RELIABILITY INDICATORS AND CONDITION MONITORING OF POWER TRANSFORMERS – CASE STUDY

REXHEPI V., NAKOV P.
*Technical University of Sofia, Faculty of Electrical Engineering, Boulevard “Sveti Kliment Ohridski”, 8, 1000, Sofia, Bulgaria,
vezir.rexhepi@gmail.com, pnakov@tu-sofia.bg

Abstract – Transformers are sophisticated equipment in the power system compared to other elements, and as such, they require a continuous monitoring and diagnosis for safe and reliable operation. Their importance in the functionality of the power system is multiple. Monitoring techniques are used to follow their operational work and consistency. There should be listed monitoring and testing methods, collection data, parameters, failures and outage statistics, electrical and thermal parameter status, and diagnosis for determining their operating performance. Based on case analysis according to loads of the power system, a load of transformers and network topology are discussed regarding the results. In this case, are taken into account the network topology of the Kosovo Transmission System, failure statistics, failure effects and reliability indices. The model and simulation cases are performed with the NEPLAN software. These models also illustrate the cost of a failure modes in the power transformers in the different scenarios.

Keywords: reliability indicators, power transformer, monitoring and diagnosis, failure modes.

1. INTRODUCTION

One of the first and significant questions is the definition of the reliability of the power system itself [1]. The importance of this definition is so high mainly because the reliability is a technical field, which is relatively new and which is used in many technical areas. Experts are not of a unique opinion about the definition of reliability and application of its definition in a common way. In some cases, the term reliability can be related to a product or a process. Also, in the power systems, where the term of reliability is divided into adequacy and security. The adequacy is related to the existence of sufficient generation of the electric power system to satisfy the consumer demand. The security is related to the ability of the electric power system to respond to transients and disturbances that occur in the system [2].

A system is a group of components, which are associated or connected to perform a specific function or more functions. A failure is an inability of a part or equipment to carry out its specified function. A fault is an event of broader meaning than the failure and includes the failures of specific equipment and their related features needed for the proper operation of the equipment [3].

Condition monitoring focuses mainly on the detection of incipient faults inside the transformer that are caused by the gradual deterioration. Some of these incipient faults may be detected during routine maintenance; however other faults may cause numerous problems before the regular maintenance cycle. Operating conditions and continuous monitoring of the status of electrical, thermal and mechanical parameters is one of the fundamental elements for determining the operational continuity safer transformers [4].

The faults which can appear in power transformers can interrupt the distribution of electricity leading to important losses [5].

The issue of sustainability and safety in operation of electrical insulating fluids is of a great theoretical complexity and practical importance [6].

The Management of maintenance, testing on-line and off-line, as well as the proper functioning of measures and protection, is among the most important factors that define the safety and prevention of power transformers of possible defects. Modern and smart devices also significantly increase security and facilitate the control and diagnosis of transformers.

2. SECURITY CRITERIA ASSESSMENT OF THE POWER TRANSFORMERS

Transformers except that they are on consumer supply services have an effect on the electrical power system configuration and topology his influence. Having in mind the placement of their respective nodes starting from the node where generators are located, and busbars for the transformation of network transmission levels 400/220/110 kV. Well, except for the effect of transformer power system security is also reflected in the optimization of the electrical network [7].

Transmission limits – for each of the transmission components (lines and transformers), power transfer should not violate its rating during both normal and contingency (N-1), so:

$$b_k(\theta_i - \theta_j) \le P^{No}{}_k \quad \forall k \in (L_c + L_t + L_e)$$
$$b^m{}_k(\theta^m{}_i - \theta^m{}_j) \le P^{Co}{}_k \qquad (1)$$
$$\forall k \in (L_c + L_t + L_e) \cap m$$

Where $P^{No}{}_k$, $P^{Co}{}_k$ are the element k ratings during normal and contingency conditions, respectively: θ_i, θ_j are the voltage phase angles of the line k during normal conditions: $\theta^m{}_i$, $\theta^m{}_j$ are the voltage phase angles of the line k, following contingency m; C is the set of contingencies, and L_c, L_t, L_e are as defined earlier [8].

Contingencies and N-1 criteria – the total number of $N-1$ security constraints is very large and equals $n(n-1)$ for the system with n transmission and transformer branches. In the practical sense, power transmission systems are usually designed well within the capacity of the system load and generation. Only a small proportion of lines and transformers may be overloaded, even if a single branch outage occurs. To detect all the possible over constrained cases, which must be considered, a fast contingency analysis for a single line and transformer outage must be performed [9].

The most accurate method is to rebuild the bus admittance matrix and resolve the load flow equations for each line outage state. The additional power $\Delta P_i + j\Delta Q_i$ and $\Delta P_j + j\Delta Q_j$ are injected at buses i and j, respectively, in the pre-outage state. If the additional power injections can produce power flow increments so that power flows on the rest of the system are the same as those in the post-outage state. In the post-outage state, we have:

$$P_i + jQ_i = P'_{ia} + jQ'_{ia}$$
$$P_j + jQ_j = P'_{j\beta} + jQ'_{j\beta} \qquad (2)$$

In the equivalent power injection case;

$$(P_i + \Delta P_i) + j(Q_i + \Delta Q_i) =$$
$$(P'_{ia} + P_{ij} + \Delta P_{ij}) + j(Q'_{ia} + Q_{ij} + \Delta Q_{ij})$$
$$(P_j + \Delta P_j) + j(Q_j + \Delta Q_j) = \qquad (3)$$
$$(P'_{j\beta} + P_{ji} + \Delta P_{ji}(+j(Q'_{j\beta} + Q_{ji} + \Delta Q_{ji})$$

