# On-Line Monitoring of HV Bushings and Current Transformers

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***Abstract*** **- There has been a pressing need for on-line monitoring and diagnostic techniques for HV bushings and current transformers where deterioration often results in catastrophic failure. This paper expands the available information on this topic and presents the technique for the on-line measurement of dielectric power-factor and capacitance using the Doble M4000 insulation analyzer.**

## WHY ON-LINE MONITORING?

The traditional off-line monitoring technique (Tan δ) 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 or weeks. Besides the obvious economic benefits from having periodic or continuous on-line diagnostics, on-line monitoring of high voltage 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 high voltage current transformers and bushings have been discussed in the literature including: ZTZ-Service experience [4,6], and EPRI [5] and CIGRE [7] studies. It may be concluded that one detection method will not catch all failures. However, irrespective of differences in diagnostic response of defective units, the relative dielectric power-factor 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 developing high voltage current transformer and bushing failures.

The effect of applied voltage on power-factor magnitude is shown in Figure 1. At the 10% of rated voltage the power-factor of the two bushings is practically the same. That means that off-line dissipation-factor or Doble power-factor tests at 10 kV will not show any defect in the bushings, but with increase of applied voltage the power-factor of the defective bushing rapidly grows. The higher applied voltage reflects in higher power-factor magnitude.

On-line measuring exploits the advantages of power-factor testing under real operating conditions (at rated voltage, at variable operating temperature) and consequently, to extend the range of diagnostic characteristics using: change of power-factor with temperature, with voltage, with time, as well as correlation between power-factor, capacitance, sum current and leakage current in case if an internal fault occurs that involves short-circuits between layers.

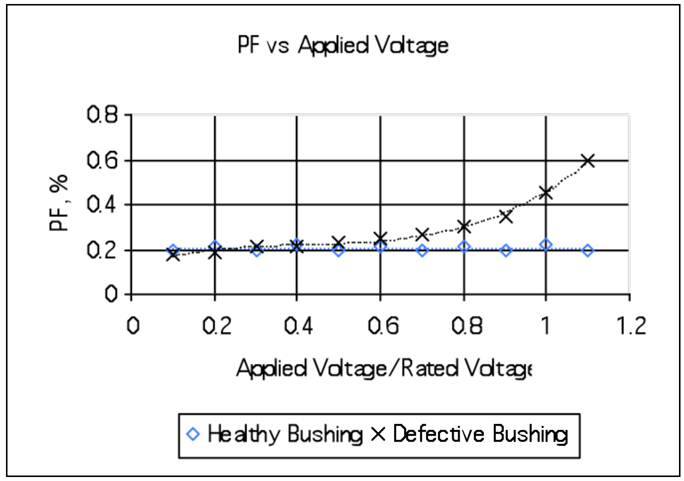


Fig. 1. Insulation power-factor versus applied voltage

Two methods of on-line monitoring of power-factor and capacitance of the high voltage current transformers and bushings have been suggested: External Reference Method, and Direct Method using a voltage transformer as external reference voltage source.

## BUSHING AND CT SENSORS

The main purposes of using sensors are:

- protect test personal from electric shock in the case of an open test tap circuit;
- protect test tap from overvoltage in the case of open test tap circuit;
- provide reliable current output from the test tap.

There are three different types of bushing sensors:

*A. Capacitor- type sensor* (Fig. 2)

In the case of 500 kV bushing that has C1 capacitance (conductor-to-tap) equal to 300 pF the output voltage when the test tap circuit is open will not exceed:

$$U_{out} = \frac{U \cdot C1}{\sqrt{3} \cdot Cs} = \frac{500 \cdot 10^{3} \cdot 300 \cdot 10^{-12}}{\sqrt{3} \cdot 1.08 \cdot 10^{-6}} = 80V$$

This sensor has two levels protection, the first one is a capacitor that reduces output voltage to the safe level and the second one the varistor that protects from spikes coming from overhead line. One of the disadvantages of this type of sensor is that the measuring circuit should have equal impedance for

