of a fleet of transformers installed at the power system of Crete is presented. Critical components are identified and the implemented measurement techniques are presented in an effort to formulate an optimum evaluation and measurement strategy.**

***Index Terms*-- Power transformers, fleet management, condition assessment.**

I. Introduction

POWER supply reliability is a critical requirement for the performance of power systems. Both for the power utility and the consumers, the possibility of a power outage may considerably affect their financial integrity, especially if long term problems are experienced. A possible failure in a power transformer is one of these cases, where the corresponding problems are considerable [1-2]. Usually a transformer failure is long term, considering that maintenance capabilities are limited on site [1-6]. In addition a possible replacement is difficult due to the size of the transformer, the availability of spare transformers and the acquisition cost. In the same time, utilities are obliged to reduce maintenance costs, including the available means and specialized personnel. Consequently the equation becomes quite difficult to solve and new methods and techniques are required in order to determine an efficient maintenance strategy, able to ensure the optimum exploitation of the equipment.

In the case of Crete, a Greek island in the Mediterranean sea, a fleet of 150kV power transformers are in service. The total installed capacity of transformers in Crete is 2600MVA, consisted of 64 power transformers.

Located in a distance from the mainland the power system of Crete is isolated, therefore the required levels of reliability are increased. In addition due to the touristic development of the island, during the periods of increased supply demand the levels of ambient temperature exceed 30^{o}C, resulting sometimes excessive stresses for the transformers.

In an effort to ensure the best possible exploitation of the transformers fleet, cooperation between the local department of HEDNO and the high voltage laboratory of the Technological Institute of Crete has been established. The purpose is to develop an asset management strategy, focused on power transformers, aiming to reorganize the transformer monitoring and maintenance operations.

In this paper the first step of the assessment procedure is presented and analyzed.

II. Power transformers management

Managing a fleet of transformers becomes a quite difficult but also necessary task that utilities have to undertake. The first step in this procedure is to develop a knowledge base for the operation of power transformers and the possible failures that could occur. In this direction it is necessary to consider the data available in the literature, since it is quite difficult for a utility maintenance engineer to develop experience otherwise. Transformers are quite reliable and failures are not often. In addition the majority of the transformers operating in Europe are entering the period of increased failure rates nowadays, considering the investments in energy installations that took place in the past resulting to an average transformer age of about 30 years. Consequently the probability of transformer failures appears to be increased for the years to come, but in the same time the field experience per utility is rather limited.

Then an assessment of the fleet health is necessary. There are available data and tools that can facilitate such a procedure [7-10]. The first step is to set up an initial transformer condition, starting from the qualification measurements performed by the manufacture and the measurements performed upon delivery. Further diagnostic measurements that have been performed since the first operation must also be considered and possible trends must be identified. The outcome of this procedure is the establishment of the current transformer condition. It must be noted of course this is estimation and there is certainly a degree of uncertainty. However, this uncertainty can be decreased the more data are collected. In addition, condition correlation between transformers that have similar characteristics (age, manufacture etc), in relevance to the experience of other utilities, may further increase the level

Kiriakos Siderakis is with the Department of Electrical Engineering, Technological Educational Institute of Crete, Estavromenon GR 71004 Heraklion Crete, GREECE (e-mail: k.siderakis@staff.teicrete.gr).

Dionysios Pylarinos is a researcher/consultant for the Hellenic Electricity Distribution Network Operator S.A (email:dpylarinos@yahoo.com)

E. Thalassinakis is the Assistant Director of the Islands Network Operations Department, Hellenic Electricity Distribution Network Operator S.A., Greece (email: e.thalassinakis@deddie.gr)

of reliability of the considered assessment.

The second step is to establish a monitoring strategy based on the data developed from the first step, the operation of the power network and the importance of each transformer unit [7-8]. The expected failure possibility and the impact of a failure to the operation of the power network and reliability of supply are key parameters. The necessary information can be combined in a assessment index, the value of which may formulate the maintenance and monitoring strategy and further facilitate a replacement decision, when necessary [12-14].

It is worth noticing that at this stage, advanced reliability assessment techniques may be implemented in order to predict the possible impact of a failure and lifetime assessment techniques for the estimation of the condition development in a transformer.

The proposed procedure is illustrated in figure 1.