Where $P_{ij} + jQ_{ij}$ the $P_{ji} + jQ_{ji}$ are the power flows on-line $i-j$ in the pre-outage state and $\Delta P_{ij} + j\Delta Q_{ij}$, $\Delta P_{ji} + j\Delta Q_{ji}$ are power increments on-line $i-j$ due to additional power injections to the pre-outage state. So, we have equations [10]:

$$\Delta P_i + j\Delta Q_i = (P_{ij} + \Delta P_{ij}) + j(Q_{ij} + j\Delta Q_{ij})$$
$$\Delta P_j + j\Delta Q_j = (P_{ji} + \Delta P_{ji}) + j(Q_{ji} + \Delta Q_{ji}) \qquad (4)$$

Voltage stability and under voltage – voltage stability is stability as being the ability of a system to maintain voltage such that when load admittance is increased, load power will increase so that both power and voltage are controllable. Voltage stability problems are manifested by several distinguishing features: low system voltage profiles, heavy reactive line flows, inadequate reactive support, and heavily loaded power systems. The voltage collapse typically occurs abruptly, after a symptomatic period that may last in the time frames of a few seconds to several minutes, sometimes hours [11].

Load shedding – load shedding is a process that applied in the case of system violations after a contingency, overloading or before collapse system. As known, this is a process more complex mechanism that results in load curtailment.

Based on policy and principle as illustrated in the ENTSO-e, transmission operators are obligated to make load shedding during severe outage events. It should be applied to load points in some of the substations. During severe outage or risk of the power system, one method is to adopt optimal power flow techniques to minimize the load shedding after severe outages. In this context, transformers should be part of the action by tap changer or optimization techniques [12].

Failure Effect Analysis – this technique is a powerful reliability assessment and use of electrical and mechanical equipment. It is powerful design tool to analyze engineering systems and analyse each failure modes on the network. By the analysis of individual failure modes, the effect of each failure can be determined by the operational functionality of the relevant system hierarchy level. So, failure analysis can be performed in seven steps based on the key concepts of systems hierarchy, operations, functions, failure mode, effects, potential failure and prevention.

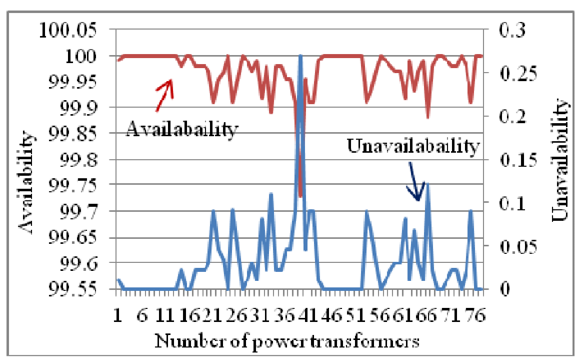

Fig.1. Availability and unavailability of power transformers in the power transmission system of Kosovo

In Fig. 1 is shown the probability of outages of the power transformers during the year of 2016 in KOSTT based on statistical data. In this picture are expressed the two components of probability such as availability, unavailability and impact on interruption of the load at buses 35/10/6 kV voltage levels.

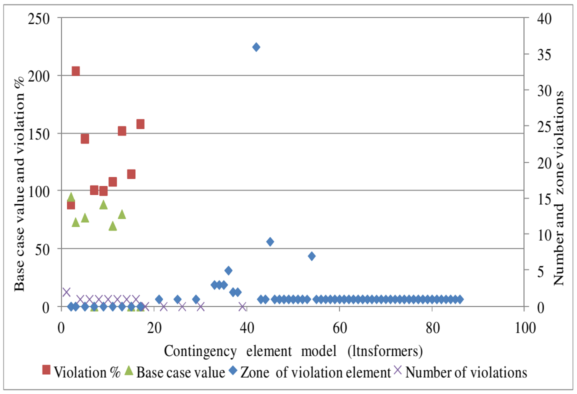

Fig.2. Violated and contingency elements (transformers) in the power system of Kosovo

In Fig.2 is presented the violated elements, zone, and contingency analysis of the power transformers in power system of Kosovo – KOSTT, simulated by NEPLAN software.

3. CONDITION ASSESSMENT MODEL FOR POWER TRANSFORMERS ANALYSIS

For detailed analysis concerning the functionality of the power system, it is essential to discuss and present concrete models that facilitate and clarify the work of key components. A variant of Failure Mode, effects and critically analysis which include a critical evaluation based on critically numbers taking into account the failure effect probability, the failure mode ratio, the components failure rate and the operating time for each item failure mode [13].

Reliability centered maintenance of a power transformers is a relatively new trend in research with important economic implications [14].

Model includes components such as transformers, generators, lines, loads, the topology of the network, focusing on transformer status. Also, taken into consideration outage cases, contingencies and unscheduled maintenance.

The case study presents the modeling of the power system from 110 kV to 400 kV voltage level, with power system components, such as; generators, lines, transformers, busbars, loads, circuit breakers, which are summarized in table 1.

Table1. Implemented components on model of transmission system operator of Kosovo

Nominal voltage kV	400	220	110	35	10	6
Number of generator units	2	3	3			
Number of transmission lines	8	10	55			
Number power transformers	9	13	57			
Number of buses	3	6	32	17	21	1
Number of load points				16	21	1

Estimation of transformer status due to failures, planned and unplanned outages, ageing, voltage levels and maintenance are illustrated in Fig. 3. The flow chart that is in the discussion for analysis describes the factors involved and should be considered into account in assessing and setting the operating conditions. The combination of methods and techniques to identify and finding the incipient and hidden failures that impact to the work transformers during their operation is the main objective. Based on this, it has been shown the ranking of factors and primary elements for monitoring and diagnosis. However, the techniques of monitoring and evaluation of operating conditions of the parameters for the development of procedures that diagnose the performance of transformers and assist in their management in working conditions should be considered.

