Bearing in mind that about 17 % of transformer failures are attributed to bushing faults, it is of prime importance to monitor and observe the bushings

ABSTRACT

This article focuses on condenser bushings monitoring, of both oil-impregnated and resin-impregnated paper bushings, for extra high-voltage class transformers in order to avoid a catastrophic transformer failure that might result from a failed bushing. A brief description of the online monitoring system is presented, highlighting its superiority over conventional offline monitoring practices. This is followed by a true case study and a specimen cost-benefit analysis related to the failure of a 160 MVA, 220/132/33 kV transformer and its assumed down time of 72 hours at a substation in India, caused by a failure of a 245 kV oil-impregnated paper bushing.

KEYWORDS

bushing, tan δ, capacitance, infrared thermography

Condenser bushings condition monitoring

1. Introduction

Bushing condition monitoring is important in order to detect incipient faults. Some of the causes of a bushing failures include:

- high dielectric stress due to switching surges and lightening surges
- ingress of moisture and other contaminants through deteriorated, aged gaskets and hairline cracks in the porcelain
- oil leakage
- high atmospheric temperature, humidity, etc.
- deterioration of dielectric properties due to: (a) an increased oil temperature caused by transformer overloading, or (b) loose joint connections in the leads of the draw-lead type bushings/draw-rod type bushings, giving rise to an excess temperature in the bushings
- failure due to improper earth connection of the test tap
- improper re-fixing of the test tap cap after dissipation factor (tan δ) and capacitance measurements

2. Bushing condition monitoring

2.1 Online bushing monitoring

Bearing in mind the research results presented at the beginning of the article *Fundamentals of condenser bushings* [1], which show that about 17 % of transformer failures are attributed to bushing faults [2], it is of prime importance to monitor and observe the bushings, identifying defective bushings whose tan δ values are increasing. If the tan δ begins to exceed the value of 0.007, then the arrangements to replace the unit must be made.

Due to a bushing failure, the dielectric distances shorten and a flash over occurs between the live extra-high voltage (EHV) conductor and the transformer body, resulting in a hazardous fire/explosion in the transformer and also damaging the nearby outdoor equipment. This is generally observed in 220 kV, 400 kV and 765 kV voltage class transformers. The losses incurred by such failure and its consequences are colossal and they ensue from:

- the cost of the bushings;
- the cost of the transformer (in case there was a subsequent transformer failure) and associated activities; and
- the losses due to power system disturbances and/or blackouts affecting large number of consumers.

All this may lead to a huge revenue loss for the generation, transmission and distribution utilities.

2.2 Offline bushing monitoring

Offline bushing monitoring is conducted at different intervals depending on the customer or a country. However, it is a general practice to monitor bushings on a six-monthly basis, or annually where shutdowns pose constraints.

3. Tan δ and capacitance measurements

Tan δ is measured offline with a 10 kV tan δ testing kit in UST mode (Ungrounded Specimen Test mode), Fig. 1. The limiting value of tan δ for condenser bushings is 0.007 or 0.7 **%** as per IEC-60137 [3].

Note: (a) The limiting value of 0.7 % is also applicable to the bushings in service; (b) Test results of new condenser bushings show that the factory value of tan δ is as low as 0.3 % to 0.4 %.

