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DEVELOPMENT OF DIAGNOSTIC SYSTEM OF 330 -750 KV CURRENT TRANSFORMER BASED ON SERVICE EXPERIENCES AND ENDURANCE TESTS

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SUMMARY

The paper discusses a scope for improvement of in-field diagnostic technique of 330..750 kV condenser – type Current Transformers (CTs) on the base of service experience and long-duration endurance-mode tests of some defective units to study mechanism and diagnostic characteristics of the typical failure modes.

KEYWORDS CTs-Failure-mode-Ageing-Endurance test - Diagnostic criteria - ON-LINE monitoring.

INTRODUCTION

Up-to-date maintenance policy for HV Power Apparatus in CIS is subjected predominately to economic considerations. Practically, it means to do the minimum maintenance, preferable ON-LINE condition, move from time-based to condition-based maintenance, life extension of equipment and prevention of violent failures.

Condition of HV condenser-type CTs is a subject of particular concern as they are responsible for Power supplies continuity. Experience has shown that traditional OFF-LINE monitoring and diagnostic system of CTs appeared to be ineffective and inefficient one. In recent years there has been considerable interest to ON-LINE monitoring system. Various aspects of the CTs monitoring at rated voltage have been introduced in the former USSR since the early 70^{th}. At least two main problems were found: how to get reliable and precise test data and how to identify seriousness of the problem.

With the goal to study mechanism of the typical failure developing and to find effective diagnostic criteria long-duration tests of 350 - 500 kV CTs have been performed in NIIPT (outdoor testing centre) and VIT. On the other hand, working group of the Ukrainian specialists was set up in 1995 to analyse effectiveness of existing ON-LINE test system.

This paper presents results of above mentioned activity and discuss the possibility to improve the CTs condition diagnostics.

1. BASIC CONCEPT FOR INSULATION DESIGNING

The following research findings [1] formed the design basis of oil impregnated condenser type HV CTs in the former USSR.

- Absence of incipient ionisation at long duration operating voltage, namely appearance of PD of 0.01..0.1 pC due to puncture of thin oil layer, particularly on the edges of conductive layers (typically of aluminium foils).
- Absence of critical ionisation at short duration test voltages (one minute power frequency, switching impulse, lighting impulse), namely appearance of PD typically of surface discharge mode, causing the gas generation which exceeds the rate of gas absorption.

In CIS lightning arresters protect all HV CTs, and the short time test voltages ratios are lessening with increasing of the rated voltage. That' s why the insulation of Um ≥ 300 kV CTs is determined by operating long- duration test voltage.

2. SERVICE EXPERIENCE

There have been two typical designs of condenser type CTs: "Hair-pin" U-shape dead tank (in service since 1961) and toroid type "Bar-primary" live tank (in service since 1971).

Population of CTs in CIS includes over 10000 of 330 kV units (of the both designs), over 3000 of 500 kV units ("Bar-primary" live tank) and over 1500 of 750 kV units (cascade design of two "Bar-primary" 330 kV units). Until 1979 all CTs were designed with open-breathing preservation system, and (after) - with plastic or rubber membrane sealed system.

Analysis of failures caused by damage of condenser core can be summarised to the following:

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- Major failures of CTs have been occurred basically at rated voltage or in some cases at excessive by 5-10% voltage over rated one.
- No failures have been registered due to PD or surface discharge appearance on the edges of conductive layers. Incipient fault appears and develops usually within the oil-paper bulk.

Most of the failures were of erratic nature regarding the time. However two groups of failures can be classified as typical ones:

1) Failures, which have occurred early in CTs, service life, often on the 3[d]…9[th] day after commissioning, predominantly in a cool (winter) time. Those involved basically "toroid shape" CTs and caused by poor impregnation of the core with oil or deimpregnation during storage, and ingress of air and water.