Therefore, the evaluation of transformer parameters and their prioritization, comparison and assessment of the probability of risk and possible disruption constitutes a necessary approach to achieving the objectives for an adequate modeling of transformer parameters [15].

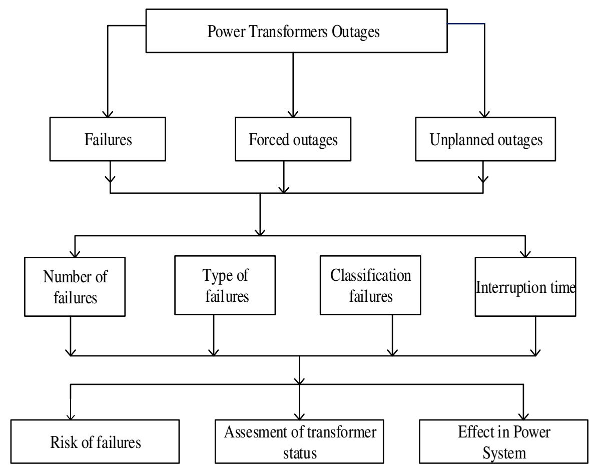

Fig.3. Factors for security and reliability assessment and transformer operation

Fig.3 summarizes the main factors for handling power transformer condition such as failure numbers, outages, failure classification, interruptions and types, unplanned outages during operation. In other words, the diagram provides a more detailed overview of problem-solving, classification, and helps in searching methods for analysis and maintenance as well as a more efficient approach to discussing transformer functionality issues.

These factors are used as a model related to discuss and analyze the situation in Kosovo's transmission system. A good classified model helps to achieve results as well as increase the reliability and safety of transformers by enabling measures to prevent possible defects and consequences they may have on the security of the power system as a whole. Previously, knowledge of the problems and the classification of the occurrences encountered by the transformers is an aid for taking remedial measures as well.

3.1Reliabiity modeling of the power transformer parameters

Models that evaluate the operational status of the transformers include some parameters that are primary in assessing their work. Among others, the performance of transformers' work is entered in several time periods. The model in Fig.4 shows the estimation of the level of reliability and status of transformer parameters. Regarding functionality and reliability, cases are dealt with according to the maximum and minimum loads scenario regimes of operation of the power system. Thus, the evaluation of transformer parameters and their prioritization, comparison and assessment of the probability of risk and possible disruption constitutes a necessary approach to achieving the objectives for an adequate modeling of transformer parameters.

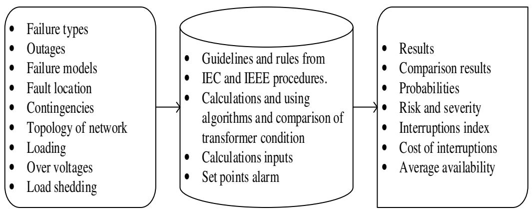

Fig.4. Flowchart design of assessment the power transformer parameters and failures

Fig. 4 includes the structuring of detailed data that describes the status of transformers in achieving results related to operational performance and analysis of their functioning. All parameters are included in the template foreseen by configuration and different load and topology scenarios. Such models are simulated and modeled through the NEPLAN software package.

The technical diagnosis of the energy-technology processes has been developed in recent years, the consequence being the appearance of some diagnosis method accepted in practice, the starting point of there is the approach the model [16]

In the model are populated data regarding the types of outages, failures, maintenance, the time to repair, and finally the cost calculations. Such parameters are processed and compared to IEC and IEEE standards, as well as other statistical methods. Whereas based on the diagnosis of each transformer, the results compared to different periods, loads, trends, alarms and events are explained.

4. FAILURE ANALYSIS OF THE POWER TRANSFORMERS

The reliability of transformers is a prime concern for power systems. The analysis will predict the transformer reliability and costs based on relevant degradation mechanism. There are several ways in which transformer can fail. This failure can usually be attributed to the failure of a component, such as; a tap changer bushings, windings, core, tank and dielectric fluid [17].

Moreover, the analysis of failure method is most important to evaluate potential failure and their effects on power transformers. The purpose of the failure assessment is to give ideas and ways to reduce and reveal hidden failures. It takes into consideration some basic steps:

- Identify failure modes associated with systems failures,
- Identify potential effects of failure modes,
- Determine severe risk and their impact,
- Identify available detection methods,
- Identify recommended actions for reducing the severity of each failure [18].

The analyzing includes causes and types of failures of the power transformers in the Kosovo Power System, for a period of nine years from 110 kV, 220 kV to 400 kV voltage levels with 20 MVA - 400 MVA power rating. Failures are calculated according to the following expression:

$$\lambda = 100\% \frac{n_1 + n_2 + \dots\dots + n_i}{N_1 \circ T_1 + N_2 \circ T_2 + \dots\dots + N_i \circ T_i} \quad (5)$$

λ - the failure rate expressed in failures per unit of time [failure/time], n_i-the number of failures by i-th population (failure/year), T_i-is the reference period of i-th population (in year), and N_i-the number of the transformers of i-th population [19].

Historical data, collection and processing constitute an essential condition for each power system to increase efficiency in preventing defects in power transformers. It is known that the ENTSO-e normative and obligations require this. Therefore, among other things, this is a future objective for data focusing and processing for different analysis and diagnosis.