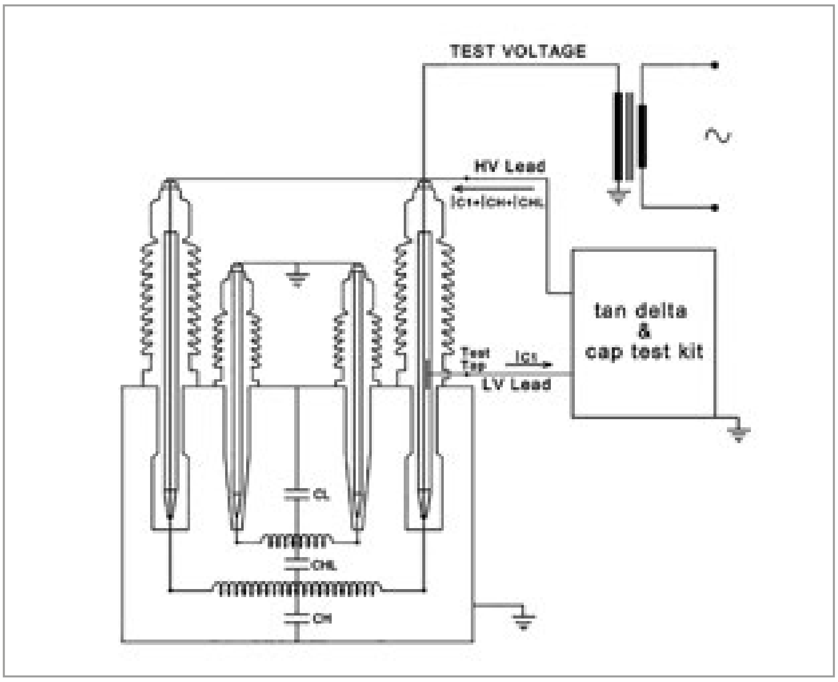

Figure 1. Offline testing arrangement/schematic diagram for the tan δ measurement of a power transformer bushing in UST mode

Bushing failures can result in hazardous fire and explosion of the transformer, which could also damage the nearby outdoor equipment

3.1 Bushing tan δ and capacitance - present trends and practices

Contrary to what is defined by IEC-60137 [3], the present practice followed by some manufacturers is that the tan δ of the bushing central conductor to the test tap, that is C_1, should not increase by 50 % in relation to the pre-commissioning value, and the bushing should be replaced if the value increases up to 75 % and >0.4 % [4].

The present practice by Indian utilities is to specify the tan δ of C_1 as less than 0.4 % at the time of procurement of the transformer/condenser bushings.

3.2 Tan δ and capacitance (C_2) measurement between test tap and flange

The tan δ measurement is done in GSTg mode (Grounded Specimen Test with guarding) only. Guarding lead is connected to the reference voltage point, in this case the ground, so that any stray capacitances between the tan δ tap and the ground can be avoided. The test voltage should be between 500 V and 2.5 kV only.

To illustrate, we may consider the typical values of 420 kV and 800 kV oil-impregnated paper (OIP) bushings of one manufacturer:

- 420 kV, 1600 A, OIP bushing, C_1 = 489 pF & tan δ = 0.33 %; C_2 = 1057 pF & tan δ = 0.64 %
- 800 kV, 2500 A, OIP bushing, C_1 = 463 pF & tan δ = 0.351 %; C_2 = 1774 pF & tan δ = 0.353 %

Since the capacitance of C_2 is much higher than that of C_1, if higher voltage (>2.5 kV) is applied, it will get charged to a very high charge Q, as C = Q/V, and may be harmful to the insulation as well as to human life.

This tan δ value does not need to be converted to 20 °C base for assessment comparison. The tan δ of the bushings test tap to flange insulation (C_2) generally varies between 0.4 – 3 % [5].

If the value of capacitance C_1 is found to be low in comparison to the factory value, this indicates a disruption due to transport damage; therefore, the bushing should not be installed [4]. While in service, if the value of C_1 exceeds the factory value by 3 %, this points to the partial puncture of the condenser of the bushing and the bushing should be replaced immediately.

4. Interpretation of tan δ and capacitance values

The dissipation factor and capacitance values should be compared with one or more of the following:

- rating plate/name plate data
- results of the prior tests of the same bushing
- results of similar tests on similar bushings

The value of dissipation factor of modern condenser bushings is generally of the order of 0.5 % after correction to 20 °C. However, as specified in IEC: 60137 [3] and IS:2099 [6], the limiting value is 0.7 %. The limiting value of the power factor, according to IEEE C57.19.01-2000 [7] is 0.5 % (+0.02/-0.04) for OIP bushings, and 0.85 % (±0.04) for RIP bushings.

Capacitances should be +/-5…+/-10 % of the name plate value, depending on the total number of condenser layers.

The significance of condenser bushing tan δ and capacitance test values with the analysis of test results is outlined in Table 1.