Some cases with CTs, which failed soon after refilling the oil on service and improper treatment of insulation can be related to this group of failures too. Failures, which have occurred after 15-25 years of service predominantly in a hot (summer) time. Those involved basi cally U-shape open-breathing CTs and caused by increased dielectric losses and followed with thermal run away. Aging of oil and oil paper bulk, and in some cases localized residual moisture have been accepted as the most probable life-limiting factors.

3. ENDURANCE TEST

Long duration endurance - mode test of 330-500kV CTs have been managed to study mechanism and symptoms of development the typical failure modes as well as effective diagnostic characteristics. Totally 39 units have been tested (table 1).

Table 1 Tested population of CT s

Type / kV	330	500
Hair-pin	12	-
Bar-primary	18	9

Two types of objects were selected:

1) Aged "Hair-pin" open breathing CTs having symptoms of deterioration: some elevated tanδ at 10 kV (0,8... 1,3%) and tanδ of the oil (3... 10 % at 90°C);
2) New apparatus after long storage or suspected to have some defects.

Basically two ageing acceleration factors have been chosen to determine endurance test procedures: maximum temperature 90…100°C by means of internal heating with rated current and external heating by halogen lamps or hot air and maximum rated or permissible voltage 1,1...1,3 Um.

One 330 kV "U-shaped" CT was specifically tested by multiple short-circuit stresses. One 500 kV toroid type CT was specifically tested to determinate the effect of gas saturation on dielectric behaviour. 12 of tested CTs failed during the test and have been dismantled and cut up to verity the cause the failure and the condition of insulation.

3.1. Thermal run away

In all cases with aged "Hair-pin" designed 330 kV CTs increase in dielectric losses were found to is the main life limiting factor. That was followed with thermal instability and breakdown in the place of laboured heat removal (typically insulation at the lag in the place of disposition of the magnetic core).

All of the CTs failed after 300…1100 hours of testing. A significant rise in tanδ has been observed after 60 - 200 hours of thermal test (fig. 1).

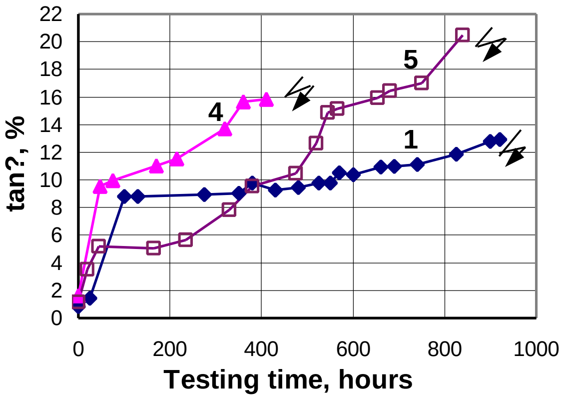

Fig. 1 Developing dielectric losses. Number of the CT see in the table II.

Characteristics of CTs prior to tests and prior to failure are shown in the table II. Distribution of tanδ of paper strips across the insulation core section is shown in the fig. 2 as evidence of excessive dielectric losses in the insulation bulk.

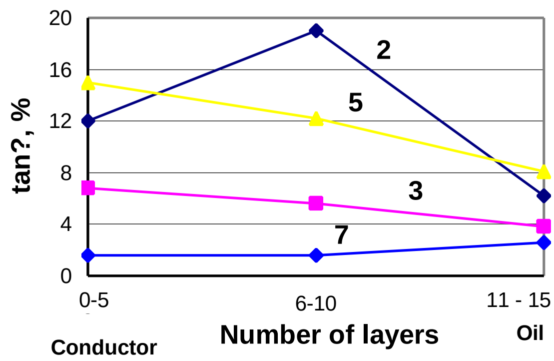

Fig.2 Distribution of tanδ of paper through the thickness of insulation of failed CTs: 2 - after 319 hours; 3 and 5 - after 880 hours; 7 - after short-circuit

No meaningful rises in concentration of faulty gases and PD intensity have been observed prior to failure. It was found some correlation between gas generation and tanδ (table III). However, DGA date has pointed out rather on oil ageing. Rise in tanδ with temperature and with time, rise temperature of CT due to increased dielectric losses and increasing or in some cases decreasing tanδ with voltage have been defined as typical characteristics of defective condition.

