STATE OF THE ART AND PERSPECTIVES REGARDING THE TECHNICAL DIAGNOSIS OF POWER TRANSFORMERS

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Abstract: The paper has four parts. In the first part are presented generalities about technical diagnosis, as in the second part is synthesized the methods and equipments used in technical diagnosis of power transformers. The second part describes the concerns and the results of the authors, scientific papers regarding the technical diagnosis of the power transformers of the distribution systems of electric energy, enclosing perspectives viewing the deepening of technical diagnosis, applied to these transformers. The last part of the paper includes the conclusion of the investigations.

Key words: power transformers, technical diagnosis, reliability centred maintenance

1. PRELIMINARY

In a complex energy process management, as the electric energy (EE) distribution and supply, the aspects related to its maintaining between the limits of good operation, with priority is assured the quality and continuity. Under aspect of supervision, the driven processes must have a higher safety in operation, i.e. a high availability, so that the tolerance at incidents becomes essential.

In principle, there are two types of strategies to ensure tolerance at incidents [1]:

- Passive strategies making use of robust design so that processes / equipment are insensitive to the incident;
- Active strategies, that suppose the adaptation of the system on incident types, appeared in sense of its reconfiguration.

The technical diagnosis (TD) of the energy-technology processes, has been developed in recent years, the consequence being the appearance of some diagnosis method accepted in practice, the staring point of there is the approach the model.

The role of the model is to make precise the processes / equipment evolution - basing on mathematic relations - for input and output size.

The alternative representing models are:

- Statically models – dynamically models;
- Linear models – non linear models;
- Continuous models – discrete models.

For complex technical equipments, such as the power transformers (PT) must be satisfied a series of supervising functions realizing one or more activities:

- Monitoring, where the measured variables are verified in relation with the allowed limits for normal operation, to the operator are generate alarm messages in case of failure;
- Protection, generates a suitable counter-action in case of a dangerous state, notified by the monitoring function;
- Supervising with diagnosis of incidents, where basing on the measured variables are computed a series of characteristics, there are generate symptoms, it is made the diagnosis of incidents and there are taken decisions to counteract the effects of the incidents.

The TD of a physical process, such as adaptation of the EE parameters made for PT, may be decomposed in two phases:

- Passive phase, this observe the process in its "natural" operation state;
- Active phase needs action on the process to emphasise the faults, or contrary, to mask it.

The operational phases of TD and PT may be presented in figure 1.

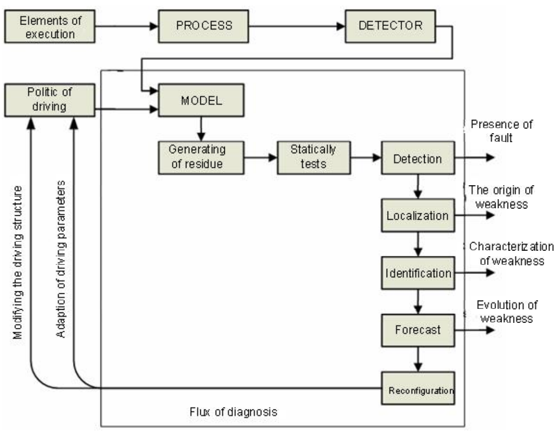

Fig. 1. Phases of operational for TD

The maintenance used after TD may be characterized as "predictive and of object", essential valence, for applying RCM strategy, [2,3]. Referring on a PT, the technical diagnosis has the following effects:

- Growing the overall investment costs;
- Reducing the fault intervals and minimizing the time of corrective maintenance in period of analyze (P_A);
- Suppressing the programmed preventive maintenance works;
- Minimizing the global (P_A), maintenance works;

- Increasing the automation and information degree of the ensemble;
- Modifying the structure of (P_A) for analyze of reliability indexes of the PT toward of classical case;
- Improving the operational reliability indexes of PT.

Obviously, the TD application has contradictory components too. Consequently, the decision for its adoption for a given PT will be preceded by application of an optimization criterion (reducing the costs, maximizing the security or of availability, a.s.o.).

Referring on the two modalities of PT monitoring, could be made the following appreciation [2,4]:

The periodical monitoring (off-line) may give useful information regarding the state of the PT, but, it has the disadvantage of omitting the random events, that may income in the period between inspections (unexpected fault of PT);

Continuous monitoring (on-line) has the advantage to follow always the state of PT, from a distance too.