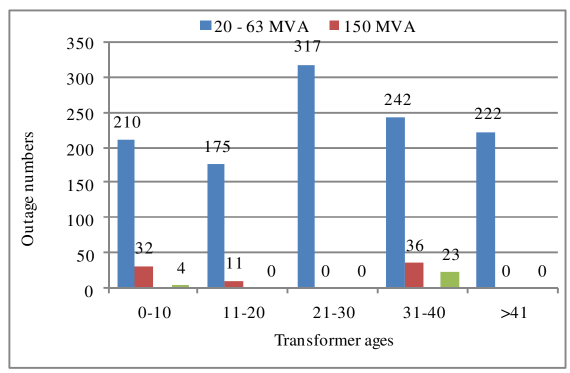

Fig.5. Power transformers outages in the Transmission Power System of Kosovo

Based on Fig. 5 summarized from the years 2007-2016 at the 110 kV to 400 kV voltage levels, the number of outages and failures is particularly highlighted in distributive transformers. Whereas, related to the consequences and causes is summarized the data from 2013 to 2016, the highest outages are at the level of distribution transformers, respectively 110 kV voltage level. According to the statistics, the short circuit's fault (external short circuit) is the main issue due to distribution power system. Then another phenomenon is the oil degradation that is reflected by the activation of the relay protections (Buchholtz relay), due to the internal short circuit, bushing, VT / CT, bus bar, tap changer and wrong operation (Table3).

Regarding the failures occurred in the power transformers, statistics are also given according to their age. Such data are shown in Table 2.

As shown in Table 2, outage/failure, are more pronounced to power transformers over 41 years old, by 17.45%, from 31 to 40 MVA power capacity is 19.02%. While in transformers from 0 – 10 MVA power capacity is 16.5%, as well as the failures in transformers aged from the year 21 to 30, is 24.92%.

Table 2. Failure occurred in the power transformer in Transmission Operator System of Kosovo

Forced outages of power transformers 2007 – 2016				
Age – years	Power installation	Number of transformers	Outages	Percent of outages
0 – 10	20 – 63 MVA	26	210	16.5
	150 MVA	3	32	2.51
	300 MVA	2	0	0
	400 MVA	1	4	0.314
11 – 20	20 – 63 MVA	6	175	13.75
	150 MVA	2	11	0.86
	300 MVA	0	0	0
	400 MVA	0	0	0
21 -30	20 – 63 MVA	15	317	24.92
	150 MVA	0	0	0
	300 MVA	0	0	0
	400 MVA	0	0	0
31 – 40	20 – 63 MVA	8	242	19.02
	150 MVA	4	36	2.83
	300 MVA	0	0	0
	400 MVA	2	23	1.8
>41	20 – 63 MVA	7	222	17.45
	150 MVA	0	0	0
	300 MVA	0	0	0
	400 MVA	0	0	0
Total		76	1272	

The classification of defects and consequences is a key factor in finding and diagnosing problems of the power transformers in continuity. According to IEEE standards and procedures, the causes are defined by the codes (Table 3), as well as the reasons related to them.

Moreover, maintenance according to the condition evaluation has a considerable weight in the proper management of electrical, thermal and mechanical aspects (Fig.6).

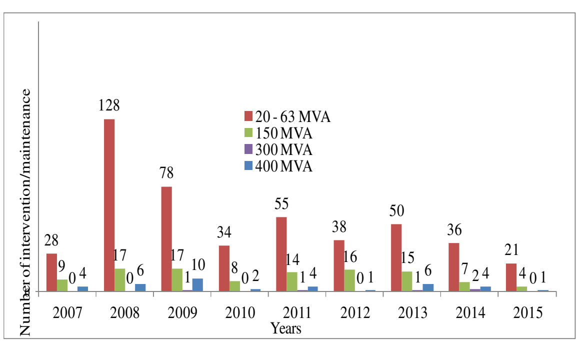

Fig.6. Number of interventions and maintenance of power transformers per year

The number of interventions is considerable; from this, it can be observed that there is a lack of proper management of transformers according to the conditions and status of the operation to their parameters. It indicates that the respective standards are not appropriate towards the monitoring and diagnosis aspects, problems and causes of the failures. Based on the statistical analysis, are analyzed transformers from 20 to 400 MVA (table 3). Based on table 3 it can be noted that the number of outages is 541. From this number, it should be concluded that the external short circuit from distribution operator with 329 outages, are very high, with the consequences of interruptions also should be mentioned the outages in the VT/CT/BB, with a significant effect on the interruption of the power transformers' work, three of them having a high effect on damage and significant economic costs.

In addition to the occurrences that have a negative impact, a significant number of them have not been identified, with a total number of 68 cases. This indicates a deficiency that promotes research into finding the most appropriate monitoring and diagnostic methods.

Table 3. Forced outage sources and probability of power transformers (2013-2016)

Outage number	Outage sources	Outage probability	Conditio 1	Condition 2	Conditio 3	Conditio 4
37/541	Over current protection	0.06		x		
22/541	Differential protection	0.04			x	
7/541	Buchholz protection	0.01	x			
13/541	Ground S.C.F	0.02			x	
1/541	Unbalance phase protection	0.001			x	
4/541	Temperature	0.007		x		
13/541	Oil leakage	0.02	x			
3/541	Tap changer	0.005	x			
2/541	Bushing	0.003				x
5/541	Reactance	0.009				x
1/541	Pump/ Coolers	0.001	x			
8/541	Lightning/ Weather	0.01			x	
329/541	External S.C.	0.6		x		
11/541	Breaker/ Disconector	0.02	x			
11/541	VT/CT/ Bus bar	0.02				x
6/541	Wrong operation	0.01		x		
68/541	Unidentified	0.12			x	

The analysis of Kosovo Operator System is essential to diagnose the power transformers. Hence, this study uses the data for monitoring of the power transformers status in many cases in normal operation, N-1 criterion and emergency operation according to the loading conditions. In this case is described reliability analysis based on network model such as; System Average Interruption Duration Index(SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), System Load Interruption Frequency (F), System Load Interruption Mean Duration (T), System Load Interruption Probability (Q), Total Interrupted Load

Power (P), Total Load Energy Not Supplied (W), Total Load Interruption Coasts (C) are calculated using NEPLAN [20]. There are three main categories of reliability indices that are estimated for every model and usage of indicators such as; 1. Average Failure (F), 2. Average Outage Time (T), 3. Average Annual Outage Time (Q). Other categories are system indices, calculated for groups of loads, areas, zones and whole distribution system: SAIFI, SAIDI, and CAIDI.