3.2. Effect of short-circuit stresses

One of 330 kV "U-shaped" CT taken out of operation after 5 years of service was subjected to multiple short-circuit stresses during long duration thermal test: 10 shocks with 27 kA after each 200 hours testing. It had withstood satisfactory long duration test during 1600 hours (table IV). However after subjection to short-circuit

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Table II. Endurance tests of 330 kV "Hair-pin design" aged CTs

?	Ser-vice Years	Input test: Dielectric test: tanδ 10 kV	Input test: Dielectric test: tanδ 210 kV	Input test: Dielectric test: PD at 210 kV pC	Input test: Oil test: H_2 ppm	Input test: Oil test: tanδ 90°C, %	Input test: Oil test: W ppm	Test time hours	Dielectric test prior to finish: tanδ, %	Dielectric test prior to finish: ΔC/C, %	Dielectric test prior to finish: PD at 210 kV pC	Cause of test finishing
1	22	0.82	1.21	< 20	2	8.2	8	1170	13	8	< 20	Excessive rise of tanδ
2	12	2.1	3.3	< 1000	6	9.8	9.5	319	16	7.6	1000	Failure
3	21	1.3	1.6	< 20	4	7.3	14.5	877	11	5	< 20	Failure
4	21	1.6	2.2	100 - 200	4	7.2	11	429	16	9.1	250	Failure
5	22	1.16	1.25	< 20	20	6.6	10	884	20	14	< 20	Failure
6	10	0.48	0.56	< 20	-	5.2	9.6	64	10	11	< 20	Failure

Table III. DGA concentration versus tanδ of insulation

Tanδ, %	Gas concentration, ppm				
	? 2	? ? 2	? ?	? ? 4	? 2? 4
0,8-1,5	7	740	102	2	5
5,6-7,8	31	1230	195	5	3
8,8-11,6	230	2030	254	4	20
12,9-20,4	330	2820	441	14	28

stresses some trend of tanδ rising with temperature appeared. The CT failed after 3900 hours due to thermal run away and breakdown in the bottom part at the core.

Table 1V. Effects of short-circuit stresses

STAGES	CONDITION: U kV	CONDITION: t °C paper	CONDITION: Time h	TEST RESULTS: tanδ 20°C	TEST RESULTS: tanδ 70°C	TEST RESULTS: PD
Initial				0.26	0.8	No
Thermal Max	102	70-90	1600	0.3	2,0	No
Thermal + Min + 60 Shocks w/27 kA	210	20-30	1600	No change		
Thermal + Medium + 30 Shocks w/27 kA	210	45-65	650	0.31	2.14 Trend to rise with voltage	No
Thermal Max	250	80-90	13	Failure		

3.3. Partial Discharge activity

Two toroid type CTs failed due to developing of dielectric-destructive ionisation at the head of the insulation core followed with short-circuit between layers.

Cause of 330 kV CT failure (table V) was apparently partly deimpregnation of insulation during long storage. Symptoms of defects had been observed after 200 hours as increasing tanδ with voltage and PD appearance. The testing was stopped after appearance of obvious signs of damage (tanδ = 6,1%, PD = 40000 pC, gas generation).

It other case with 500 kV CT improper impregnation of insulation core with oil was suspected. Sign of fault had appeared after 28 hours tanδ increasing from 0,32% up to 0,6% and capacitance by 0,27% and PD intensity from < 50 pC up to 3000 pC. After subsequent 17 hours tanδ increased up to 1,06%, ΔC/C - up to 0,6% and PD intensity - up to 30000 pC. Soon after the last measurement the unit failed (fig. 3).