2. PRINCIPLES AND USABLE METHODS FOR TD OF PT

The insulation subsystem is the most vulnerable in a PT, so the most part of studies are based on the method of diagnosis, the controlled parameters in principle are [2,4,5,6]: the leakage current, partial discharge, the concentration of the gases in the oil. Near direct or indirect analyzes, of the insulation state (inclusive the oil of the transformer), the methods of TD aims other components of PT too, having significant values in the intensity of failure: step switcher, electric contact areas, magnetic circuit, subsystem of cooling and of tank, (in this case, liner, filters and valves).

To monitories the step switcher it is used: measuring the difference of temperature between the tank and switcher, measuring the proper consume, comparing the data with the footprint – normal values, in the same case of stress – may evidence the state of the switcher [7].

On-line measuring of the partial discharges with sensors based on piezoelectric effect [(50 ÷ 350) kHz], isn't applied on large scale, because the sensitivity is relatively reduced and the number of the sensors for noise elimination, is indicated to localize de source of discharges.

The combination of on-line and off-line monitoring techniques is a powerful tool to a complete evaluation of the PT, under technical and economical aspect.

The transfer function of the PT is a characteristic with high univocal grade [8]. Small changes in geometry of the winding or in insulation parameters, leads to value changes of the LC circuit parameters (L, C), of impedances and transfer function. Applying one from the methods: impulse at high voltage, at low voltage, response analyze at frequency the transfer function of the PT, is determined. By comparing the footprint, for each winding may be decide if and which component from windings is fault.

Detection of early damages in PT by analyzing the fault gases is based on the fact that the isolation fails in some heat and electric stress, resulting volatile and un-volatile degraded products.

For PT in oil, (PTO) there are 7 key gases used to determine the type of damages that took place in a transformer [9,10], table 1.

Table 1. Correspondence damages of PTO – released gases

	Partial discharges	Electric arc	Overheat of	
			insulation	oil
Hydrogen (H_2)	●	⦿	⦿	○
Methane (CH_4)	⦿	○	○	⦿
Carbon Monoxide (CO)			●	
Carbon Dioxide (CO_2)			⦿	
Ethan (C_2H_6)		○		●
Acetylene (C_2H_2)		○		⦿
		●		

● - key gases ⦿ - second as importance ○ - present

Combining the obtained results regarding the absolute concentration of the 7 gases, with fuzzy, the ratio of concentrations, may increase the accuracy of the diagnostic. The method is based on using of the 4 gas concentration ratios to be diagnosed the 15 affection states of PTO [9,10,11].

The values of four ratios are classified such: low (L), medium (M), high (H), very high (VH). The used ratios are:

- Acetylene / Ethylene (C_2H_2/C_2H_4):AE;
- Methane /Hydrogen (CH_4/H_2): MH;
- Ethylene /Ethan (C_2H_4/C_2H_6): EE;
- Ethan / Methane (C_2H_6/CH_4): EM.

The mode of diagnostic basing on the three ratios as recommended by IEC / IEEE, is given in table 2.

The methods of monitoring through the control of the cooling subsystem temperature and by the identifying of the hot spot of the winding, was developed in direction to utilize some performance sensors and by elaboration of adequate software too [12,13].

To detect some geometrical modification in the windings or to observe the trend of the isolation degradation (of the windings or of the magnetic circuit), are measured off-line one or more state parameters of the PT: the equivalent resistance, equivalent impedance, power losses in the transformer, at different frequencies, and the results are compared with the footprint. The methods are in regress toward the method that aims to the transfer function of PT analyze.

Table 2. Codes for DGA methods interpretation (recommended by IEC/IEEE)

Code of fault	Type of the fault	Ratios		
		$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
0	without fault	< 0,1	0,1 ÷ 1	< 0,1
1	overheating	< 0,1	0,1 ÷ 1	1 ÷ 3
2	overheating with $\theta \in (150 - 300)^o C$	< 0,1	> 1	< 1
3	overheating with $\theta \in (300 - 700)^o C$	< 0,1	> 1	1 ÷ 3
4	overheating with $\theta \rangle 700^o C$	< 0,1	> 1	> 3
5	partial discharges with low energy	< 0,1	< 0,1	< 1
6	partial discharges with high energy	1 ÷ 3	< 0,1	< 1
7	discharges with low energy	< 0,1	0,1 ÷ 1	> 1
8	discharges with high energy	0,1 ÷ 3	0,1 ÷ 1	> 3

Nowadays, the most used method to determine the state of the PT insulation in on-line mode, uses monitoring of partial discharges (PD).