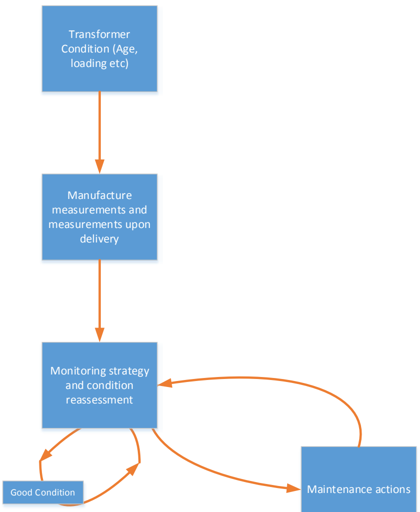


Fig. 1 First step condition assessment procedure for power transformers aiming to develop a maintenance and monjitoring strategy.

III. Power Transformers Failures

A. Transformer failures according to the literature

A failure in a power transformer can be the result of different causes, with a degree of influence depending on the features of the transmission system. Further there are many components in a power transformer that can have a considerable impact on the ability of the system to operate within its nominal values and serve its purpose. Many failure surveys can be found in the literature, usually as case studies for specific power systems (country wide)[3-6,11]. In addition there is a CIGRE survey, which is international and quite reliable due to the number of samples registered[1]. The results from the above surveys, as far as the types of failures are concerned are summarized in figure 2. In fig. 2a a typical distribution of causes of failures according to the available literature is illustrated. Further in Fig 2b failures are classified in relation to the transformer subsystem influenced.

It must be noted that there are many failure scenarios that can be experienced, thus different classification schemes can be found in the literature. This is due to the different service conditions experienced in each power system and also due to the different features evident in each transformers fleet. In figure 2, the results of four failure surveys available in the literature are illustrated.

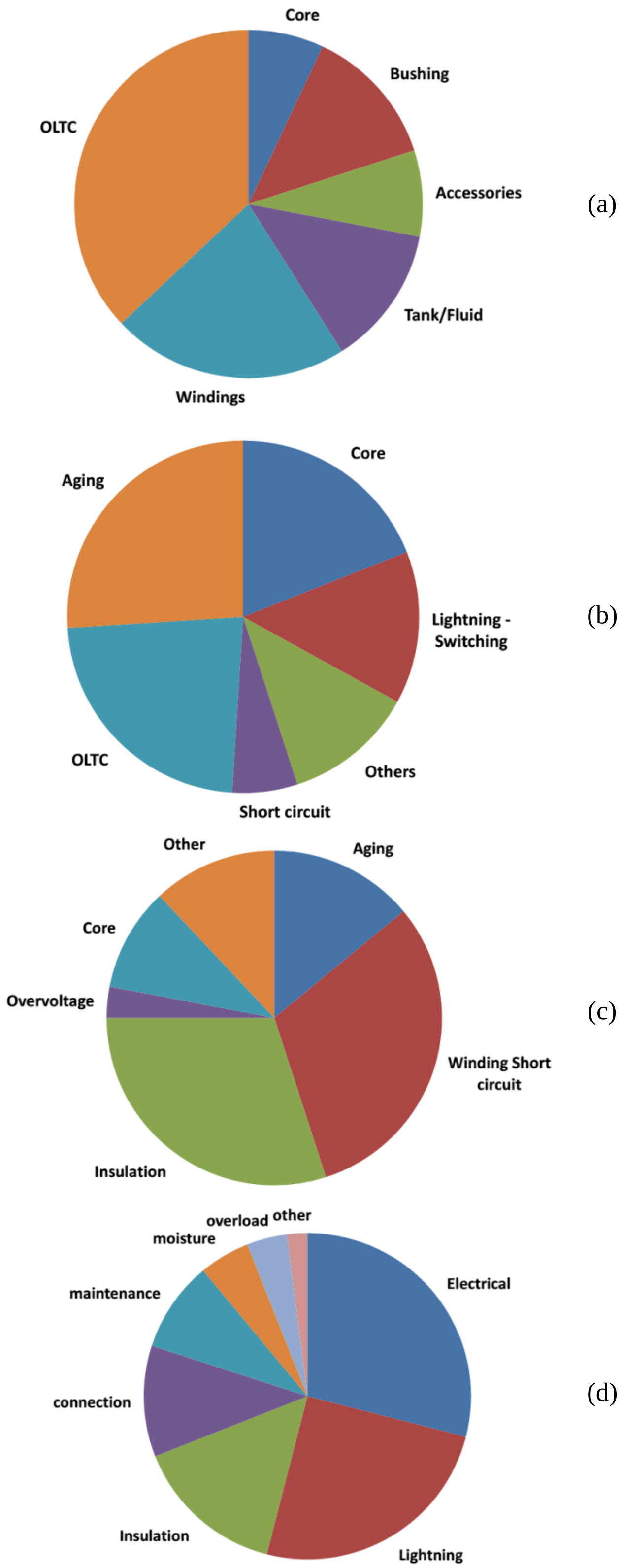


Fig.2 Failure surveys available in the literature (a) Cigre [1], (b) ESKOM [3], (c) Russia [11] and (d) Utilities in USA[17]