Tear down of the CT has revealed obvious evidences of PD activity at the head of the unit. Rise in tanδ, ΔC/C

Table V. Characteristics of 330 kV toroid type CT with developing ionization-mode dielectric failure

Testing Stages	tanδ, % 10 kV	tanδ, % 210 k V	PD PC	DGA, ppm H_2	DGA, ppm CO
Prior to test	0.36	-	< 50	5	300
200h t ≈ 80°C	0.36	0.58	3000	11	354
40h t ≈ 29°C	0.35	1.0	-	750 103	390 387
8h t ≈ 55°C	0.24	4.5	200000	4000 1590	430 340
7h t ≈ 60°C	0.3	6.1	400000	10460 2560	394 390

and PD intensity with voltage and time as well as intensive gas generation was found to be diagnostic criteria of defective condition.

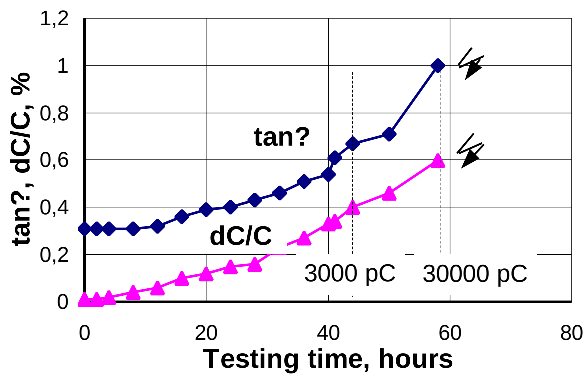

Fig.3. 500 kV CT with deimpregnation insulation

It seems remarkable that gas concentration in the oil sample taken from the top was significantly higher than in the sample taken from the bottom.

3.4. Effect of gas saturation

Two sets of 500 kV toroid type CT were subjected to long duration tests (of 1000 hours) on the following condition: temperature in the head - 95...100°C (internal heat through current in secondary winding and external heat with hot air), voltage 395 kV = 1,3Um. After each 100-150 hours fast cooling of CT down to 55-65% was scheduled by means of cold air.

CT1 was sealed, CT2 - rubber sealing was removed and oil was saturated with air (total gas 9% at the upper part and 4% at the lower part). CT1 has withstood 1000 hours tests satisfactory. CT2 has with stood two cycles of testing (250 hours). PD intensity reduced from initial values 50-100 pC to the noise levels 3-5 pC (due to improvement of insulation impregnation). During the third circle off PD level suddenly increased up to 500-800 pC and slow increasing tanδ has been observed (fig.4).Tanδ rised from 0,29% to 2,35% and test was stopped. DGA has shown the level: H_2 = 950 ppm, CH_4 = 1600 ppm, C_2H_6 = 1060 ppm, C_3H_6 = 17 ppm. After dismantling the CT the oil-paper insulation damage at the centre of upper part of the head was revealed.

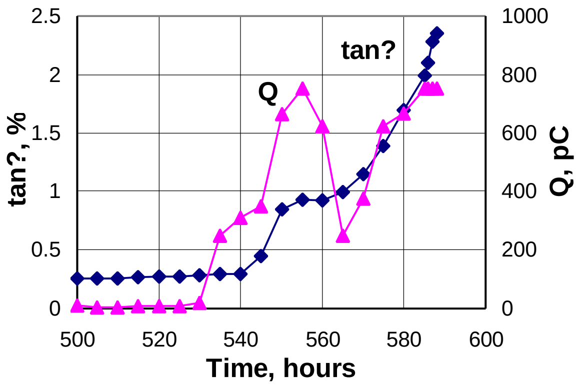

Fig.4 500 kV gas saturated CT damage mode

4. DIAGNOSTIC CRITERIA

4.1. Diagnostic model

Irrespective of origin, two types of physical developing of incipient faults can be expected:

1) Electric - destructive ionisation in the place of overstressing;
2) Thermal - dielectric heating.

In any case a defective area occurred between two or more conductive layers of the core can be characterised with two parameters:

– relative portion of defective section;
– dissipation factor of defective area.