The measuring devices of ultrasonic signals produced by PD, must be placed closer to the measured object. In [4], is proposed the positioning of ultrasonic transducer at various angles, at 1 m from the measurable object at frequency between 20 and 100 kHz (fig. 2).

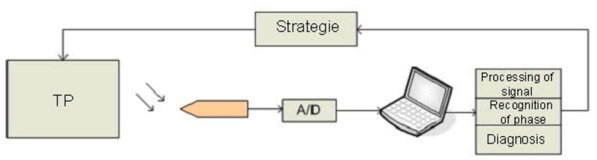

Fig. 2. Circuit for ultrasonic measuring of PD

Many of dry PT (PTd) are equipped with a device to detect the temperature of the optical fibre sensor (OFS) integrated in the low voltage windings [11,15] to signalize the increases of temperature due to over currents (fig. 3).

The system is build from a OFS and a control unit, that processes the measured data and in case of overheating give alarm signals to the control center of the supplying station.

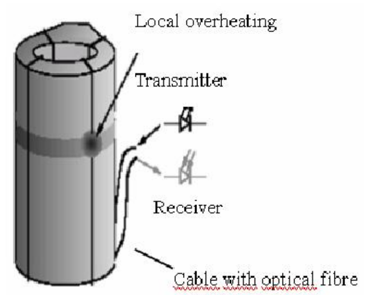

Fig. 3. The scheme monitoring system with OFS of PTO over-temperature

The Buchholz relay is used for decades as a tool of protection for PTO, it was modernized with a sensor, with a cylindrical capacitor, usually installed on the top of relay over the degassing valve. The electric capacity of the sensor varies in function with the gases contains. The change of capacity allows the gases quantity assessment. After measuring the gases volume, there are transferred into a gas collector where they may be collected and analyzed. The gases time detection and the measured quantity are stored in memory. If the level of the oil decreases it is activated an alarm.

The state of the step switcher SSw is strategically for PT safety [6,13]. There are some methods to realize on-line monitoring for SSw, for example: measuring the difference of temperature of principal tank and SSw to detect the weak contacts. In Romania the main equipment used for TD of PT in distribution systems of EE are [2,7,16,17,18,19]: MS - 2000, AMS – 500 and TRAFOMON.

The applying grade analyzes of TD equipment in PT implies corroboration at least of two essential properties: efficiency (e) and simplify (s). There will be defined [20] the level of the two properties in 4 steps (table 3), and will be deduced the level of applying of the TD equipment of PT (table 4).

Table 3. Steps of efficiency (e) and simplify (s)

Level	Significance (e/s)
1 ≡ low	It is necessary to corroborate the results of at least 4 tests to make a diagnosis of the fault (e)
	It is necessary to make special analyzes, additional testing, special devices, important costs (s)
2 ≡ medium	It is necessary to make three tests for diagnosis (e)
	Requires the withdrawal from service and expert analysis (s)
3 ≡ good	It is necessary to make two tests for diagnosis (e)
	Isn't necessary to withdrawal from exploitation and nor special analyzes, but needs adequate devices (s)
4 ≡ very good	Diagnosis of failures is made by the test results analyzing
	The simple maintenance operations that needs a minimal support

Table 4. The hierarchy of TD equipment for PT

The system of diagnosis	Level of indicator „a" = e ⊗ s
Monitoring of dissolved gases in oil (7 gases, 4 ratios)	(3,2) ≡ 2
Monitoring the partial discharges	(3,2) ≡ 2
Measuring the parameters (R, L, C) and of power losses	(2,2) ≡ 1
Assessment of PT transfer function	(3,2) ≡ 2
Analyze of frequency response	(3,2) ≡ 2
Monitoring by on-line and off-line methods combination (dissolved gases concentration in oil + response on frequency)	(3,2) ≡ 3
Monitoring of PT state parameters (currents, voltages, frequency, temperature, level and the oil pressure, concentration of the gases on of the water in the oil, the state of the cooling installation and of the Buchholz relay) and comparing with footprint.	(3,2) ≡ 2

3. OPERATIONAL AND PREVISIONAL IN DOMAIN OF TD OF PT FROM SDEE ORADEA

In SDEE Oradea are monitoring and diagnosing on-line and off-line operation 29 PTO in 18 electric stations (ES) de 110 kV / MV. For PTO from the most important 5 ES is applied complex TD by multiple means (fig.4.).