In all cases however the registered failures can be classified in four main categories, which are related to four main subsystems that may be considered in a power transformer [7]. These subsystems are:

(a) the electromagnetic system ,
(b) the current carrying system,
(c) the dielectric system and
(d) the mechanical system

An average classification based on the surveys in [1,3-6,11] is illustrated in figure 3. It is evident that the dielectric and the current carrying system in a transformer demonstrate increased failure levels. However all four systems appear to have significant impact in the possibility of a failure and thus must be considered.

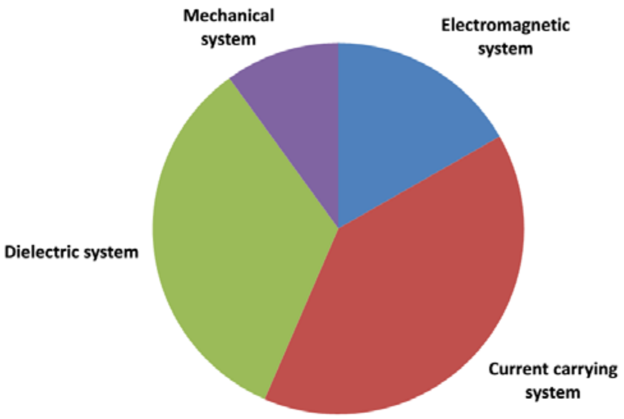


Fig. 3 Failures classification (average) according to the surveys in references (average)

In addition to the classification illustrated in figure 3 the ability of maintenance must be considered. There are failures that can be repaired on site and the mean repair time can be limited and failures that can result to long term unavailability of the transformer. Further failures that can be found inside the transformer tank, usually require increased repair times.

B. In the case Crete

In the case of Crete, a failures survey specifically for substations has been performed, including the period from 1995 until 2013. The results of this survey are illustrated in figures 4 to 6. Firstly the distribution of failures per year is illustrated in figure 4, where there appears to be an increase of failures since 2000, reaching a peak at 2005 and then maintaining increased levels until 2008, with the exception of 2006. For the same time period and group of reported failures in figure 5 the monthly distribution of failures is depicted. It is evident that an average occurrence per month can be considered.

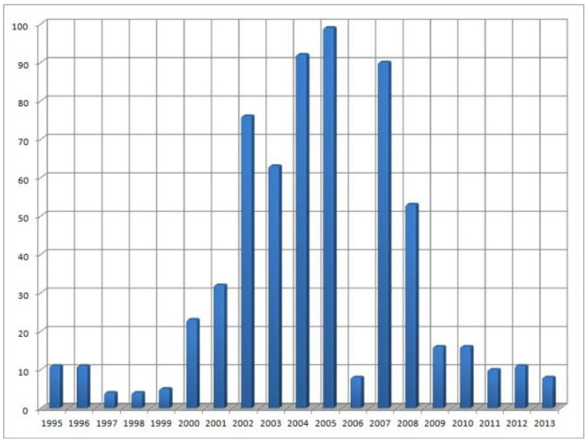


Fig. 4 Failures distribution per year in the case of substations in Crete, period 1995-2013.

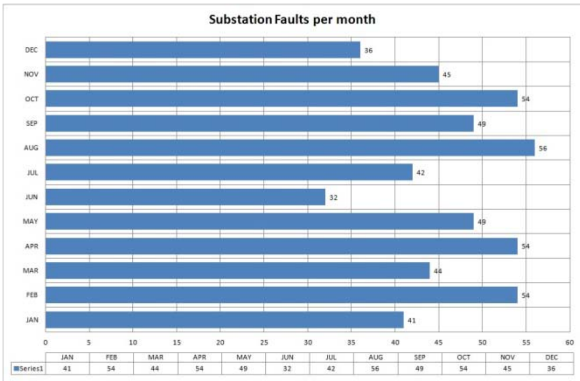


Fig. 5 Failures distribution per month, in the case of substations in Crete, period 1995-2013.