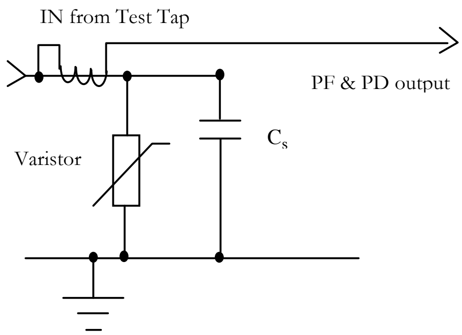

Fig. 2. Capacitor-type sensor

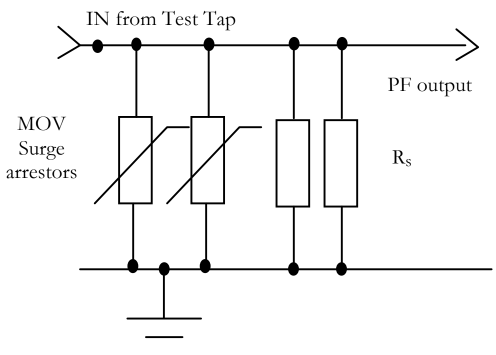

Fig. 3. Resistor-type sensor

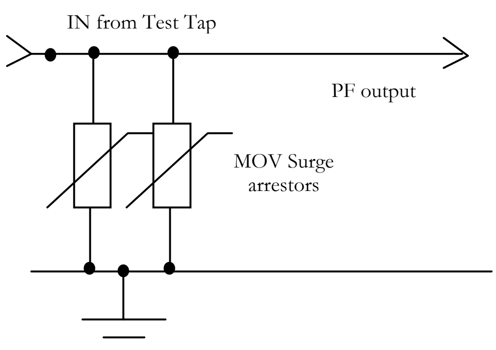

Fig. 4. MOV arrestor-type sensor

the reference object and the tested one. In other cases systematic error appears which is proportional to:

$$\varphi_s = \arctan\left(\frac{1}{\omega \cdot Cs \cdot Rd}\right)$$

Where:
$\varphi_s$ – error angle, deg.;
$Rd$ – difference in measuring channel impedance.

*B. Resistor-type sensor* (Fig. 3)

In the case of 500 kV bushing that has C1 capacitance equal to 300 pF the output voltage will not exceed:

$$U_{out} = \frac{U \cdot \omega \cdot C1 \cdot Rs}{\sqrt{3}} = \frac{500 \cdot 10^3 \cdot 314 \cdot 300 \cdot 10^{-12} \cdot 2000}{\sqrt{3}} = 54V$$

This sensor has two levels protection, the first one consists of resistors that reduce output voltage to a safe level and the second one MOV surge arrestors that protect from spikes coming from overhead line.

*C. MOV arrestor-type sensor* (Fig. 4)

This sensor has only one level of protection. In the case of open circuit all voltage is applied to the arrestors. The safety margin depends on how long the arrestors can withstand applied voltage.

## External Reference Method

This 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 comes from special bushing sensors that provide accuracy of the signal as well as safety precautions for employees.

Results of the measurement are shown in Fig. 5:

- Two current vectors via the insulation of the first and the second test 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 $\varphi_1$ current and the second object $\varphi_2$ current, i.e. $\varphi = \varphi_1 - \varphi_2$.

In order to perform on-line tests the bushings or CTs are provided with sensors. The measurement includes the difference in power-factor angles between the Specimen and Reference units and the relevant ratio of capacitance. The power-factor angle of the CT in question is estimated as:

$$\varphi_x = \varphi_{REF} + \Delta\varphi + \delta_e$$

Where $\varphi_{REF}$ is the PF angle of the healthy reference object.
$\Delta\varphi$ is measured difference between Specimen & Reference.
$\delta_e$ is the angle error.
Correction is made for capacitance of the connecting cables.

The main factors affecting 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.

Eliminating influence of grounding potential on test results is very important. In Fig. 6. is shown an equivalent circuit with influence of grounding potential. AC current source reflects the leakage current flowing through the tested object: bushing, CT, etc. AC voltage source imitates grounding potential. $Z_1$ – is an impedance of the bushing sensor. In our case resistor-type sensor is used. $Z_2$ – is input impedance of measuring instrument. In Table I is shown the influence of grounding potential changing phase from 0 to 10 degrees.