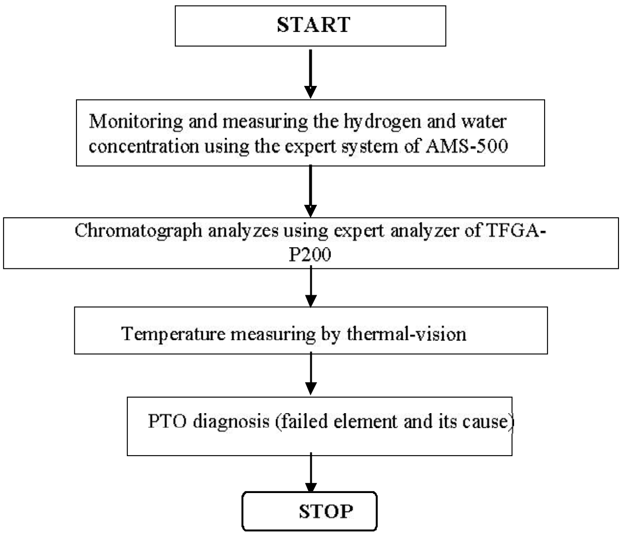

Fig. 4. Logical succession of TD by PTO of SDEE Oradea

For example, in fig. 5 and 6, are given the presentation mode of the results from chromatography tests. DT of PT is made to improve the level of the reliability of the equipments useful for quality of the EE distribution service. Taking into account this necessity, authors of the paper include as methodology aspect, TD in a more general frame of the PT parametrical reliability [21].

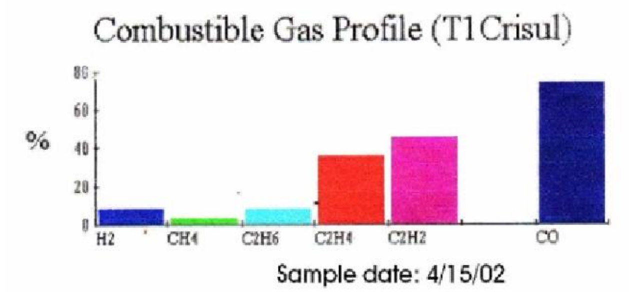

Fig. 5 – Chromatograph off –line analyze of the PT oil no. 1 from Crisul ES

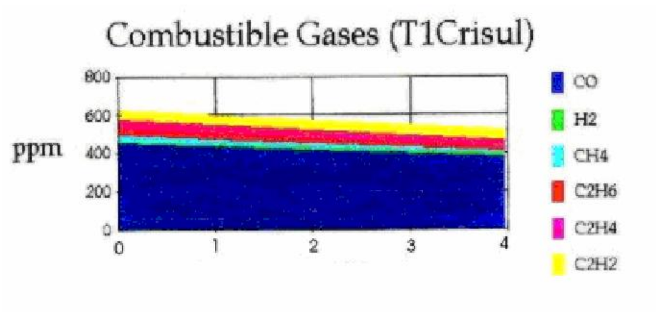

Fig.6 – Evolution of DGA in PTO no.1. in Crisul ES period [24.04 – 20.05] 2002

The state of PTO is characterized by the values of some parameters that may be grouped in three categories:

- Parameters regarding the general state of the isolation (y_{1i}):
  - Resistance of insulation at 15″($R_{15} \equiv y_{11}$);
  - Resistance of insulation at60″($R_{60} \equiv y_{12}$);
  - Coefficient of absorption ($k_A \equiv y_{13}$);
  - Tangent of the angle of losses (tg $\delta \equiv$ y14);
- Traditional parameters of the oil of PT (y_{2i}):
  - Dielectric rigidity (E ≡ y21);
  - Tangent of the angle of losses (tg δU ≡ y22);
  - Water content (CH20 ≡ y23);
  - Density (ρU ≡ y24);
  - Indexes of acidity (ia ≡ y25);
  - Flammability point (PIF ≡ y26);
  - Cinematic viscosity ($v_U \equiv y_{27}$);
- Gases contains in oil and its weight (y_{3i}):
  - Hydrogen (H2 ≡ y31);
  - Methane (CH4 ≡ y32);
  - Ethan (C2H6 ≡ y33);
  - Ethylene (C2H4 ≡ y34);
  - Acetylene ($C_2H_2 \equiv y_{35}$);
  - Carbon monoxide (CO ≡ y36);
  - Carbon dioxide (CO2 ≡ y37);
  - Acetylene / Ethylene (y38);
  - Methane / Hydrogen (y39);
  - Ethylene / Ethan (y3.10);
  - Ethan / Methane (y3.11);
  - Carbon dioxide / Carbon monoxide (y3.12);
  - Total contains of gases in oil ($y_{3.13}$);

The values of state parameters have evolution in time, in sense of their degradation. Under quantity aspect the parametric reliability of PTO represents the probability that the state parameters of PTO are maintained in allowed limits.

$$\begin{cases} R_p = R_1 \cdot R_2 \cdot R_3 \\ R_1 = P_{rob}\left(y_{11} \geq y_{1m1}; y_{12} \geq y_{1m2}; y_{13} \geq y_{1m3}; y_{14} \leq y_{1M4}\right) = \prod_{i=1}^{4} \int_{y_{1mi}}^{y_{1Mi}} f(y_{li})dy_{li} \\ R_2 = \underset{i=1,7}{P_{rob}}\left(y_{2mi} \leq y_{2i} \leq y_{2Mi}\right) = \prod_{i=1}^{7} \int_{y_{2mi}}^{y_{2Mi}} f(y_{2i})dy_{2i} \\ R_3 = \underset{i=[2,13]}{P_{rob}}\left(y_{3mi} \leq y_{3i} \leq y_{3Mi}\right) \prod_{i=1}^{13} \int_{y_{3mi}}^{y_{3Mi}} f(y_{3i})dy_{3i} \end{cases} \quad (1)$$

where,
$f(y_{ji})$ – the distribution density of variable y_{ji};
(y_{jmi}, y_{jMi}) – value of inferior and respectively, superior limits of yji parameters;

In SDEE Oradea for all PTO, yearly is made the measurement for the three parameters categories. In fig. 7 ÷ 9 are given for example, the Paretto diagrams regarding the evolution of some parameters by a PTO from Velenta – Oradea ES (ES1).

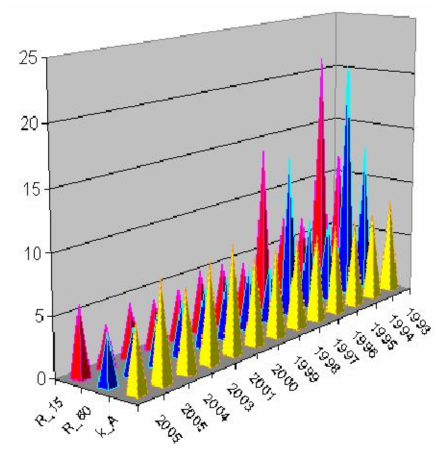

Fig. 7. Time evolution of „y_{1i}” parameters for T1 from ES1

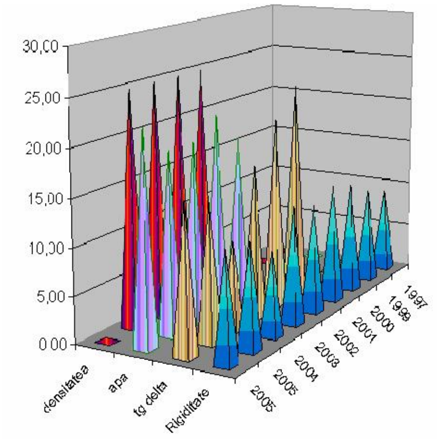

Fig.8. Time evolution of parameters from „y_{2i}” category, for T1, ES1

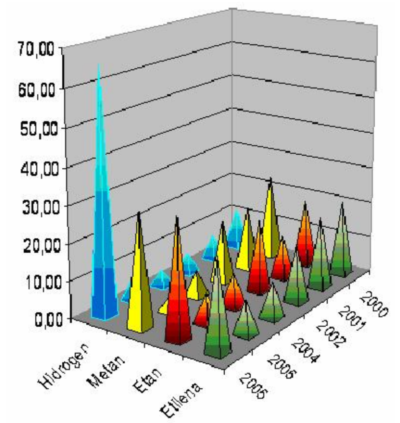

Fig. 9. Time evolution of parameters from „y_{3i}” category for T1, ES1

To evaluate the parametrical reliability it is necessary to know the evolution in time of parameters allowed limits (table 5).