The monthly distribution of failures in figure 5, indicates that there is no reference between the failures occurrence and the time of operation. Thus the possible environmental influence, including pollution of outdoor insulators, and lightning, is less considerable in the case of substations than transmission lines. Further the incremental tendency of the experienced failures in substations, found from 2000 until 2008, can be attributed to the fleet of circuit breakers that were in service in Crete. The contribution of circuit breakers to the total amount of failures is evident also in figure 6, were the frequency distribution of failures, in function of the equipment type is illustrated. It is evident that circuit breakers related failures are the primary occurrence reported, power transformers are second and finally high voltage capacitors third.

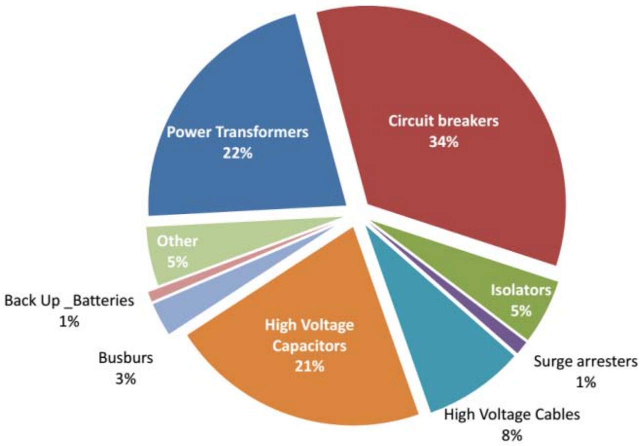


Fig. 6 Failures classification in reference to the type of equipment year in the case of substations in Crete, period 1995-2013.

In response to this tendency, a replacement program for circuit breakers was established in 2007 and the improvement achieved is evident in the reported failures after 2008. This reveals the impact that a group of equipment can have in the reliability of a power system. Fortunately, in the case of circuit breakers, replacement is possible, both technically and financially, thus the problem was resolved. In the case of power transformers on the other hand, most of the times replacement is not an option.

C. The power transformer fleet in Crete

The condition assessment of a transformer fleet is quite difficult, considering that there are many parameters to be considered and there are not clear criteria to evaluate the importance of each parameter for the transformer condition. The first step is to evaluate fundamental parameters such as the transformer age and the experienced loading. As already has been mentioned there are 64 150kV power transformers in service. Thirteen manufactures have been reported, were two of them can be considered more frequent, as illustrated in figure 7.

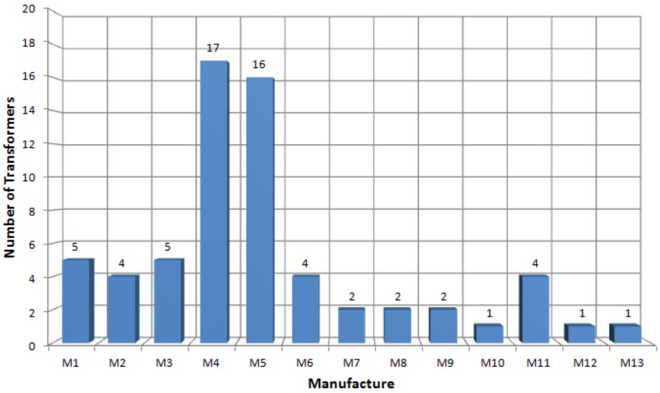


Fig. 7 Transformer distribution per manufacture in the case of substations in Crete, (2013).

The majority of these transformers, especially in the case of step down substations have a nominal power of 50MVA and also there is a considerable number of 25MVA. Further there are transformers at other power levels, mainly step up transformers and the largest at 78MVA.

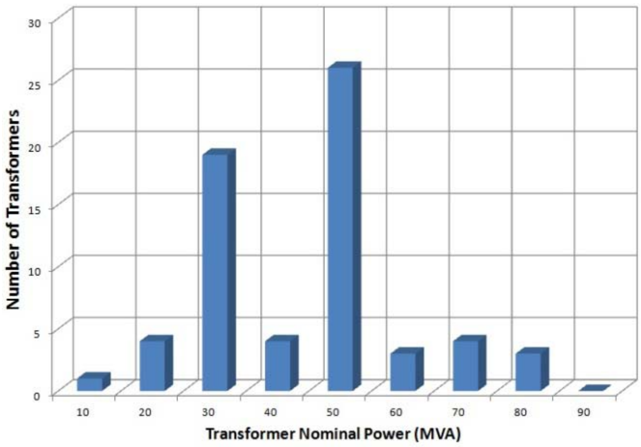


Fig. 8 Transformer distribution per nominal power in Crete, (2013).