5. Conversion of tan δ values to the base temperature of 20 °C

Since the value of tan δ varies with temperature, the tan δ recorded at different oil temperatures needs to be converted to a common base temperature for comparison purposes. The base temperature of 20 °C is taken for the comparison of tan δ measured at different temperatures, as presented in Table 2 [4].

The value of tan δ increases with temperature. The main tank oil temperature is measured while testing the tan δ of the bushings. In order to compare the tan δ values taken at different oil temperatures, a correction factor is applied to the reading in order to bring the values to a common reference temperature which is universally accepted as 20 °C (the correction factor table is shown in Table 2) [4].

The temperature correction factors for tan

Table 1. Significance of condenser bushing tan δ and capacitance test values – analysis and interpretation of results [5, 8]

Tan δ and capacitance - trend of test results	Analysis
Increase in tan δ (between 0.7 % and 1 %) accompanied by marked increase of capacitance	Points to excessive moisture in the insulation
Very high increase in tan δ alone (over 1 %)	Points to thermal deterioration, aging or contamination other than moisture
Low tan δ	Points to weak potential connections
Increased capacitance	Points to possible short-circuited condenser layers
Decreased capacitance	Points to possible floating ground sleeve, or open or poor test tap connection
Very large variation in tan δ and capacitance values	Points to no oil in the bushing
Negative tan δ accompanied with small reduction in capacitance	May result from external surface leakages or internal leakages resulting from carbon tracking, etc.

δ or power factor (PF) are dependent on the insulating material, material structure, the moisture contents, etc. The following relationship holds good:

$$PF_{20} = \frac{PF_{mt}}{K} \text{ or } \tan\delta_{20} = \frac{\tan\delta_{mt}}{K} \qquad (1)$$

where

PF_{20} = power factor at 20 °C
PF_{mt} = power factor at the measured test object temperature
$\tan\delta_{20}$ = tan δ at 20 °C
$\tan\delta_{mt}$ = tan δ measured at test object temperature
K = correction factor

5.1 A specimen calculation

Let us assume the tan δ measured was 0.0075 at the oil temperature of 45 °C for the OIP type bushing:

- from Table 2 it follows that the conversion factor K equals 1.25 (for the temperature range 43-47 °C)
- applying the equation (1), the following is obtained:

$$\tan\delta_{20} = \frac{\tan\delta_{mt}}{K} = \frac{0.0075}{1.25} = 0.006 \qquad (2)$$

6. Variation in power factor with temperature and voltage

Considering that the values of tan δ and power factor of insulation vary with temperature, the bushing tan δ or PF measured in offline condition will not paint a true picture of the bushing, corresponding to the dynamic operating conditions.

Thus, the researchers have studied the influence of the variation in temperature and voltages on the power factor of the bushings, reaching the conclusion that the bushings power factor varies not only with temperature but also with voltage changes, Fig. 2 [9].

Based on these studies, Figure 2 illustrates four curves which were drawn for different temperature and voltage conditions over a period of 210 hours versus power factor:

- Curve 1 depicts the response at 25 °C at the applied voltage of 10 kV, i.e. during offline monitoring. It can be seen that the PF is quite stable.
- Curve 2 refers to the response at 25 °C and 70 kV voltage applied on the same bushing, with the temperature remaining constant, which indicates that PF varies with voltage.
- Curve 3 refers to the response at 70 °C and the applied voltage of 10 kV, which indicates that PF varies with temperature. It may be observed that the voltage applied is same as in the case of curve 1, 10 kV.
- Curve 4 presents the response at 70 °C and the applied voltage of 70 kV, with both temperature and voltage raised.

