BUSHING AND HV CURRENT TRANSFORMER ON-LINE MONITORING USING M4000 ANALYZER

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INTRODUCTION

There has been a pressing need for On-Line monitoring and diagnostic techniques for HV- bushings and HVCT's, where damage results often in catastrophic failure.
Recently an efficient technique that is based on monitoring of sum current has been presented [1-3]. This paper continues this topic and presents the technique for On-Line measurement of dielectric Power Factor and Capacitance using Dielectric Test Device, particularly M4000 Analyzer.

ON-LINE MONITORING, WHY?

Traditional Off-Line monitoring technique has proved itself to be very effective to detect and identify defects that involve slow diffusion of moisture and air, slow accumulation of particles and oil aging products, and occurrence of faults that can develop for years. It is not the case when defects can advance during months of weeks.
Besides obvious economic benefits from having periodical or continuous on-line diagnostics, On-line monitoring of HV bushings and current transformers permits the user to improve significantly the capability to detect more problems with apparatus at an earlier stage of development.
Typical failure modes and most effective diagnostic tools for HVCT and bushings are summarized in the Table 1 on the basis of ZTZ-Service experience [4,6], and EPRI [5] and CIGRE [7] studies.
One may conclude that one detection method will not catch all failures. However, irrespective of difference in diagnostic response of defective units, relative PF ratio at operating voltage has been successful practically in all typical cases of developing failure.
An on-line method is required because of the erratic and sometimes rapid nature of HVCT and bushing failures.
On-Line measuring exploits the advantages of PF testing under real operating conditions (at rated voltage, at variable operating temperature) and consequently, to extend the range of diagnostic characteristics using:
Change of PF with temperature, with voltage, with time, as well as correlation between PF, capacitance, sum current and leakage current in case if an internal fault occurs that involves short-circuits between layers.

Two methods of On-Line monitoring of PF and capacitance of the HVCT and bushings have been suggested: External Reference Method and Direct Method using PT as External Reference voltage source.

TABLE 1

Typical failure modes of bushings and HVCT and most sensitive diagnostic tools

Typical Failure mode	**Diagnostics Most Sensitive to Failure Mode**
HVCT Thermal instability of the oil/paper dielectric	Dielectric Power (Dissipation Factor) Rise with temperature and with time DGA(CO and CO2) Furans Oil aging by-products
HVCT Dielectric overstressing and partial discharge activity	Partial Discharge DGA Dielectric Loss (Dissipation) Factor; tip up with voltage Capacitance; Leakage current
HV Bushings Local defect / fault in the bushing core that results in short-circuit between layers: Thermal-dielectric overheating Electric ionization in the place of overstressing	Relative PF C_1 (tan delta) and imbalance (sum) current ratio Rising PF C_1 with temperature and time (thermal) Relative capacitance C_1 and leakage current ratio if short-circuit between layers occurs. Partial Discharge (Ionization) DGA (CO, CO2), furans (Thermal) DGA PD-mode (Ionization)
HV Bushings Degradation of the dielectric withstand strength of oil and across the porcelain surface that results in flashover along the surface Critical aging the oil, formation of semi-conductive residue on the lower porcelain;	Rising PFC2 (Test Tap) with temperature (oil deterioration) Reduction of PF C_1 below some minimum value Reduction of PF C_1 with temperature Relative sum current ratio Oil aging by-products Partial Discharge DGA

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EXTERNAL REFERENCE METHOD

The method permits comparison between the dielectric parameters of two similar units.
To perform on-line measurement of the insulation power factor two objects are used. One of them named as Reference and another one – as Specimen
The output signal is coming through special bushing sensors that provide accuracy of the signal as well as safety precautions for employees.
Direct results of the measurement are (Fig.1):

- Two current modules via the insulation of the first and the second checking objects I_1 and I_2;
- Phase angle between the current vectors I_1 and I_2.

Loss angle δ is equal to the difference of the loss angles of the second and the first measured objects $\delta=\delta_1 - \delta_2$, or the difference of the phase angles between the voltage vector and the first object φ_1 current and the second object φ_2 current, i.e. $\varphi = \varphi_1 - \varphi_2$.
In order to perform On-Line tests the bushings or CTs are provided with special sensors .Two types of sensors have been used: resistor type and capacitance type.
The measurement includes the difference in PF angles between the Specimen and Reference units and the relevant ratio of capacitance. The PF angle of the CT in question is estimated as

$$\varphi_x = \varphi_{\mathrm{Re}\,f} + \Delta\varphi + \sigma_e$$

Where φ_{Ref}–is the PF angle of the reference object that is assumed to be in good condition, $\Delta\varphi$- tested difference between the Specimen and the Reference units; σ_e is the angle error . δ_e is the angle error. Correction for the capacitance of cables connection is considered as well.