Change in dielectric parameters of defective area causes dielectric response of the conductor core. The parameters of defective area can be determined with the following characteristics:

– change in tanδ of the core;
– change in capacitance due to increasing permittivity or due to short-circuit between layers;
– change in leakage current mainly due to change in capacitance as well as change of modules of the relative change in leakage current due to change in tanδ and capacitance.

Correspondingly, rise in temperature of defective co-re, appearance of PD and generation of destructive by-product. Apparently, nature of the incipient fault and conditions of its development determine effectiveness of diagnostic technique.

4.2. Rise in dissipation factor with temperature

Dissipation factor of dry well-impregnated oil-paper core can be easily calculated depending on density of the paper and tanδ of oil. U-shaped relationship of tanδ with temperature and maximum value less than 0.4% at 90°C is a typical characteristic of insulation with water content 0.5% or less and tanδ of oil 0.3...0.5% at 90°C.

Deterioration of insulation (water, ageing) causes exponential rise in tanδ with temperature

$$\tan\delta = \tan\delta\ \alpha^{(T-To)},$$

where α - index of deterioration level.

Many years experience with thermal stability tests have shown that permissible value of α shall be in the range 0.01 <α< 0.015. Endurance tests results have shown that values of α = 0.015...0.03 shall be recognised as characteristics of defective or questionable condition, and α > 0.03 is a sign of dangerous or alarming condition.

4.3. Rise in dissipation factor with voltage

Defect free condition is characterised by minor or even negligible tip-up tanδ with voltage.

In CIS permissible tip-up of tanδ at the range of voltage 35kV...1.1Um/√3 has been specified as Δtanδ = 0,03%. Typical data for 330...500kV CTs are Δtanδ = 0.01...0.015%. The critical cause of tanδ tip-up appearance is effect of destructive ionisation, which was obviously convinced by endurance tests. The results have shown that tanδ tip-up over 0,1% (measurements at 10kV and at rated voltage) can indicate on PD activity of the order of 1000pC. On the other hand, the service experience has shown that contamination of the condenser core surface with oil ageing products can also be the cause of tip-up tanδ.

4.4. Decrease of dissipation factor with voltage

Decreasing tanδ with voltage (Fig.5) can be also characteristic of defective condition, particularly of aged overheated insulation and at increased conductance of the oil.

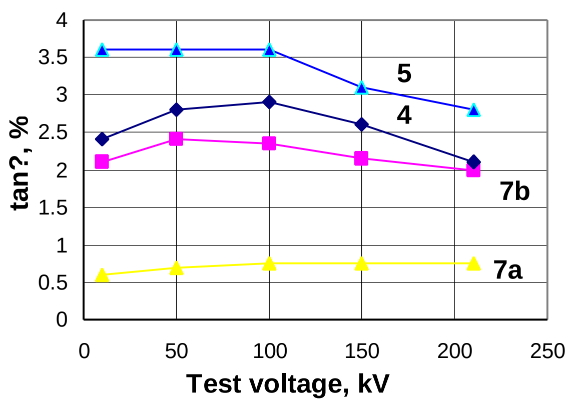

Fig. 5 Change tanδ with voltage (CT 330 kV "U-shaped"): 4, 5, 7b - after endurance test; 7a - before endurance test.

This phenomena can be explained as decreasing instantaneous values of dielectric loss current due to distortion of the sinusoid form on the area of maximum instantaneous values of applied voltage.

4.5. Increase of CTs temperature

Increasing dielectric loss causes relevant increase in the temperature of CT, which can be detected by thermovision technique. Temperature response of "Hair-pin" and "Bar primary live tank" CTs is different due to quite different reflective surface and time constant of heating (cooling). Experience has shown that the meaningful difference in temperature for these two types can be of 1°C ("Hair-pin") and of 2-3°C (toroid type).