The losses incurred by a transformer failure caused by a bushing and its consequences are colossal

Table 2. Tan δ and power factor correction factors for OIP & RIP bushings to 20 °C

Temperature range in °C	Correction factor to 20 °C	
	OIP bushing	RIP bushing
0-2	0.80	0.76
3-7	0.85	0.81
8-12	0.90	0.87
13-17	0.95	0.93
18-22	1.00	1.0
23-27	1.05	1.07
28-32	1.10	1.14
33-37	1.15	1.21
38-42	1.20	1.27
43-47	1.25	1.33
48-52	1.30	1.37
53-57	1.34	1.41
58-62	1.35	1.43
63-67	1.35	1.43
68-72	1.30	1.42
73-77	1.25	1.39
78-82	1.20	1.35
83-87	1.10	1.29

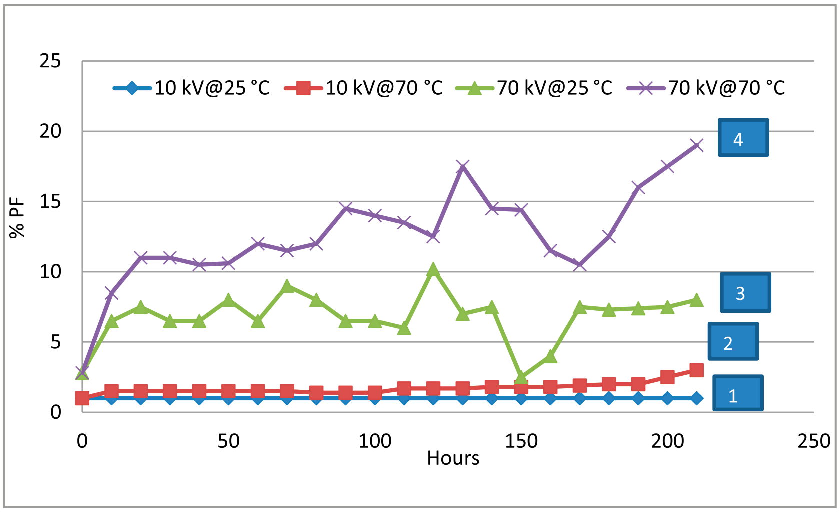

Figure 2. Curves indicating variation of % power factor with voltage and temperature over a period of 210 hours

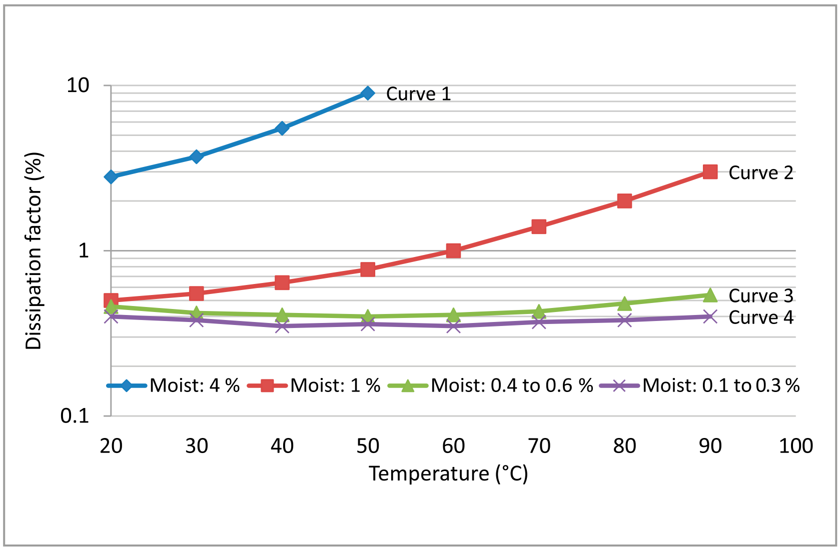

Figure 3. Tan δ as a function of temperature and moisture for OIP bushings [4]

The curve shows that the PF increases with the increase in temperature and voltage on the bushing insulation.

Since the power factor increases with higher voltage and higher temperature, the need for online tan δ measurement is essential. In this way, any abnormality observed can be addressed timely by the utility, preventing enormous revenue losses due to down time or transformer outage caused by a bushing failure.