The third category is power and energy-oriented indices, calculated for both single loads and groups of loads; 1. Energy Not Supplied (ENS), 2. Peak Power Not Supplied (P) [21].

5. FAILURE INDEX ASSESSMENT OF POWER TRANSFORMERS

Monitoring the transformers' work and their status by assessing events and modeling different load conditions and regimes is an essential component. The case study describes the aspects of security and reliability. It is also discussed the cost concerning the load. Transformer status monitoring includes cases according to;

1. Peak load,

2. Number of power transformers,

3. Transformer status (outages, failures, planned outages, maintenance and network topology).

For the status analysis of the power transformer operation related to failures and reliability evaluation, NEPLAN software packages is utilized. The model includes cases for the peak loads during the winter and summer.

The study includes the cases; with load up to 1090 MW and 650 MW. In the model are included substations (37), interconnection lines (4), 400 kV lines (4), 220 kV lines (10), power transformers (76), power generation units in TPP Kosovo B (2), (B1 = 265MW, B2 = 265 MW), TC Kosovo A (4), (A1 = 80 MW, A3 = 140 MW, A4 = 140 MW, A5 = 140 MW), units in TC Ujmani (2), (U1 = 16 MW, U2 = 16 MW) and TC Lumbardhi (L = 35 MW). The cases are discussed for analyzing of power transformers impact on the power, distribution and generation systems, as well as to consumers.

According to the results, as shown in Fig. 7, the failure index varies by year to year, is important to say that the index changes by load and interruption time. According to the Fig.7, the index of failures is more pronounced in peak loads. That means the short circuits form distribution systems due to loads at low voltage levels, as well as various overloads from distribution systems have an impact on it.

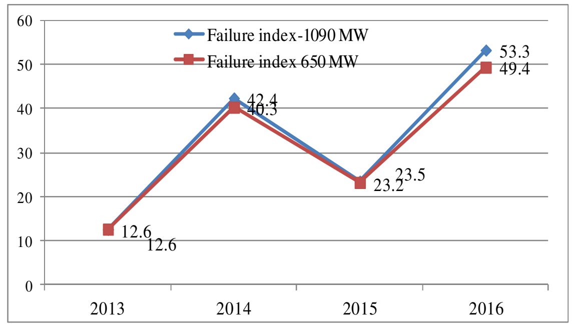

Fig.7. Failure index of power transformers

According to the analysis, the number of failures is higher during the autumn of 2016. The Fig.8 and Fig.9 show the parameters and performance of indicators for the power transformers.

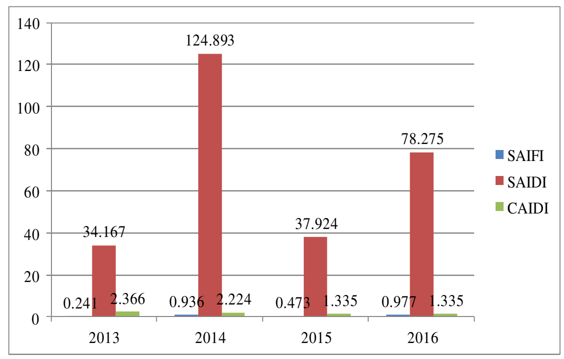

Fig.8. Monitoring of power transformer reliability indicators for peak load 1090 MW based on outages with single mode failures

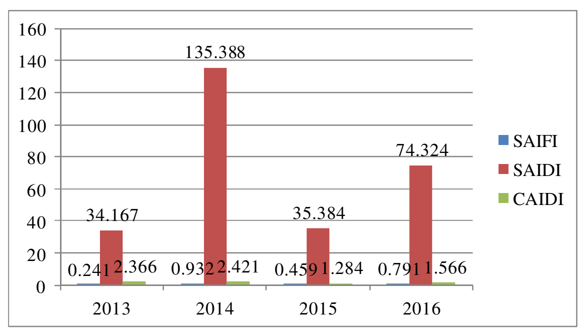

Fig.9. Monitoring of power transformer reliability indicators for peak load 650 MW based on outages with single mode failures

It can be concluded that the evaluation of parameters such as; SAIFI, SAIDI and CAIDI is significant and necessary to know the performance of power transformers and their status operation.

The most important factor is availability index (Fig.10) to identify the status operation of the power transformers. Regarding the analysis based on simulation are presented the state of parameters condition and their availability index over the years. Results are compared to statistical and simulation method. This factor should be taken into consideration to make analysis and to be efficiently related to parameter condition and so on.

However, Average Availability Index (ASAI), is usefully related to topology and security margin.

$$ASAI = 100\% \frac{\sum N_i \times 8760 - \sum U_i N_i}{\sum N_i \times 8760} \quad (6)$$

Also, ASAI can be represented in relation to SAIDI as below;

$$ASAI = 1 - \frac{SAIDI}{8760} \quad (7)$$

U_i - is the annual outage time (in hours) for substation-i and N_i -is the number of customers [21].

From statistics analysis, it can be concluded that the performance of indicators regarding values is more pronounced in 2014 compared to other years. This implies that the level of reliability should be evaluated according to the time of interruption, unplanned outages, topology and customer supply.