Table 5. References values of determinant parameters for state of PTO

Parameter	Value of reference	Parameter	Value of reference
Resistance of isolation (R_{15})	5000 MΩ	Cinematic viscosity (v_u)	22%
Resistance of isolation (R_{60})	6000 MΩ	Hydrogen (H_2)	100 ppm
Coefficient of absorption (k_A)	1,2	Methane (CH_4)	120 ppm
Dielectric rigidity (E)	160 kV / cm	Ethan (C_2H_6)	65 ppm
Tangent of angle of losses (tg δ)	0,15%	Ethylene (C_2H_4)	50 ppm
Water content (C_{H2O})	30 ppm	Acetylene (C_2H_2)	35 ppm
Density (ρ_U)	0.89 g/cm^3	Carbon monoxide (CO)	350 ppm
Indexes of acidity (i_a)	0,3 mg KOH / g	Carbon dioxide (CO_2)	2500 ppm
Flammability point (PIF)	135^{o}C	Carbon dioxide / Carbon monoxide	[3; 10]

The reference values are given at 20^{o}C, and represents:

- Maximal values for: tg δ, CH_2O;
- Minimal values, for: R15, R60, kA;
- Intermediary (medium) values for: H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO_2, CO, CO_2/CO.

In case of (R15, R60, kA) parameters, were represented the smallest values from the set of 6 values. Based on the obtained results for the 29 PTO of SDEE Oradea, results the parametrical reliability values presented in table 6.

Table 6. Parametrical reliability values for PTO of 110 kV / MV in SDEE Oradea

Category of parameter / No. values	y_1	y_2	y_3	Total
Measured	4029	1280	772	6081
Reference value exceeded	488	66	151	705
R_i	0,88	0,95	0,79	0,88

Another developed research direction for TD and parametrical reliability of PTO, is that of investigation, based on results of prophylactic measurements, impact of stress level on the state parameter's value of PT. In this respect, were defined and were rated the following measures that reflects the static and dynamic stress level:

- Relative average voltage (u);
- Relative average load (β);
- Risk indicator related to voltage (IRU);
- Overstress factor at short circuit current (KSI1);
- Overstress factor at overload current (KSI2);
- Frequency of short circuit current overstress and overload current (FSS).

The obtained results are detailed in [22,23], for example in fig. 10, are given the results for the two PTs from ES1.

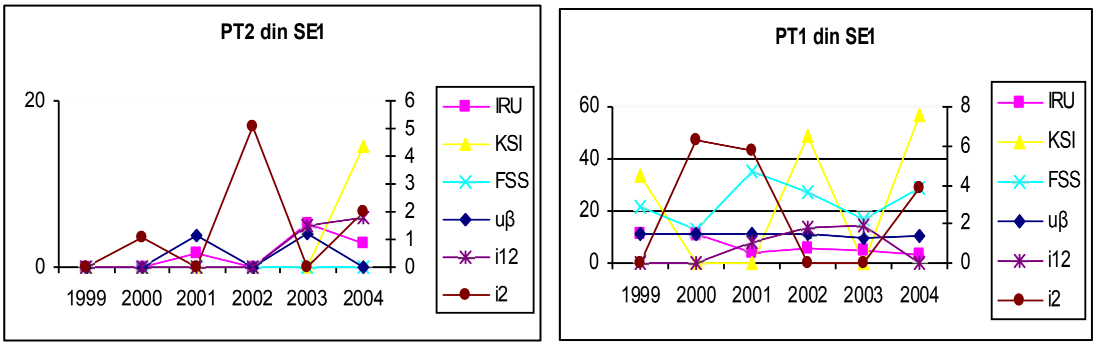

Fig. 10. Comparative evolution of the PT oil and stress state parameters
$i_{12} \equiv (tg\,\delta \cup C_{H2O} \cup i_a)$; i_2 – global indicator regarding the dissolved gazes in oil (the 7 gases)

4. CONCLUSIONS

The general architecture of the detection system and incidents diagnosis implies expert systems, where the combined methods are based on analytical models related to models of quality. An evaluated detection system and incident diagnosis must contain: data base, analytical knowledge base, Heuristic knowledge base, inference engine, explain component.