7. Tan δ vs. temperature and moisture of OIP bushings – interpretation of curves

As discussed in the previous section, the tan δ (PF) of condenser bushings varies with temperature and voltage. Based on the curves plotted in Figure 2, further conclusions may be drawn about the relationship between the dissipation factor and rising temperature and moisture contents in the OIP bushings, which are presented by the following curves in Figure 3:

- Curve 1 for the moisture content of 4 %
- Curve 2 for the moisture content of 1 %
- Curve 3 for the moisture content of 0.4 to 0.6 %
- Curve 4 for the moisture content of 0.1 to 0.3 %

It can be observed from Curves 3 and 4 that the tan δ remains almost constant at temperatures from 20 °C to 90 °C. For Curve 2, the tan δ is 0.7 % at 50 °C and with a further rise in temperature the tan δ shows a rising trend from 0.7 % to 3 % at 90 °C. Curve 1 shows that the tan δ at 20 °C is as high as 2.8 %, but then abruptly rises to 9 % at 50 °C.

Based on this interpretation, if the tan δ is continuously monitored and its values show that at different temperatures they follow the trend of any of the mentioned curves, the bushing moisture content can be easily established as well as a faulty OIP bushing. In this case, the faulty unit should be immediately replaced.

8. Monitoring of hot spots in the bushings through infrared thermography

The hot spots in the bushings can only be detected by infrared thermography scanning carried out remotely with thermovision cameras while the transformers are on load.

The hot spots in the bushings develop due to the following reasons, which cannot be detected in off-load conditions:

- loose terminal clamps
- improper fixing of draw lead at the adopter (also known as thimble) with top terminal
- improper soldering of lead with cable adopter (thimble)

Such hot spots are attended to by tightening the identified loose connections while the transformer is offline.

The bushings power factor varies not only with temperature but also with voltage changes

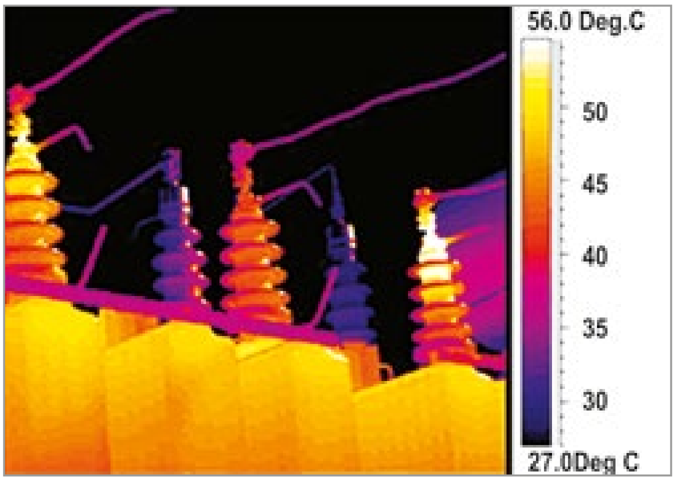

Figure 4a. Hot spot at the top of the extreme right bushing

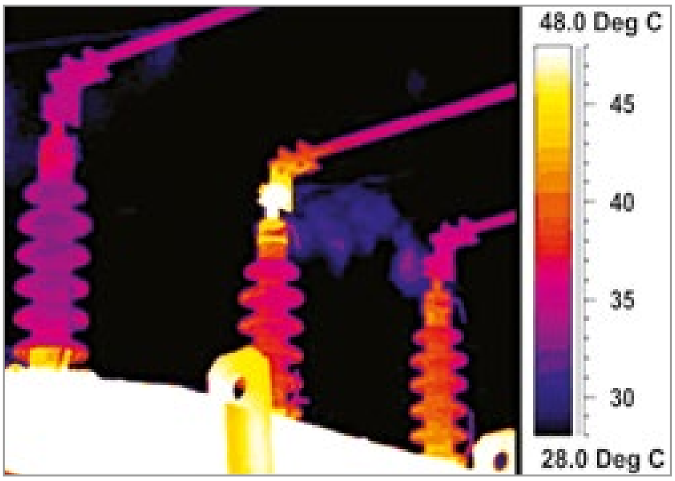

Figure 4b. Hot spot on the terminal clamp of the middle bushing

The specimen scanned images of hot spots are shown in Figures 4a and 4b [10], along with vertical temperature scales. The white colour on top of the far right bushing in Figure 4a indicates that its hot spot temperature is 54 °C to 55 °C, while the stud and the clamp of the middle-phase bushing indicated in white in Figure 4b show that the temperature at these points ranges from 46 °C to 48 °C.