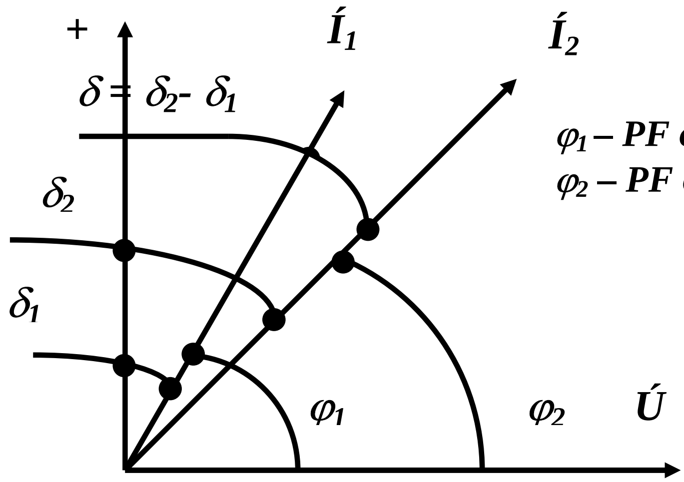

FIGURE 1
Basic points for On-Line PF comparison testing

The main factors that impact on test accuracy are:

- Influence of grounding potential of different objects and interference of overhead lines
- Systematic error of bushing sensors and CT's;
- Difference in the unit's temperature that is more important for bushings.

In 1996 "ZTZ – SERVICE " developed a new Test circuit based on M4000 Analyzer adaptation instead of commonly utilized so-called "bridge" method based on a Schering bridge application.
Diagram of the measurement using M4000 is shown in Figure 2. The M4000 analyzer is connected through the matching unit to the test taps of the bushings and current transformer located on the same phase

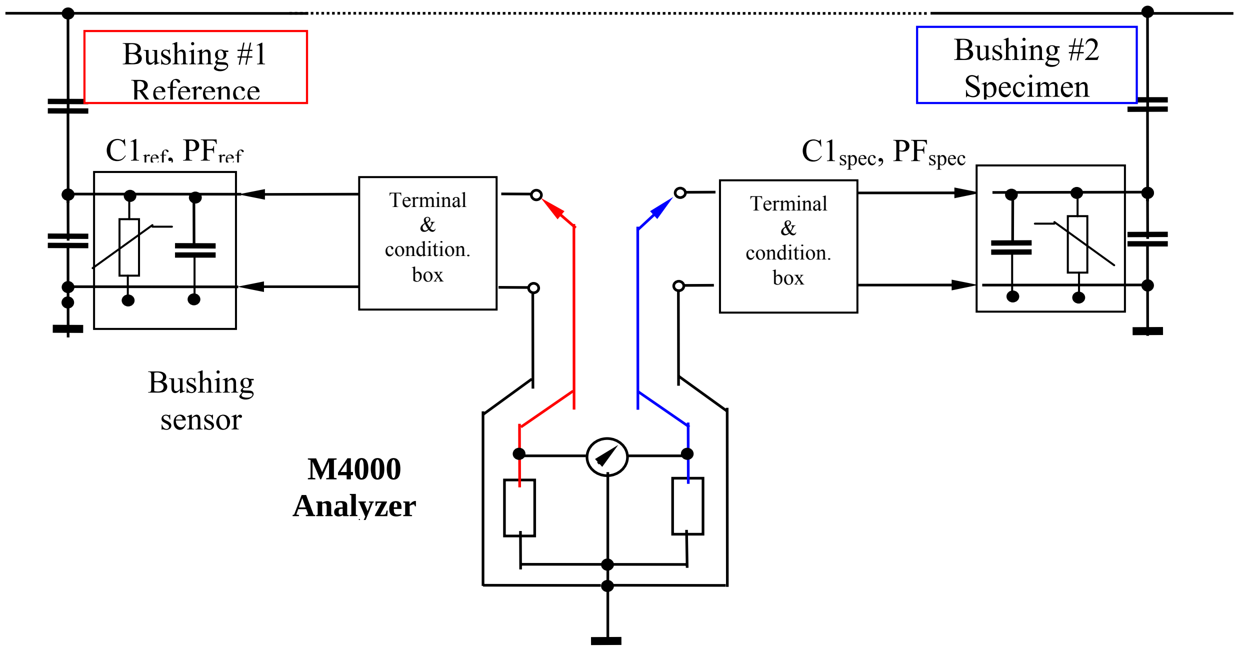

FIGURE 2
Reference test circuit using M4000 Analyzer

The terminal and condition box developed by ZTZ-Service Co performs the following functions:

- Provides the galvanic bypass of the measuring circuits connected with non-equipotential grounding points of the tested objects and grounding points of the instruments;
- Limits the current passing through measuring circuits of M4000 up to 15 mA;
- Provide safety of tests;
- Provides possibility of switching the objects from the Reference to the Specimen object and vice versa.
- Provides overvoltage protection

Comparative tests have been performed to ascertain accuracy, sensitivity and repeatability of suggested test technique using as reference data off-line tests results by means of the Mobile Test Device and traditional tests at 10 kV.
On-line tests data was found to be quite consistent (Table 2).
The absolute methodic error of PF measurement has been typically not more than that 0.02%.
Accordingly the absolute error during repeat tests (Table 2) did not exceed 0.05%

TABLE 2

Comparative tests on two cascades 750 kV CT **at** the Zaporozhskaya Nuclear Power Plant

Top cascade phase A, SerNB1064			
U-кV	Mobile Test Device PF, %	M4000 PF, %	M4000 On-Line PF, %
10		0.213	
120	0.21		
225	0.209		0.210
250	0.209		
Bottom cascade phase A, Ser NB1082			
U-кV	Mobile Test Device PF %	M4000 PF%	M4000 On-Line PF %
10		0.223	
120	0.22		
225	0.219		0.228
250	0.219		

TABLE 3

Repeatability of On-Line Reference test of two cascades 750 kV CTs

Data,	Ambient temperature	Cascade	PF % Off- Line at 225 kV	PF, % On Line	ΔPF, % .
26.09.97	+15°C	Top	0.219	0.201	-0.018
		Bottom	0.243	0.261	0.018
30.09.97	+13°C	Top	0.219	0.210	-0.009
		Bottom	0.243	0.252	0.009
01.06.98	+28°C	Top	0.219	0.200	-0.019
		Bottom	0.243	0.262	0.019
12.11.98	+3°C	Top	0.219	0.177	-0.042
		Bottom	0.243	0.285	0.042
13.11.98	+5°C	Top	0.219	0.202	-0.017
		Bottom	0.243	0.260	0.017

POTENTIAL TRANSFORMER AS EXTERNAL REFERENCE VOLTAGE SOURCE

Diagram of the measurement using M4000 is shown in Figure 3

The main problem of this method has been accounting for the phase angle errors of the PT

The Transformer Research Institute in Zaporozhye and ZTZ-Service have suggested methodology for the determination of PT errors and correction on the basis of factory test data and real operation conditions (voltage, PF, load)