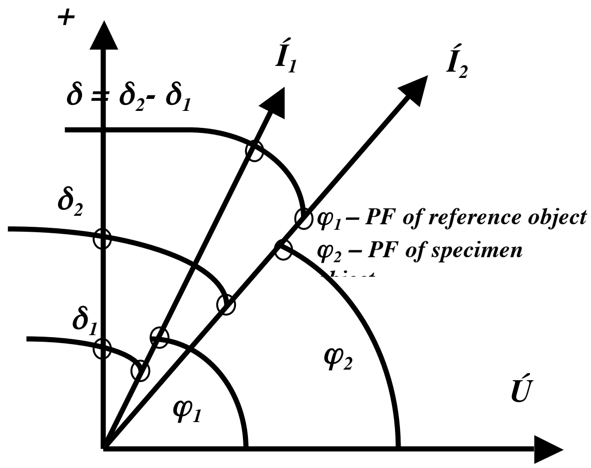


Fig. 5. On-line power-factor comparison

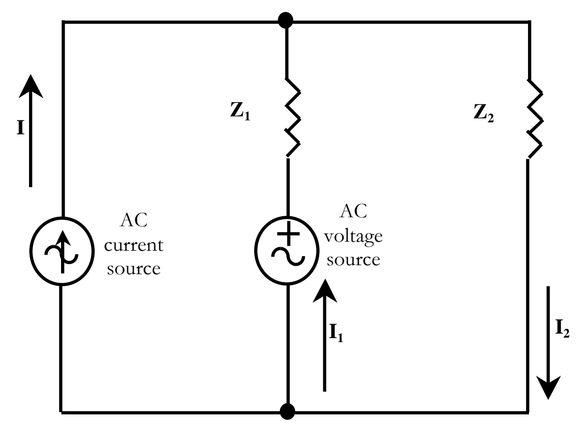


Fig. 6. Equivalent circuit showing influence of grounding potential

TABLE I
CALCULATED RESULTS OF δ, I vs. φ

| *φ*, deg | *δ*, deg | *Tanδ %* | ***I***$_2$, A | ***I***$_1$, A |
|---|---|---|---|---|
| 0 | 0.000 | 0.000 | 0.0257 | 7.43E-04 |
| 1 | 0.038 | 0.067 | 0.0257 | 7.42E-04 |
| 2 | 0.077 | 0.134 | 0.0257 | 7.42E-04 |
| 3 | 0.115 | 0..201 | 0.0257 | 7.41E-04 |
| 4 | 0.154 | 0.268 | 0.0257 | 7.40E-04 |
| 5 | 0.192 | 0.335 | 0.0257 | 7.39E-04 |
| 6 | 0.230 | 0.402 | 0.0257 | 7.37E-04 |
| 7 | 0.269 | 0.469 | 0.0257 | 7.35E-04 |
| 8 | 0.307 | 0.535 | 0.0257 | 7.33E-04 |
| 9 | 0.345 | 0.602 | 0.0257 | 7.30E-04 |
| 10 | 0.383 | 0.668 | 0.0257 | 7.28E-04 |

From Table I it is seen that deviation of phase angle φ only to 1 degree leads to error in Tan δ test result of 0.067%. In the substation the phase angle of grounding potential depends on numerous factors such as overhead lines interference and of course it cannot have a stable or defined value.

In 1991 ZTZ – Service developed a new test circuit based on the Doble M4000 Analyzer instead of a "bridge" method based on a Schering bridge application. The diagram of the measurement using the M4000 is shown in Fig. 7. The M4000 analyzer is connected through the matching unit to the test taps of the bushings or the current transformers located on the same phase. The terminal and condition box developed by ZTZ-Service 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 the proposed test technique using as reference data off-line results obtained by means of a mobile test device and traditional tests at 10 kV. On-line test data were found to be quite consistent (Table II). The absolute methodic error of the power-factor measurement has been typically not more than that 0.02%. Accordingly the absolute error during repeat tests (Table III) did not exceed 0.05%.

TABLE II
COMPARATIVE TESTS ON TWO CASCADES OF 750 kV CT
AT ZAPOROZHSKAYA NUCLEAR POWER PLANT

| Top cascade phase A, Ser NB 1064 | | | |
|---|---|---|---|
| U-кV | Mobile Test Device PF, % | M4000 Off-Line PF, % | M4000 On-Line PF, % |
| 10 | | 0.213 | |
| 120 | 0.210 | | |
| 225 | 0.209 | | 0.210 |
| 250 | 0.209 | | |
| Bottom cascade phase A, Ser NB 1082 | | | |
| U-xV | Mobile Test Device PF, % | M4000 Off-Line PF,% | M4000 On-Line PF, % |
| 10 | | 0.223 | |
| 120 | 0.220 | | |
| 225 | 0.219 | | 0.228 |
| 250 | 0.219 | | |