The type of maintenance practiced to electric equipments with on-line technical diagnosis is "predictive and on object", essentially for RCM operational strategy.

The main effects of TD implementation to PT are: the ensemble complexity and cost, technical grade, reliability and lifetime increase.

The PT requires special attention in exploitation because they are: complex equipments, having special impact on the safety level of electric power systems and on the availability of electric energy to the consumers, implying high values of maintenance costs.

For TD of PT are utilized equipments of on-line monitoring and off-line testing equipments too. Combining the on-line procedures with the off-line procedures leads to the diagnosis accuracy and efficiency.

TD of PT is realized by following parameters: gases and water content in oil of PT, characteristic parameters of the insulation (resistance at insulation, dielectrically rigidity, tangent of losses angle), the temperature of the ensemble or / and of some components, R, L, C parameters, leakage current, partial discharges intensity and frequency.

TD is used by transformers with oil cooling and by dry transformers too.

For on-line monitoring of the 7 gases in oil, is the most efficient and most widespread method. The accuracy of diagnosis basing on the gas content in oil, increases significant if there are calculated 3 ratios of concentration corresponding to 5 gases, on which can diagnose 9 state of PTO faults.

The most frequently methods used by PTO for TD, is based on the measuring of temperature in the windings, the transfer function evaluation, detection and localization of partial discharges.

The modern equipments of TD for PT, are with (hardware, software) artificial intelligence components using fuzzy models for monitoring and diagnosis processes.

The expert system of AMS-500 is an efficient tool to prevent possible faults of PT, by monitoring of hydrogen and other dissolving gases in the oil of transformer. SDEE Oradea in its exploitation has 5 equipments of AMS-500 type, operating very well over six years, monitoring the PT from the electric stations from: Sinteza, Crisul, Oradea, CLA and Stei.

Near this expert system AMS-500, for TD of PT is very useful to utilize the analyzer of "gas chromatograph" type coupled with a computer with software corresponding, is an expert system that analyses off-line the gases content in oil of PT. In SDEE Oradea is utilized the chromatograph of TFGA-P200 type, for all PT of 110 kV/MV with very good results.

A complete and exactly diagnosis of PT isn't possible only basing on the gas contents in oil. So, for PTO in SDEE Oradea it was stabilized the order of verifying that allows the complete and exactly TD:

- On-line monitoring the hydrogen concentration;
- Off-line analyzes of the other 6 gases concentration;
- Classical prophylactic measurements;
- Temperature measuring by thermo-vision.

The starting of the procedure is provoked by attaining of the alert values at monitoring the hydrogen concentration. The state parameters of PT may be treats as random variables important in statistical procedures. By determining and interpreting the selection characteristics of these random variables, basing on parametrical reliability, results the momentary level of the PTO reliability and the optimal rhythm of the reliability centered maintenance (RCM).

The PTO parametrical reliability may be evaluate, differentiate in relation with three parameters category:

- Parameters regarding the general state of the insulation (R_1);
- Traditional parameters (classical) of the transformer oil (R_2);
- Content of gases in oil and its weight (R_3);

The made evaluations for PTO in SDEE Oradea shows the fact that the R_1 and R_2 values are very high, as the parametrical reliability level related to the gases concentration in oil is small.

The TD of PTO basing on the oil's electro-insulating state is a very important method, its valence isn't yet total researched and evidenced. An unexploited research direction consists in identifying of the mode where the stress grade reflects on the electro-insulating oil state, aiming to identify some models to prevision the state in relation with the stressing level, to utilize in RCM strategy.

The registered and processed data reflects clear and significant influences, to the stress level of PT on the electro-insulating oil state. It is recommended as at the analyzing program of PTO oil, to be taking in consideration this aspect, the purpose of frequency analysis in the practice varies according to the request.

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