4.6. Oil as diagnostic medium

Faulty gas generation can be related to the primary signs of developing failures in case of electrical fault occurrence. The phenomena follows to PD activity and DGA are really very effective means to verify whether e.g. rise in tanδ involves the destruction of insulation material. On our experience, the electrical fault is more typical for "Bar-primary" design. In case of thermal fault occurrence, DGA can be as some complementary tool. Total gas concentration measurement is a useful tool to verify sealing condition and probability of oil oversaturation.

Measurements of the water content in the oil and tanδ and resistively of oil are important tools to identify dielectric behaviour of the CT, particularly in case when tanδ is increased.

4.7. Characteristics of local fault developing

Increasing conductivity and tanδ of defective area appearance of partial discharge cause burning of paper and occurrence of the short circuit between two or several layers. The image of local defects can be determined with the following characteristics:

– Co-ordinated change in tanδ and ΔC/C (fig.3) which can be calculated through parameters of defective area [2].
– Appearance of PD with intensity, which can be co-ordinated with dissipated energy.
– Gas generation with amount and rate, which can be co-ordinated with dissipated energy.

Analysis of above-mentioned diagnostic characteristics has shown that their benefits can not be realised by means of traditional measurement of tanδ and capacitance at 10 kV and ambient temperature. Effective diagnostic system needs in provision of working condition, particularly maximum voltage and temperature.

5. EXPERIENCE WITH DIAGNOSTICS OF CTs AT RATED VOLTAGE

Modification of traditional OFF-LINE diagnostic techniques started in the early 70^{th} in some Russian and Ukrainian utilities with construction of transmission system 750 kV. Several lines of monitoring CTs have been introduced:

- ON-LINE continuos monitoring of imbalance in 3-phases leakage current or modulus of change in complex conductivity. Similar system was used successfully for monitoring and protection of HV bushings [3]. Complementary periodical (usually daily) tanδ tests using analogue wattmeter circuit have been provided also with signal of increasing tanδ by 1 per cent.
- OFF-LINE tests of tanδ and capacitance with voltage up to the maximum rated one using movable test devices [4].
- ON-LINE periodical (2-4 times a year) tanδ and capacitance tests by means of bridge circuits with a coupling specimen unit [4]. More than 20-years experience was analysed in 1996 by the working group of specialists, who came to the following conclusion.

5.1. ON-LINE monitoring (Experience with 750 kV collected from three substations since 1975)

There were no CTs failures in the period of observation. One case of violent failure of 750 kV CT was predicted by the system. However a lot of wrong signals have been registered. A necessity in periodical calibration of the test system was found as well as need of expert advisories.

5.2. Experience with movable test device (over 2000 of 330-750 kV units observed since 1973)

A meaningful success has been achieved by using as a diagnostic tool tip-up tanδ with voltage particularly for "U-shape" CTs of open breathing design. In the early period up to 15…20 defective units have been detected. For the last 5 years a number of defective CTs has been reduced to 2-3 per year. In the most documented cases the cause of increasing tanδ with voltage was ageing of the oil and contamination of the core surface with ageing products. After treatment using vapour-phase processing techniques the units usually met the tests requirements and returned in service. Disadvantages of the method are high costs of tests for periodical application and necessity to de-energise of units.

5.3. ON-LINE tan dtest on operating condition (experience with about 1000 CTs since 1985)

The units were provided with special device to manage the tests directly at operating voltage. Introduction of the method was very successful. In one Ukrainian utility 38 defective units since 1988 was revealed. Critical condition was confirmed by subsequent test with movable test device. In another utility 11 violent failures have been prevented during the period 1990-1996. However metrological analysis in 1996 has shown some unproper sensibility of the method and poor repeatability of the test data with respect to advised diagnostic criteria, particularly using Shering bridge for tanδ measurement.

In spite of essential improvement of diagnostic techniques – three failures of 330 kV CTs occurred in the last three years. In all cases some problems with the units were suspected due to increased tanδ at operated voltage, however seriousness of the condition has not been identified properly. The typical case is failure of 330 kV CT of "U-shaped" design after 28 years in service. The unit was under suspicion since tanδ = 0.91% at 210 kV was measured. After two years the value of 1.03 % was tested. A decision was taken to leave the unit in the service but repeat the test after 6 months. However after 2,5 months in very hot period (ambient temperature about 35°C) the CT exploded with destruction at porcelain and fire.