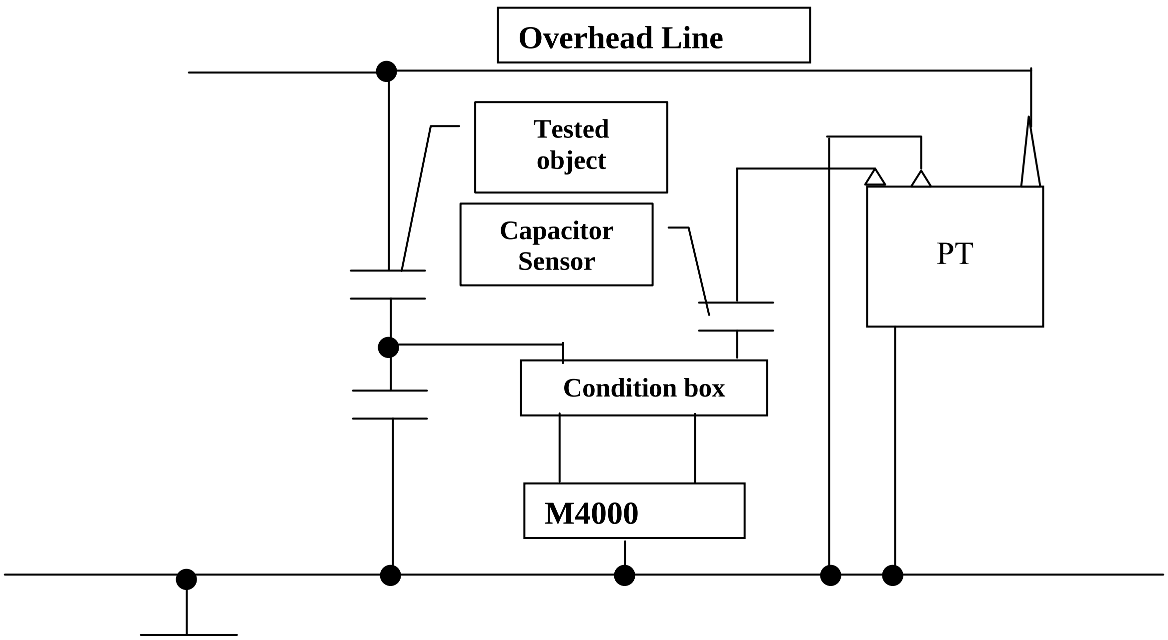

FIGURE 3
Test circuit using M4000 Analyzer and potential transformer

Threshold quantities

EXPERIENCE WITH ON-LINE TESTS OF HV CTs AND BUSHINGS

Experience On-Line Monitoring of HVCT in Ukraine has included the tests on more than 1000 units of 330 kV and 750 kV CTs.. The method appears to be very successful. In one Ukrainian utility, 43 defective units were identified. In another utility 14 violent failures were prevented during 1990-1999. Possibility to provide testing under maximum temperature of the HVCT in summer time has permitted detection of a number of defective units having symptoms of dielectric overheating presumably due to excessive aging of oil-paper bulk.
Test circuit with adaptation of M4000 was suggested and implemented at the Zaporozhskaya Nuclear Power Plant.

ON-LINE HVCT PF MONITORING AT THE ZAPOROZHSKAYA NUCLEAR POWER PLANT

52 two cascades inverted eye – bolt design 750 kV CTs (104 units) have been tested periodically since 1998 [4].
Ranking methodology was suggested to identify the units that required particular attention
The following limits have been advised to select questionable units:
Normal condition: PF<0.5%
Warning :0.5≤ PF ≤ 0.7 %; Rise of PF with temperature: 0.015 ≤ α 0.03
Alarm: PF>0.7%; Rise of PF with temperature α>0.03
Where $PF = PF_{T_0} \cdot e^{\alpha(T-T_0)}$

α (1/grad) is the index of deterioration.
Some test results are shown in Fig.4. Here, 3 top cascades were found to be a serious condition.
A forensic investigation revealed that reason for increase of dielectric losses involved occurrence of polar contaminants due to excessive aging of oil.