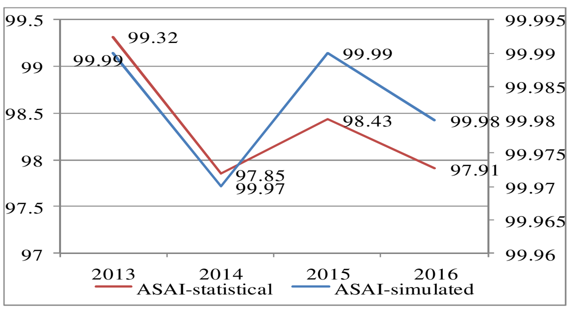

Fig.10. Availability index for the power transformers in the power transmission of Kosovo (2013-2016)

Statistical and simulation methods are compiled, to describe the power transformer availability index during the year 2013-2016.

In Fig. 10 is presented ASAI as calculated by two methods (statistical and simulated) for the power transformers from the years 203 up to 2016 that should be concluded, both results are approximated, except of the year 2015. This means all statistical data and simulated method are approximately each other. Therefore, statistical data must be processed as precisely as possible, so that analysis will result as more accurate.

5.1. Parameter indices assessment

The evaluation of the indicative parameters regarding the status of transformers during their operation is essential regarding continuity of operation for different cases and loading regimes. These indications of the mode operation are determined for a specified period. The monitoring and assessment of such components like; P, Q, F, W, T and C are essential to achieving better reliability of the power transformers.

By implementing correct methods and operational strategies can be controlled and extended their lifespan operation. Also, the performance of the power transformer depends on the reliability indicators and their management by condition assessment of parameters.

In Fig.11 is depicted the performance of reliability indicators. Data recording and processing include methods to evaluate the power transformer parameters in the different conditions and occurrences.

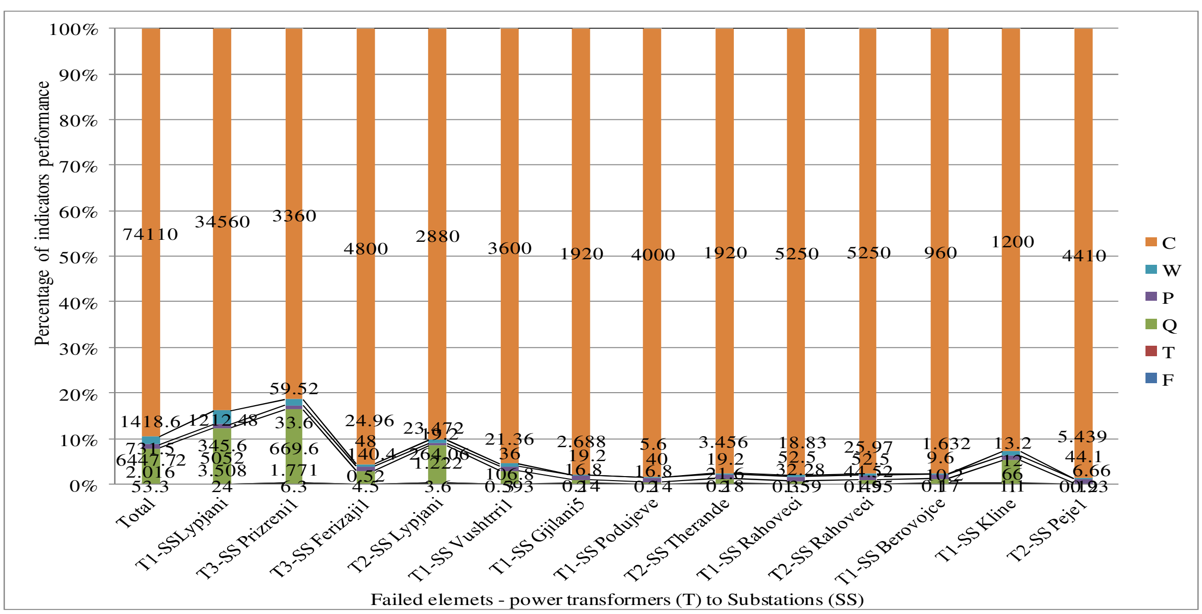

Fig.11. The performance indicators of power transformers

According to the simulations, Fig.11 shows the performance indicators, unloaded P in (MW / yr), the time shown in the interruption of the load with the indices Q [min/yr], the time in hour T (h), the maximum W load (MWh /yr), and the cost of failures for each transformer. It can be concluded that the cost of outages for one year is 74110 €/yr. The higher cost is displayed in SS Lypjani, about 34560 €/yr. It can be assumed that due to non-fulfillment of the N-1 criterion, as well as load capacity is main factors that affect the risk of power system operation. Also, the number of failures is very high as a consequence mainly of the impact of the lines at the distribution network side. Thus, the estimation of the indicators for each transformer gives a more realistic picture of the power transformer operation, and the calculation of the cost of interruptions is also a good opportunity for economic evaluation.

6. FAILURE MODES AND EFFECTS ANALYSIS OF THE POWER TRANSFORMERS AND ECONOMIC COST

The assessment of the status of transformers during their operation in the different failure mode plays a significant role in determining the security situation and supplying of several nodes of the power systems.