Thus, it was concluded that besides of improvement of monitoring techniques, traditional approach to monitor characteristics but not the condition of equipment has to be changed cardinal.

6. ADVANCEMENT OF MONITORING AND DIAGNOSTICS SYSTEM

Recently the following economically based concepts for Life Management of CTs have been approved to be implemented in Ukrainian utilities.

6.1. Monitoring

- Full rejection of traditional time-based OFF-LINE tests program (tanδ at 10 kV, oil analysis, etc.)
- Modification of the existing ON-LINE condition monitoring of imbalance current with phase indication for rough detection of problems with CTs and for signalling about alarm condition. The proper calibration of the system taking into account local interference is necessary to reduce errors in dielectric tests. As the future advancement the introduction of digital test techniques and development of expert systems have been advised
- Main focus on developing the techniques of periodical dielectric tests on operating condition. A new specification has been developed to provide accuracy of tanδ test at rated voltage on the level of 0.02%.
- Developing the movable test devices in some sort of Test Labs to use them for calibration of tests and identification of defective condition of CTs.

6.2. Diagnostics Tests Procedures

Multi-step Tests Program is advised:

The 1st step – periodical (usually twice a year) tests of tanδ, capacitance and temperature distribution (thermo-scanning).

The 2nd step – (for suspected units)

- Repetition of the tests on conditions when maximum temperature of CT is expected taking into accounts ambient temperature and load.
- Observation of change in tanδ and temperature during some time of subjection of the unit to excessive temperature.

The 3rd step – (for defective units)

- OFF-LINE tests using the mobile test device.
- Tests of the oil (DGA, tanδ, water, ageing products and furans).

6.3. Limited Data (dielectric characteristics)

- "Hair-pin" - 0,7% $\le$ tanδ $\le$ 0.9%
  "Bar primary" - 0,5% $\le$ tanδ $\le$ 0.7%
  The upper limits refer to some "hot condition"
- Rise of tan δ with temperature, $\alpha \le 0.015$
- Tip-up with voltage "Bar primary"- Δ tanδ = 0.05%
  "Hair-pin" - Δ tanδ = 0.1 %

6.4. Diagnostic approach

- Determination of failure-model taking into account the design features, service experience of CTs type and service background.
- Determination of image of defect and diagnostic model. Typically:
  - Dielectric heating – rise in dielectric losses, rise in tanδ, tip-up tanδ with temperature and time, tanδ reduction with voltage, rise in CT temperature (with time), appearance of faulty gasses, appearance of PD, in parallel – ageing of the oil, water in oil
  - Ionisation - appearance of PD, tip-up tanδ with voltage, co-ordinated change in tanδ, capacitance, leakage and imbalance current, appearance of faulty gasses.

In 1996-1997 about 100 units of 330…750 kV CTs have been tested using new conceptual methodologies. At least two meaningful results can be emphasised:

- Improving the techniques of dielectric tests at rated voltage has allowed improving the precision of the method significantly. Errors in determination of tanδ and capacitance were less than 0.02 % and 0.6 % correspondingly
- Repetition of tests of 60 units of 330 kV "Hair-pin" design CT in the hottest period of the year allow to detect 12 defective units, 6 of them were removed out of service due to excessive dielectric losses.

CONCLUSION

1. CTs monitoring under operating conditions is the most fruitful way to improve serviceability of the apparatus and to move from time-based to condition-based maintenance. Experience has shown that the techniques are available to detect appearance of typical defects in the condenser core of the CTs of typical design.
2. The next step is to move from traditional approach to monitor some characteristics of the equipment to the condition monitoring. Expert systems shall be developed using correlation between diagnostic characteristics of the particular failure mechanism in the particular design.

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