TABLE III
REPEATABILITY OF ON-LINE REFERENCE TEST ON TWO CASCADES OF 750 kV CT

| Date | Ambient Temp | 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 |

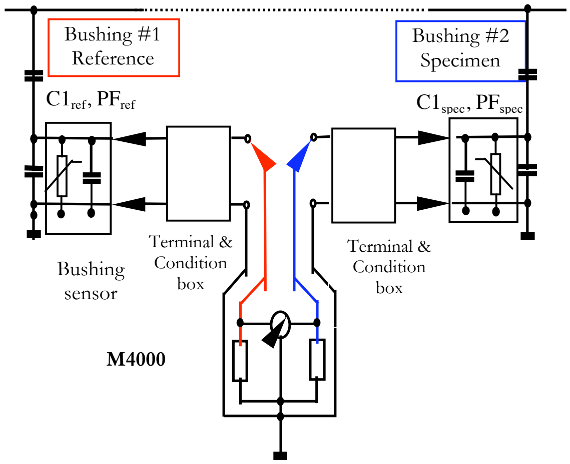


Fig. 7. Reference test circuit using M4000 analyzer

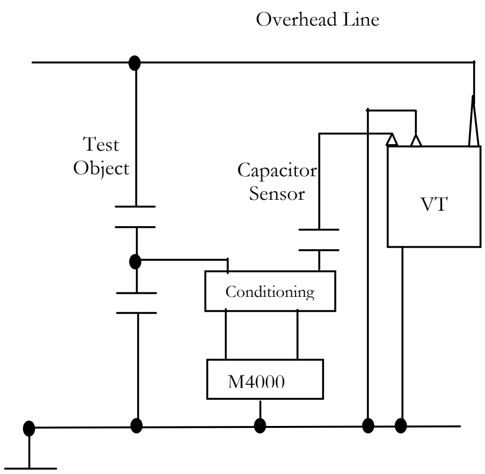


Fig. 8. Direct test circuit using M4000 analyzer and voltage transformer

## VOLTAGE TRANSFORMER AS EXTERNAL REFERENCE

Diagram of the measurement using the M4000 and a voltage transformer as an external reference is shown in Fig. 8. The main problem with this method has been accounting for the phase angle errors of the voltage transformer. The Transformer Research Institute in Zaporozhye and ZTZ-Service have suggested methodology for the determination of voltage transformer errors and correction on the basis of factory test data and real operating conditions (voltage, power-factor, burden).

## EXPERIENCE WITH ON-LINE TESTS ON HV CTS AND BUSHINGS

Experience with on-line monitoring of HV CTs in Ukraine has included the testing of more than 1000 units rated 330 kV and 750 kV. 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. The possibility of testing under maximum temperature of the HV CT in summer time has permitted detection of a number of defective units having symptoms of dielectric overheating presumably due to excessive aging of the oil-paper bulk.

A test circuit with adaptation of the M4000 was suggested and implemented at the Zaporozhskaya Nuclear Power Plant. 52 two cascade 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 determined to identify questionable units:

- Normal condition: PF<0.5%
- Warning :0.5≤ PF ≤ 0.7 %; Rise of PF with temperature: $0.015 \le \alpha$ 0.03
- Alarm: PF>0.7%; Rise of PF with temperature $\alpha > 0.03$

Where $PF = PF_{T_0} \cdot e^{\alpha(T-T_0)}$

$\alpha$ (1/grad) is the index of deterioration. Some test results are shown in Fig. 9. Here, 3 top cascades were found to be in serious condition. A forensic investigation revealed that the reason for increase of dielectric losses involved occurrence of polar contaminants due to excessive aging of oil.

## ON-LINE BUSHING PF MEASUREMENT AT MONET SUB.

The following on-line bushing power-factor measurements were made at the Monet Substation of Florida Power & Light.

- Test objects ABB Type O+C 138 kV bushings
- External reference method using M4000
- Date: 14.05 – 15.05.2001

The on-line test data (Table V) have been compared with off-line Doble tests at 12 kV (Table IV). It was found that the difference between off-line and on-line power-factor tests did not exceed 0.05 – 0.07%.