The age of these transformers can be evaluated from the distribution of figure 9. Considering a transformer effective lifetime of 40 years, it is evident that 65% of the transformers are today around the middle of their estimated lifetime, 13% are relatively new and 22% are reaching the end. It must be noticed that the limit of 40 years is selected according to the available literature and it is not absolute. Thus a transformer older than 40 years may perform as desired.

Nevertheless, the distribution of transformers according to their age reveals a considerable number of transformers, which are either too old or new. If this condition is correlated to the typical bathtub curve, usually employed to describe the expected failure rate of equipment, 35% of the power transformers that are in service, operate within a critical period. Further if the maximum transformer age is increased to 60 years, this amount is limited at 13%.

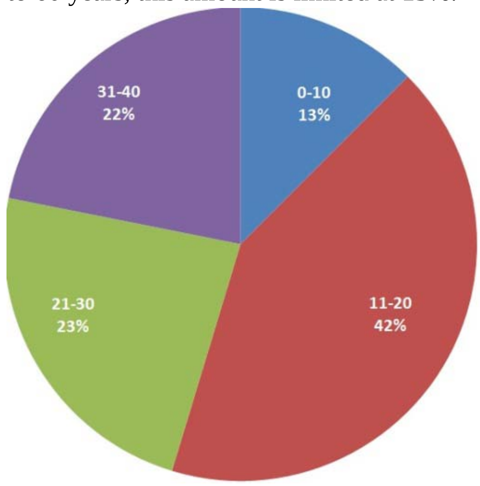


Fig. 9 Transformer distribution per age in the case of substations in Crete, (2013).

Finally, transformer loading is also an issue. Considering that for the reliability of the power system, the loading capability is evaluated at the substation level, the possibility of substation operation, in the case of a transformer failure is evaluated. In Crete, in the majority of the step down substations, two power transformers are installed. The typical configuration of such a substation is illustrated in figure 10. In addition there are three substations with three transformers and two with one.

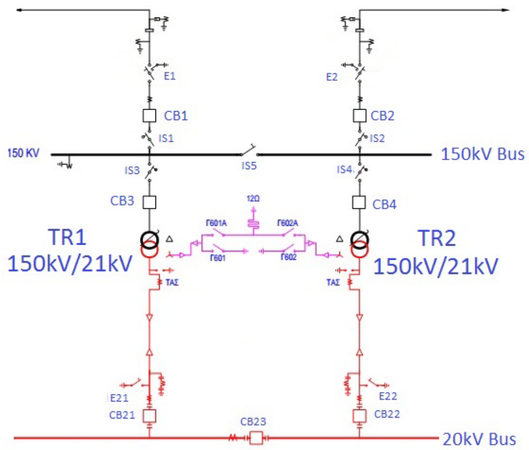


Fig. 10 Typical substation configuration with two 150kV/20kV power transformers.

Further the possibility of full substation operation with one transformer in service, for both two and three transformers operation, is evaluated in figure 11, considering the loads reported in 2013. In addition, operation with two transformers in the case of three transformers substations is also included in figure 11. It is evident that 58.62% of the installed transformers will be overloaded, in a case of single transformer operation. Also in the same case 13,79% will loaded at a level exceeding 80% of the nominal power. In the case of substations with three installed transformers, the number of transformers overloaded is limited to 11,11%.

Consequently, considering that transformer repairs may be time consuming and in many cases cannot be implemented in the field, in order to ensure electricity supply and maintain sufficient levels of reliability, monitoring and preventive maintenance are required.

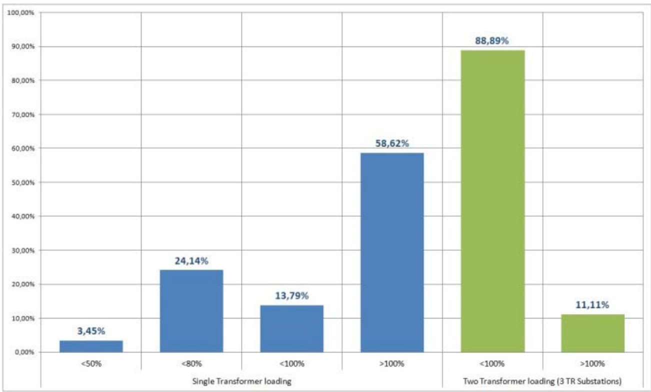


Fig. 11 Loading in the case of single transformer operation in two and three transformer substations (blue) and two single transformer operation in three transformer substations, considering maximum loads in 2013.

IV. POWER TRANSFORMER MONITORING TECHNIQUES

There are many monitoring techniques available today that can be implemented in order to facilitate the condition assessment of a power transformer [11, 15-17]. In figure 12, a classification of the most important techniques, according to the literature is illustrated.