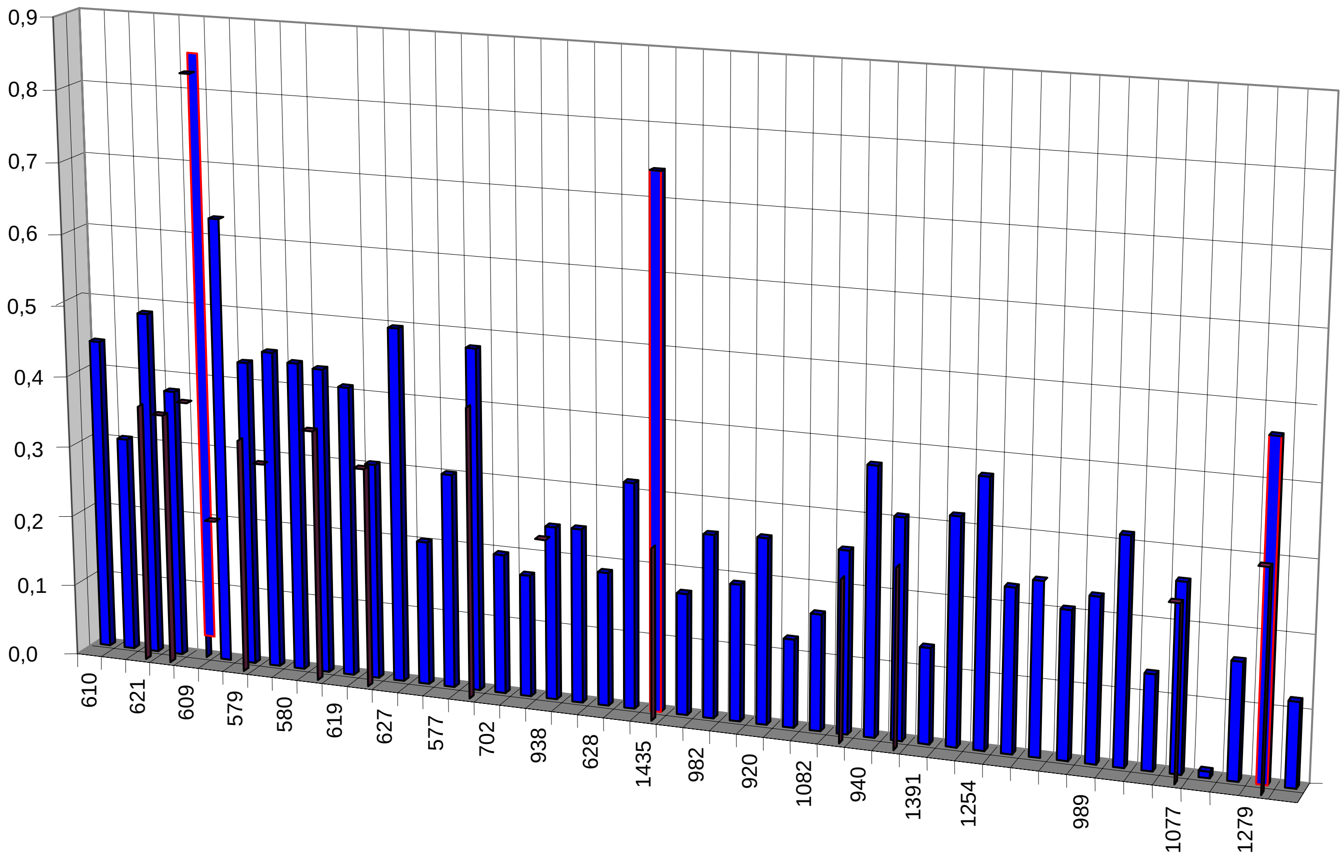

FIGURE 4
On-Line Power Factor Tests on 750 kV CT at Zaporozhskaya NPP

ON-LINE BUSHINGS PF MEASUREMENT AT THE MONET SUBSTATION, FLORIDA POWER AND LIGHTS CO

Objects: ABB plus O/ 138 kV bushings
External Reference Method using M4000
Date: 05.14 – 05.15.2001

The On-Line test data (Table 5) have been compared with Off-Line Doble test at 12 kV (Table 4). It was found that the difference between Off-Line and On-line PF test results did not exceed 0.05-0.07%.

TABLE 4
Last Doble M4000 test results @ 12 kV prior to On-Line Measurements

Transformer Serial Number	Bushing Serial Number	Phase	PF C1,%	C1,pF
491268	22583291325	H1	0.42	435
	22583291943	H2	0.35	430
	22583291329	H3	0.45	436
491374	7C00933901	H1	0.23	374.60
	7C00933903	H2	0.24	376.80
	7C00933902	H3	0.24	375.10

TABLE 5
On-Line PF and C1 test results

Phase	Reference#	Specimen#	Off-Line values		Measured values		Calculated values PF_{ref}+ delta PF
			PF, %	C1, pF	delta PF%	C1, pF	
H1	7C00933901	22583291325	0.42	435	0.22	434.98	0.45
H2	7C00933903	22583291943	0.35	430	0.16	428.63	0.40
H3	7C00933902	22583291329	0.45	436	0.28	432.88	0.52
Phase	Reference#	Specimen#	Off-line values		Measured values		Calculated values PF_{ref}+ delta PF
			PF, %	C1, pF	delta PF%	C1, pF	
H1	22583291325	7C00933901	0.23	374.6	-0.12	373.20	0.30
H2	22583291943	7C00933903	0.24	376.8	-0.10	377.10	0.25
H3	22583291329	7C00933902	0.24	375.1	-0.14	375.28	0.31

ON-LINE HVCT PF TESTING AT THE DORSEY STATION, MANITOBA HYDRO

Date: October 21-22, 2001

Tested objects:
1.Current transformers 230 kV with installed resistor type sensors.

TABLE 6
Test data of the Reference object (Circuit Breaker R53 CTs)

Phase	Serial No.	C1, pF	PF, %
A	7149206	192.7	0.284
B	7149203	188.2	0.349
C	7149210	192.7	0.271

TABLE 7
Off-Line and On-Line measurement on the Specimen object (Circuit Breaker R54 CTs)

Phase	Serial No.	C1, pF	Off-line PF %	On-line PF, %
A	6617729	204.9	0.355	0.344
B	6617721	196.9	0.371	0.379
C	6677746	207.0	0.350	0.211

To evaluate effect of interferences due to influence of grounding potential, measurements were performed without and though the conditioning box . Table 8 shows that test results without the conditioning box are very unstable and have poor correlation with actual values of PF.