TABLE IV
LAST DOBLE M4000 TEST AT 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 |
| | 7C00933903 | H2 | 0.24 | 376 |
| | 7C00933902 | H3 | 0.24 | 375 |

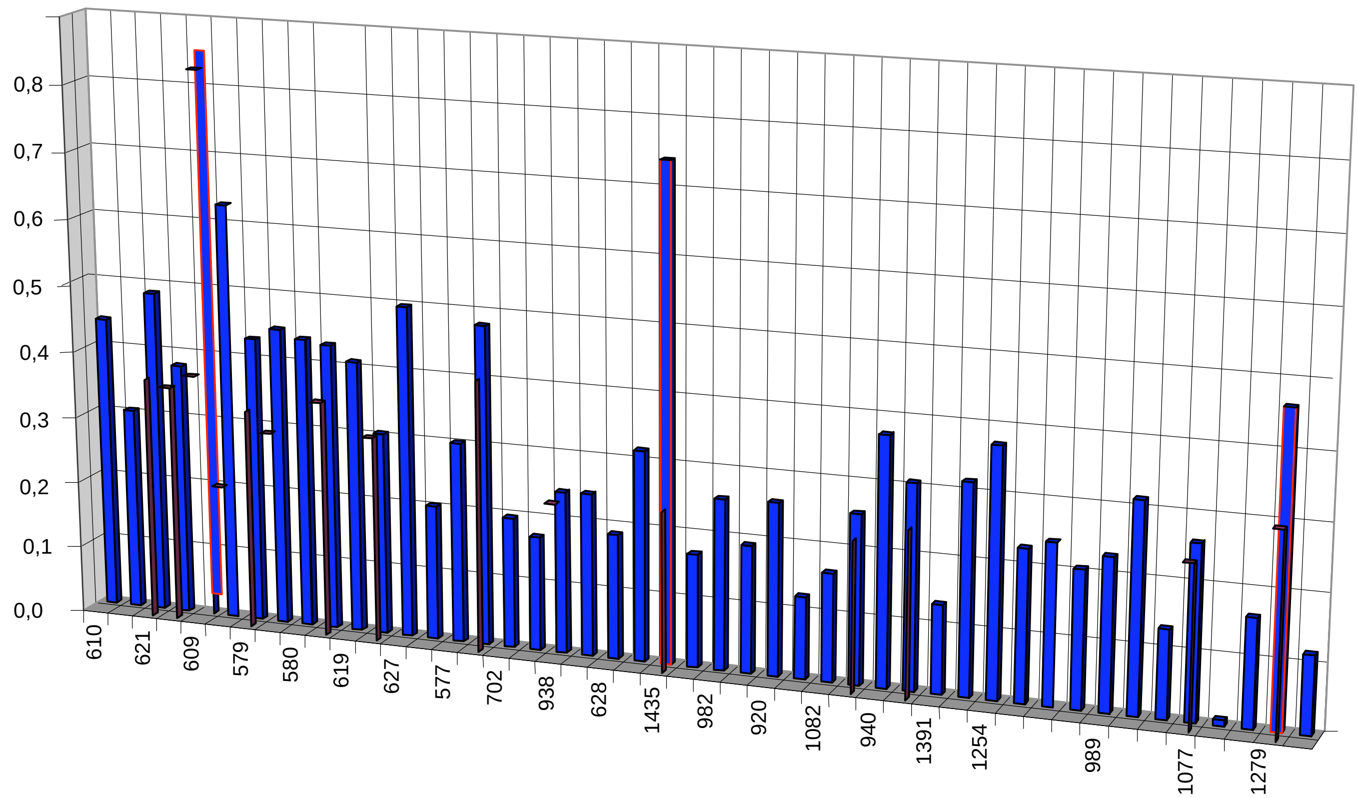


Fig. 9. On-line power-factor tests on 750 kV CT at Zaporozhskaya NPP (vertical scale 0.0 – 0.8% Tanδ)

TABLE V

ON-LINE POWER-FACTOR AND C1 TEST RESULTS

| Ph | Ref. # | Specm. # | Off-Line values | | Measured values | | Calc values $PF_{ref}$+ delta PF |
|---|---|---|---|---|---|---|---|
| | | | PF, % | C1, pF | delta PF% | C1, pF | |
| H1 | ..01 | …325 | 0.42 | 435 | 0.22 | 434.98 | 0.45 |
| H2 | 03 | …943 | 0.35 | 430 | 0.16 | 428.63 | 0.40 |
| H3 | 02 | …329 | 0.45 | 436 | 0.28 | 432.88 | 0.52 |
| Ph | Ref. # | Specm. # | Off-line values | | Measured values | | Calc values $PF_{ref}$+ delta PF |
| | | | PF, % | C1, pF | delta PF% | C1, pF | |
| H1 | ..325 | …01 | 0.23 | 374.6 | -0.12 | 373.20 | 0.30 |
| H2 | ..943 | …03 | 0.24 | 376.8 | -0.10 | 377.10 | 0.25 |
| H3 | ..329 | …02 | 0.24 | 375.1 | -0.14 | 375.28 | 0.31 |

## ON-LINE POWER-FACTOR TESTS ON DORSEY CTs & BUSHINGS

On-line CT and bushing power-factor measurements were made at Dorsey Station, Manitoba Hydro on 23-24 Oct. 2001.