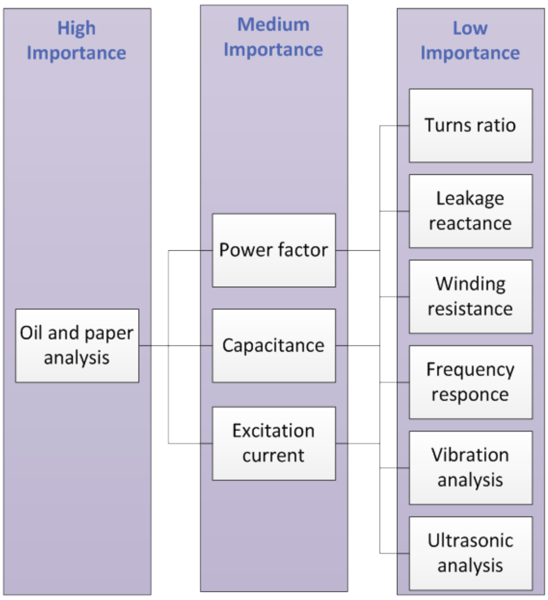


Fig. 12 Importance classification of transformer diagnostic techniques usually implemented [11].

The classification of figure 12 is based upon the fact that the insulation system is very important for the power transformer and in most cases it has the greatest repair difficulty. Thus dielectric failures can be very critical and characterized by long repair times. However, in a more general perspective, the importance of diagnostic techniques related to the current carrying system should also be increased, since failures in this system are equally often, as illustrated in figure 3.

Finally in all cases the realization of reliable criteria is also an issue, difficult to fulfill. In this case results from the literature, comparison with similar transformers and systematic measurements can help, in order to detect possible tendencies that may reveal problems. Therefore, a systematic methodology is required, in order to determine the optimum monitoring intervals and techniques that will ensure reliable condition transformer condition assessment.

V. ASSESSMENT OF A MAINTENANCE MONITORING INDEX

The aim of this study is to develop a simple estimation technique that will enable an efficient formulation of the maintenance strategy. The final outcome of this technique is an index, called Condition and Maintenance Index (CMI) which will reveal a priority sequence for maintenance and monitoring actions. The value of this index is the result of a multi parameters weighted calculation, which for the first step is quite simple. The considered parameters are the following:

a) Transformer status

- Age of the transformer: considering the "bathtub" curve and an estimated transformer lifetime of 40 years, the influence of age is considering by the parameter ka, where:

$$k_a = \begin{cases} 1, \ \ 0-10 \ years \ old \\ 0.5, 10-30 \ years \ old \\ 1, > 30 \ years \ old \end{cases}$$

- Estimated failure rate evaluated mainly from the failure history of the same type transformers, indicated by the parameter kf, where:

$$k_f = \begin{cases} 0.3, low \ failure \ rate \\ 0.6, moderate \ failure \ rate \\ 1.0, high \ failure \ rate \\ 0.8, no \ info \end{cases}$$

b) Transformer loading

The capability of maintaining customers supply is the criterion that is primary evaluated in this case. Further, in multi transformer substations, assuming that one or more of them are in failure condition, the loading level of the transformer in service is considered. The importance of the transformer loading is included in parameter k_l, where:

$$k_l = \begin{cases} 1.0, single \ transformer \ operation \\ 1.0, overloaded \ transformer \ in \ MTO \\ 0.5, MTO, loading \ level < 70\% \\ 0.7, MTO, loading \ level \ 70-100\% \end{cases}$$

MTO: Multi Transformer Operation

c) Monitoring status

There are many diagnostic techniques that can be implemented in order to estimate the condition of a transformer. The techniques usually implemented are illustrated in figure 12. For a four levels evaluation is adopted as follows:

Poor:	kt=1	(immediate action)
Low:	kt=0.9	
Moderate:	kt=0.7	(presently action)
Acceptable:	kt=0.4	
Good:	kt=0.1	(no action)

Further the impact of each method, according to the level of importance illustrated in figure 12 is weighted by the λi factor as follows:

$$\lambda_i = \begin{cases} 0.8, & low\ importance \\ 0.9, & medium\ importance \\ 1.0, & high\ importance \end{cases}$$

Thus for the monitoring status an index (MI) is formed, illustrated in Equation 1.

$$MI = \sum_{i=1}^{N} k_{ti}\lambda_i \quad (1)$$

The proposed technique is summarized in figure 13:

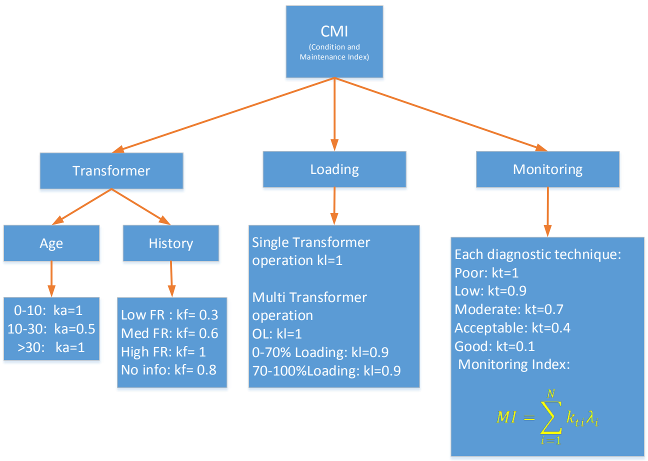
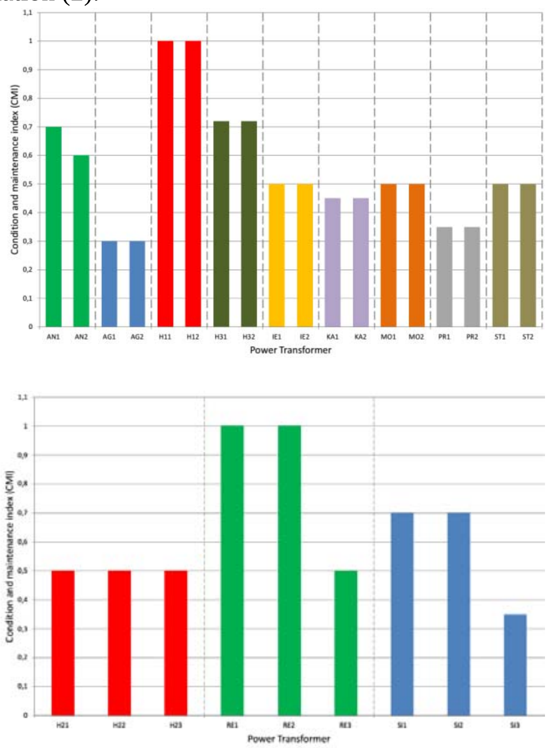


Fig. 13 Condition and maintenance index (CMI) assessment.

Furthermore, the condition and maintenance index can be calculated from equation (2), where A1 to A4 are employed in order to set the importance of each condition parameter.

$$(CMI) = (A_1k_a) * (A_2k_f) * (A_3k_l) * (A_4MI) \quad (2)$$

Assuming the same monitoring index (MI) for all the transformers, the results of the application for the step down substations in Crete are illustrated in figures 14a and 14b, for two and three transformer configuration. The calculations result in the same CMI index for transformers of the same substation, since usually they are of the same power, age and manufacture. In this case the difference will occur when the results of the monitoring techniques are incorporated. Nevertheless, there are differences between substations, which are found due to the degree of loading, if a single transformer operation is enforced. Further in the case of substation H1, the increased level of the CMI index is related to the age of the transformers. In this substation a dielectric failure in transformer No1 occurred and was detected by the operation of the differential protection and buchholtz relay. Further, the failure occurred in the main winding and it was verified by the measurement of the winding resistance and the transformer ratio. In the case of three transformer configuration, assuming the worst scenario, where two of the transformers are out of service, the CMI index is higher for the transformers that are able to supply the full substation load, thus the transformer of the higher power capacity. Of course, in this case also the calculated CMI index can be changed when the monitoring index is considered. Finally the technique can be further optimized, by weighting parameters such as A1 to A4 in equation (2).



(a)

(b)

Fig.14 Calculation and maintenance (CMI) index for a part of the step down power transformers fleet in the 150kV transmission system of Crete

VI. Conclusions

The performance and reliability of power transformers are critical issues for a power utility. The possibility of a failure, especially when the dielectric system is concerned, can become critical, since both the maintenance cost and difficulty are increased. Considering in the same time that reduced maintenance cost and maximum transformer exploitation are required, efficient monitoring and maintenance strategies are necessary in an effort to achieve the optimum fleet management. The first step in this direction is to implement simple techniques able to classify the evaluated transformers and further develop a monitoring and maintenance sequence. In this paper such a technique is introduced, as part of a systematic assessment procedure, implemented in the case of Crete.