TABLE 8
Test results with 4000 instrument with condition box and direct measurements

Measuring scheme	Phase	I_x, mA	Δtanδ, %	U_R, kV
Through conditioning box	A	9.515	0.06	141.868
Without conditioning box	**A**	**9.623**	**-0.24**	**146.868**
Through conditioning box	B	9.473	0.03	137.847
Without conditioning box	**B**	**9.835**	**1.59**	**142.326**
Through conditioning box	C	9.634	-0.06	142.178
Without conditioning box	**C**	**10.029**	**-1.32**	**147.090**

2.Tested objects: 230 kV bushings with Cutler-Hammer capacitance type sensors

TABLE 9
Test data of the Reference object (Transformer T42D)

Phase	C1, pF	tanδ, %
H1	424.2	0.35
H2	419.1	0.36
H3	420.0	0.35

TABLE 10

Actual test results with M4000 instrument

Measuring scheme	Phase	I_x, mA	ΔPF %	(ΔPF_{normal} - $\Delta PF_{reverse}$) /2, %	C_x, pF
Normal	H1	3.326	0.01	-0.05	423.52
Reversal	H1	3.326	0.11		
Normal	H2	3.399	0.02	-0.05	434.34
Reversal	H2	3.275	0.12		
Normal	H3	3.271	0.00	-0.04	420.37
Reversal	H3	3.263	0.08		

TABLE 11

Off-Line and On-Line tests on the Specimen object (Transformer T42S)

Phase	Off-line C1, pF	Off-line PF, %	On-line C1, pF	On-line PF, %
H1	425.2	0.30	423.52	0.30
H2	435.6	0.37	434.34	0.31
H3	421.8	0.31	420.37	0.31

A notable difference was found between normal and reversal tests which could be explained by different impedance of M4000 reference and specimen circuits. The impedance of reference circuit is stable in the order of 7.5 Ohm and the impedance of the specimen circuit varies from 0.012 up to 0.36 Ohm depending of the measured current. To avoid this phenomenon it's proposed to use a special adapter in the specimen circuit to increase it's impedance to the level of 7.5 Ohm

ON-LINE BUSHING TESTS AT THE TPP DARNITSA (UKRAINE) USING PT AS A EXTERNAL REFERENCE VOLTAGE SOURCE

Tested objects;
110 kV, 630 A bushings of free-breathing design, about 38 years in service
Date: March 01, 2002

Tests of the bushings were carried out on two transformers: T5 (Reference) and T1 – (Specimen) using direct circuit and external reference circuit as well to compare the data. The bushings were tested last time in 1996 but unfortunately the previous tests data was not available.

TABLE 12

External reference test results (PT as a external voltage reference source)

Object	Phase	PF, %	C, pF	U, kV
Bushings of the transformer T1	A	1.59	227.6	65.83
	B	0.95	223.1	65.76
	C	0.66	229.6	65.83
Bushings of the transformer T5	A	1.78	250.9	65.84
	B	2.98	164.2	65.73
	C	2.24	167.2	65.83

TABLE 13
Comparison of test results gained by two methods

Phase	PT as a reference (PFT1 – PFT5), %	ΔPF, % by direct tests	ΔPF, % by reference tests	Error, PF, %	C, pF By Reference tests	C, pF By direct tests
A	1.59-1.78	-0.19	-0.19	0.00	227.3	227.6
B	0.95-2.98	-2.03	-2.01	-0.02	223.1	223.1
C	0.66-2.24	-1.58	-1.58	0.00	220.3	220.6

It was found that the difference between the test results is fairly low that shows the direct method as wholly satisfactory one.

CONCLUSION

On-Line monitoring of PF and Capacitance of HVCTs and bushings, besides economical considerations, permits the use of the advantages of PF testing under real operating conditions which extends the range of the diagnostic tools.
External Reference method using comparison between two objects permits to estimate parameters in question through the difference in PF angles between the Specimen and Reference units and the relevant ratio of capacitance.
Accuracy, sensitivity and repeatability of the test technique using M4000 Analyzer are quite appropriate to be used for On-Line monitoring.
Some modification of the test circuit is recommended to exclude external interferences.
Direct PF test using PT reference voltage source has shown to be very promising as well.

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