### *A. 230 kV Current transformers with resistor- type sensors*

The capacitance taps of two sets of 230 kV current transformers were fitted with resistor-type sensors.

TABLE VI

OFF-LINE MEASUREMENTS ON R53 CTs – REFERENCE OBJECT

| 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 VII

OFF-LINE & ON-LINE MEASUREMENTS ON R54 CTs – SPECIMEN OBJECT

| 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 the effect of interference due to the influence of grounding potential, measurements were performed with and without the conditioning box. Table VIII shows that test results without the conditioning box are very unstable and have poor correlation with actual values of power-factor.

TABLE VIII

TESTS WITH M4000 WITH & WITHOUT CONDITIONING BOX FOR R53CT

| Conditioning Box | Phase | $I_x$, mA | Δtanδ, % | $U_R$, kV |
|---|---|---|---|---|
| with | A | 9.515 | 0.06 | 141.868 |
| **without** | **A** | **9.623** | **-0.24** | **146.440** |
| with | B | 9.473 | 0.03 | 137.847 |
| **without** | **B** | **9.835** | **1.59** | **142.326** |
| with | C | 9.634 | -0.06 | 142.178 |
| **without** | **C** | **10.029** | **-1.32** | **147.090** |

### *B. 230 kV bushing with Cutler-Hammer capacitive sensors*

The capacitance taps of the 230 kV bushings of two HVDC converter transformers had been fitted with Cutler-Hammer capacitive sensors for on-line sum-current measurements.

TABLE IX

OFF-LINE MEASUREMENTS ON T42D – REFERENCE OBJECT

| Phase | C1, pF | Tanδ, % |
|---|---|---|
| H1 | 424.2 | 0.35 |
| H2 | 419.1 | 0.36 |
| H3 | 420.0 | 0.35 |

TABLE X

ON-LINE MEASUREMENTS WITH M4000 ANALYZER

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

TABLE XI

OFF-LINE AND ON-LINE MEASUREMENTS ON T42S – SPECIMEN OBJECT

| 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 reverse measurements 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 ohms and the impedance of the specimen circuit varies from 0.012 up to 0.36 ohms depending on the measured current. To avoid this phenomenon it's proposed to use a special adaptor in the specimen circuit to increase it's impedance to the level of 7.5 ohms.

## ON-LINE BUSHING TESTS AT DARNITSA – VT AS REFERENCE

On-line measurements were made on 1 Mar. 2002 at the Darnitsa thermal power station in Ukraine using a voltage transformer as the reference. The bushings were rated 110 kV 630 A and were of a free breathing design and had been in service for about 38 years. The tests were carried out on the bushings of two transformers: T5 (Reference) and T1 (Specimen) using the direct and the external reference circuit. The bushings had previously been tested in 1996, but unfortunately these data were not available.

TABLE XII

MEASUREMENTS USING VOLTAGE TRANSFORMER AS REFERENCE

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

TABLE XIII

COMPARISON OF RESULTS FROM TWO METHODS

| φ | VT as a reference PFT1– 5 % | ΔPF, % by direct tests | ΔPF, % by reference tests | Error, PF, % | C, pF by ref. 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 measurements was fairly low and shows that the direct method as being entirely satisfactory.

## CONCLUSIONS

1. On-line monitoring of power-factor and capacitance of high voltage CTs and bushings, besides the economical considerations, permits the use of the advantages of power-factor testing under real operating conditions which extends the range of the diagnostic tools.
2. External Reference method using comparison between two objects permits estimation of parameters in question through the difference in power-factor angles between the Specimen and Reference units and the relevant ratio of capacitance.
3. Accuracy, sensitivity and repeatability of the test technique using the M4000 Analyzer are quite appropriate to be used for on-line monitoring.
4. Some modification of the test circuit is recommended to exclude external interference.
5. Direct power-factor measurements using a voltage transformer as a reference voltage source has been shown to be very promising as well.

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