VII. References

[1] CIGRÉ Working Group 05, “An international survey on failures in large power transformers in service,” Electra, no. 88, May 1983

[2] M. Wang, A.J. Vandermaar, K.D. Srivastava, Review of condition assessment of Power Transformers in service, IEEE Electrical Insulation Magazine, Vol 18, No 6, November/December 2002

[3] J.N. Jagers, J. Khosa, P.J. De Klerk, C.T. Gaunt, Transformer reliability and condition assessment in a South African utility, XVth International Symposium on High Voltage Engineering, Ljubljana, Slovenia, August 27-31, 2007

[4] M. Abdelfatah, M. El Shimy, H.M. Ismail, Reliability analysis of 220kV power transformers in Egypt, Ain Shams Engineering Journal, Vol 2, 2011

[5] M. Abdelfatah, M. El Shimy, H.M. Ismail, Outage data analysis of utility power transformers based on outage reports during 2002-2009, Electric POwer and Energy Systems, Vol 47, 2013

[6] M. Mirzai, A. Gholami, F. Aminifar, Failure analysis and reliability calculation for power transformers, Journal of Electrical Systems, Vol 2, issue 1, 2006

[7] Cigre brochure No 227, Life management techniques for power transformers, WG A2.18, June 2003

[8] Cigre brochure No 298, Guide on Transformer Lifetime data management, WG A2.23, August 2006
[9] Cigre brochure No 343, Recommendations for Condition Monitoring and Condition Assessment Facilities for Transformers, WG A2.27, April 2008
[10] E.J. Figueroa, Managing an aging fleet of transformers, 6th Southern Africa Regional Conference, CIGRE 2009
[11] X. Zhang, E. Gockembach, Asset-Management of Transformers Based on Condition Monitoring and Standard Diagnosis, IEEE Electrical Insulation Magazine, Vol 24, No 4, July/ August 2008
[12] A. Jahromi, R. Piercy, S.Cress, J.R.R. Service, W.Fan, An approach to power transformer asset management using health index, IEEE Electrical Insulation Magazine, Vol 25, No 2, March/April 2009
[13] P. Wouters, A. van Schijndel, J. Wetzer, Remaining lifetime modeling of power transformers: Individual assets and fleets, IEEE Electrical Insulation Magazine, Vol 27, No 3, May/June 2011
[14] M. Fischer, S. Tenbohlen, M. Schafer, R. Haug, Determining power transformer's sequence of service in power grids, IEEE Transactions on dielectrics and electrical insulation, Vol 18, Issue No 5, October 2011
[15] M. Wang, A.J. Vandermaar, K.D. Srivastava, Review of condition assessment of Power Transformers in service, IEEE Electrical Insulation Magazine, Vol 18, No 6, November/December 2002
[16] T.K.Saha, Review of modern diagnostic techniques for assessing insulation condition in aged transformers, IEEE Transactions on dielectrics and electrical insulation, Vol 10, Issue No 5, October 2003
[17] R. James, W. Bartley, Transformer asset management, Weidmann-ACTI Inc Second Annual Conference, New diagnostic concepts for better asset management, November 2003

VIII. Biographies

Kiriakos Siderakis was born in Iraklion in 1976. He received a Diploma degree in Electrical and Computer Engineering in 2000 and the Ph.D. degree in 2006 from the University of Patras, Greece. Presently, he is an Assistant Professor at the Department of Electrical Engineering, at the Technological Educational Institute of Crete. His research interests include outdoor insulation, electrical discharges, high voltage measurements and high voltage equipment diagnostics and reliability. He is a member of the Greek CIGRE and of the Technical Chamber of Greece.

Dionisios Pylarinos received a Diploma degree in Electrical and Computer Engineering in 2007 and the Ph.D. degree in the same field in 2012 from the University of Patras, Greece. He is a researcher/consultant for the Public Power Corporation Greece and the Hellenic Electricity Distribution Network Operator, Greece since 2008, in the field of HV insulator testing and monitoring and he is a part of the team behind Talos High Voltage Test Station. He is a member of the Technical Chamber of Greece and of the Greek National CIGRE Committee. His research interests include outdoor insulation, electrical discharges, leakage current, signal processing and pattern recognition.

Emmanuel Thalassinakis received the Diploma in Electrical and Mechanical Engineering and also the Ph.D. degree from the National Technical University of Athens. After working for the Ministry of the Environment, in 1991 he joined the Public Power Corporation (PPC). He is the Assistant Director of the Islands Network Operations Department of the Hellenic Electricity Distribution Network Operator S.A., a former part of PPC.