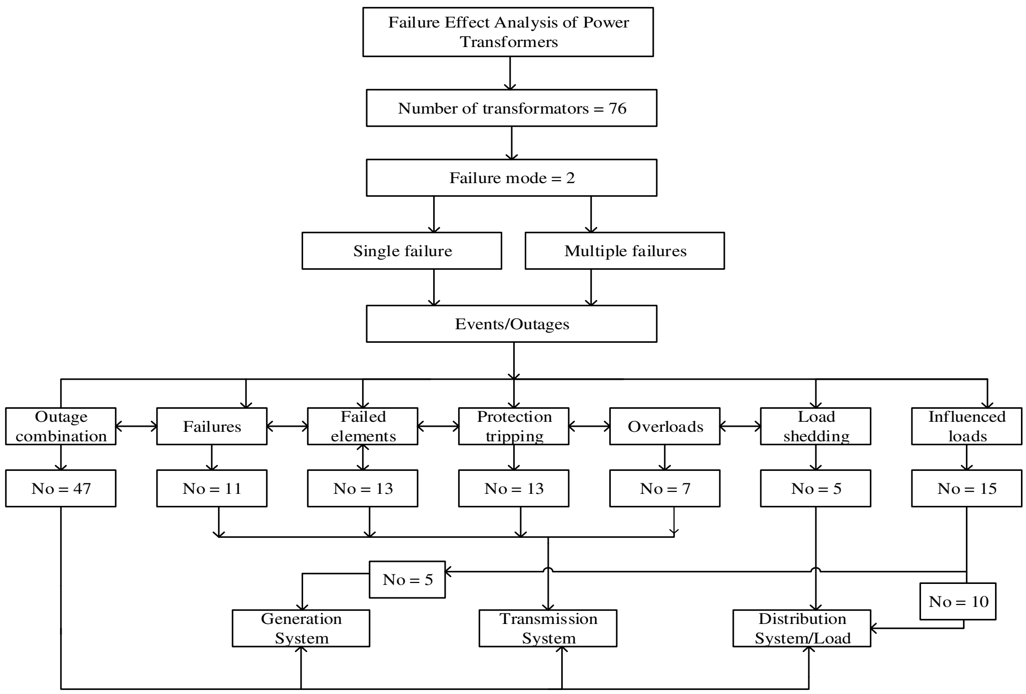

Fig.12. Failure effect analyses of the power transformers in KOSTT during the year 2016, simulated by NEPLAN

Table 4. Reliability indicators of power transformers by NEPLAN

N	-	Total number of customers served	-	403	403
SAIFI	1/yr	System average interruption frequency index	1/yr	0.977	0.797
SAIDI	min/yr	System average interruption duration index	min/yr	77.69	43.02
CAIDI	h	Customer average interruption duration index	h	1.326	0.9
ASAI	%	Average service availability index	%	99.98	99.992
F	1/yr	System load interruption frequency	1/yr	53.3	44
T	h	System load interruption mean duration	h	2.012	1.431
Q	min/yr	System load interruption probability	min/yr	6435.4	3777.0
P	MW/yr	Total interrupted load power	MW/yr	731.5	614.5
W	MWh/ yr	Total load energy not supplied	MWh/yr	1411.4	820.7
C	€/yr	Total load interruption costs	€/yr	74110	6217

The assessing of the failures is useful and their impact on the respective nodes, as well as in the power quality. However, the impact has also an effect on energy balances.

The effect of transformers failure is shown through two cases-modes (single and multiple failures). Also, are described the number of power transformer outages, the number of outage combinations, failures, failed elements, protection tripping, load shedding, overloads, influenced loads, as shown in the Fig.12.

The Table 4 includes reliability indicators and economic costs of electric power system due to transformer outages and their failures. In the first case are included all failures that occur in the power transformer, and in the other case are included single failures (bushing, Buchholz relays, leakage oil and VT/CT/BB (Voltage transformer (VT), Current Transformer (CT) and BusBar (BB).

Moreover, in Fig.13 are depicted results regarding the foremost indicators such as; SAIFI, SAIDI and CAIDI. The analyses are simulated by NEPLAN package, based on modeling of the power system, with focus on the power transformers status.

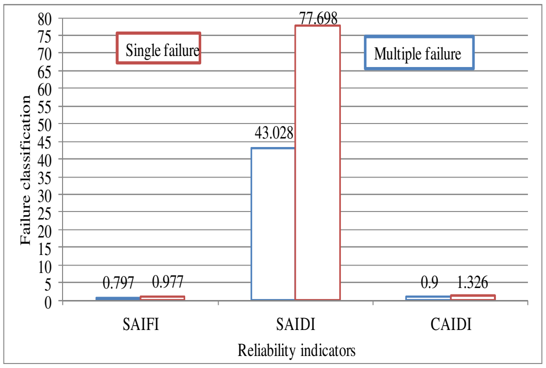

Fig.13. Monitoring transformer reliability indicators by modeling failure mode (single and multiple)

Such cases can be practiced for any combination and configuration of power transformers, and it is most helpful for topology and optimization. The results can be used to indicate the effectiveness of the technique and accuracy in estimating power transformer strength and weakness in the power system. The simulation results can be adapted to power transformers operation and created the algorithm related to their performance.

Hence, evaluation of the reliability indicators describes the components which are out of service at the same time and to others as result of maintenance activity. Thus, processing of failure combination determines the reliability characteristics of the power transformers. The contribution of the failure combination is a picture to obtain the interruptions occurring at each loading node and overall busbars in the power system. However, the way of assessing supply reliability is to estimate it in money. The costs are determined as a result of the power transformers interruptions and unplanned outages.

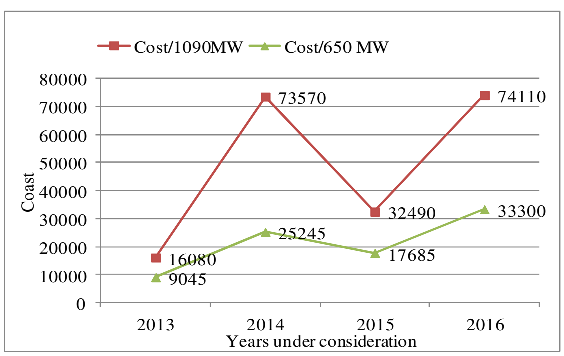

Fig.14. Cost simulated power transformers failure for the years 2013 and 2016

According to the Fig.14, economic cost varies from one or other case, so when taking into consideration all failures the financial cost is 74110 €, while in the second case the cost is lower 33300€.

In the first case all failures are analyzed, and in the second some of the failures are taken into consideration, such as; bushing defects, dissolved gasses, breaker/disconnector, leakage oil, et cetera. Therefore, considered that, if it is taken into account the continuous and timely monitoring, then supposed failures will be considerably smaller.

Assessing the failures except in the aspect of security, reliability and customer supply, it is also necessary to economically evaluate. Then, the analysis is also discussed considering the ratio of outages to two peak loads (winter and summer). Fig. 14 shows the economic cost trend for the reported failures. As compared to the years, the diagram shows that the cost of the failure is higher in the year 2016.

Based on the economic analysis that is supported and dealt with load ratios for two cases, 1090 MW, and 650 MW, it can be concluded that the continuous monitoring and diagnosis approach should be carried out in the configuration of the relay protection and mitigation of the short circuits.

Moreover, in the diagram (Fig.14) is shown the performance of the cost of the failures, according to the modeling power transformers, loads, failures, duration time of the failures and their cost interruption.

7. CONCLUSION

One of the most significant techniques and methods in the operational and functional performance of power transformers are the measurements carried out by the on-line and off-line method. To get acquainted with the working conditions of the transformer and its performance of electrical parameters such as power, active and reactive, currents, voltages, dissolved gas, moisture in oil, oil temperature, winding temperature and other parameters such as electrical ones, thermal and mechanical is needed the practice of smart techniques.

The collection of data showing the performance of electrical, thermal and mechanical parameters of the power transformer plays a primary role in assessing the working conditions and status of electrical and mechanical parts. The statement of the gases, temperatures in the winding and oil, as well as the ambient, is indicative of how the transformer works in the power system.

By IEC and IEEE standards, the reliability indicators through monitoring techniques are performed by analyzing the trend of failures, mode cases and cost of the power transformers' outage/failure during different loading regimes.

Based on the analysis of the outages in power system and impact on customer supply as well as economic costs, more efficient management and continuous or partial monitoring of transformer parameters should be considered, taking into account the importance of transformers in the overall electrical network regarding the security and supply of customers.

REFERENCES

[1]. Short T. A. – Distribution Reliability and Power Quality, Taylor & Francis, Boca Raton, 2006.

[2]. Allan R. N. Billinton R. – Reliability Evaluation of Power Systems, Springer, US, 2011.

[3]. Cepin M. – DEPEND-HRA – A Method for consideration of dependency in human reliability analysis. Reliability engineering and system safety, Elsevier, 2008, pg. 1452 – 1460.

[4]. Nikolina Petkova, Petar Nakov, Valeri Mladenov. – Real time monitoring of incipient faults in power transformer, Springer – Verlag Berlin Heidelberg, 2016.

[5]. Ciulavu C. A. – Techniques for incipient fault diagnosis. Journal of Sustainable Energy, June 2013, Vol.4, Issue 2, pg. 1 – 4, 4p.

[6]. Voina A., Oprina G., Patru I., Ungureanu L. C., Stanoi V., Pica A., Serban F., Lingvay I. – Gassing of the electrical insulating fluids – A determinant factor of the transformers safety in operation. Journal of Sustainable Energy, June 2017, Vol. 8, Issue 2, pg 41 – 46 6p.

[7]. Rebennack S., Pardalos P. M., Pereira M. V. F., Iliadis N. A., - Handbook of Power Systems II, Springer – Verlag Berlin Heidelberg, 2010.

[8]. Hossein Seifi, Mohammad Sadegh Sepasian, - Electric Power Planning, Issues, Algorithms, and Solutions, Springer – Verlag, Berlin Heidelberg, 2011.

[9]. Bosi A., Dind J. E., Frisson J. M., Khoudiakov U., Light H. F., - An Internal survey of failures in large power transformers in service, CIGRE Working Group 12.05., Electra, 1983.

[10]. Tinney W. F., Hart C. E., - Power flow solutions by Newton's method, IEEE, Trans. Vol. 86, November 1967.

[11]. Leonard L. Grigsby, - Power System Stability and Control, Taylor & Francis Group, LLC, 2012.

[12]. Ulf Hager, Christian Rehtanz, Nikolai Voropai, - Monitoring, Control and Protection of Interconnected Power Systems. Springer-Verlag, Berlin, Heidelberg, 2014.

[13]. Albeanu G., Popentiu-Vladicescu FL., - Risk priority number estimation using intuitionistic-fuzzy numbers in power engineering, Journal of sustainable Energy, Vol.6, No.3, September 2015.

[14]. Felea I., Oltean M., Secui D. C., - Experimental research of the electric stress level impact on traditional state parameters of power transformers. Journal of Sustainable Energy, Vol.2, Issue 1, March 2011.

[15]. Vezir Rexhepi, - An analysis of power transformer outages and reliability monitoring. 4th International Conference on Power and Energy Systems Engineering, Energy Procedia, Elsevier, Volume 141, pg.148 – 422, CPESE 2017, 25 – 29 September 2017, Berlin, Germany.

[16]. Felea I., Boja I., Barla E., - State of the art and perspectives regarding the technical diagnosis of power transformers. Journal of Sustainable Energy, Vol.1, Issue 1, March 2010.

[17]. Christian Osorio, Nandan Sawant, - Transformer Lifetime Prediction, April 2014, Stanford University, California, USA.

[18]. Anna Franzen, Sabina Karlsson, - Failure modes and effects analysis of transformers. Royal Institute of Technology, KTH School of Electrical Engineering, January 2017, Stockholm, Sweden.

[19]. Stefan Tenbohlen, - Transformer Reliability Survey. Tutorial of CIGRE A2.37.04, May 2011, Germany.

[20]. BCP Busarello+Partner AG. NEPLAN, Power System Simulator, htpp/:www.neplan.ch, 2016.

[21]. Mokoka O. K. P., Awodele K. O., - Reliability Evaluation of Distribution Networks using NEPLAN & DigSilent Power Factory. Africon, pg. 1 – 5, 2013.