9. Case study of a 245 kV bushing failure at the 220 kV substation

Transformer and bushing details:

- Transformer rating: 220/132 kV, 160 MVA
- OIP bushing, manufactured in 1993
- Period of offline monitoring: one year
- Period elapsed after last monitoring of tan *δ* prior to failure: five months
- Tan *δ* and capacitance values last measured with a 5 kV kit, tan *δ*: 0.52 %; capacitance: 393.9 pF (Table 3)
- Load at the time of failure: 20 MW
- Season/weather conditions and date: rainy season, cloudy conditions, 14 August 2013
- Relay indications: differential relay, ABC, instantaneous; differential, instantaneous over-current, PRV (Pressure Release Valve) and Buchholz Trip
- Thermovision survey (in service and in loaded condition) was also carried out about four months prior to the failure. No hot points were observed in any of the bushings.
- Condition of the transformer: the transformer was tested and found healthy. It was successfully re-energized after the replacement of the failed bushing with a new one.

The tan *δ* and capacitance values of the failed bushing taken periodically are presented in Table 3.

Since the power factor increases with higher voltage and higher temperature, the need for online tan δ measurement is essential

Table 3. Tan *δ* and capacitance values of the failed bushing measured and recorded with a 5 kV kit

Date of testing	Ambient temperature [°C]	Capacitance [pF]	Tan *δ* [%]
12.09.05	30	396.5	0.35
29.11.07	32	394.1	0.42
01.10.08	45	352.6	0.53
07.03.09	43	392.1	0.50
25.05.09	40	391.2	0.45
05.12.09	39	392.5	0.40
19.05.11	38	394.2	0.49
29.09.11	40	390.6	0.51
05.06.12	40	393.9	0.56

9.1 Analysis

Based on the details presented in Table 3 and the photographs of the failed bushing, Fig. 5a and 5b, it can be inferred that the bushing failed between the successive periods of offline monitoring.

To assess the condition of the 160 MVA transformer after the failure of the 245 kV bushing of '1U' phase, the following diagnostic tests were performed by using the naked bare lead of the failed bushing:

- IR (Insulation Resistance) test with a 5 kV megger
- magnetizing current test with LV supply
- magnetic balance test with LV supply
- measurement of winding resistance
- ratio test

The test results revealed that the transformer was in a healthy condition.

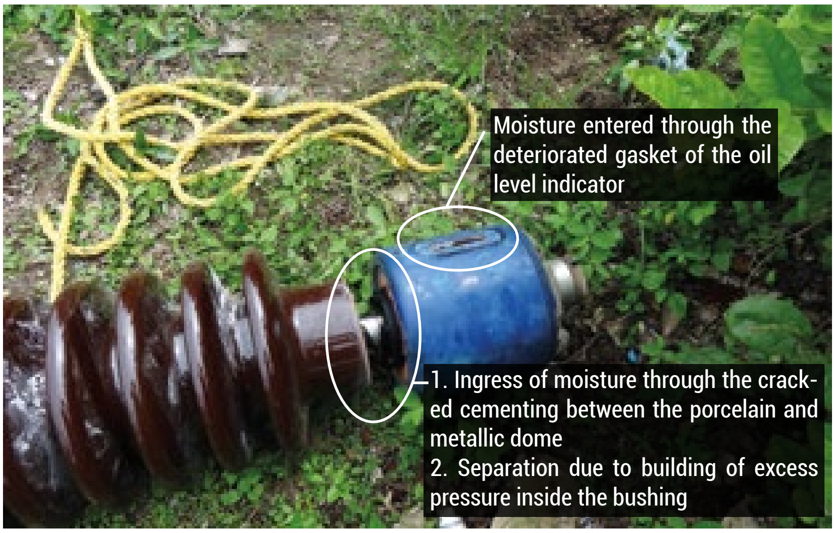

Figure 5a. The failed 245 kV, 1250 A OIP bushing showing cracked and separated oil expansion metallic chamber/dome from the porcelain insulator

Figure 5b. The failed 245 kV, 1250 A, OIP bushing showing bursting of lower oil end insulator

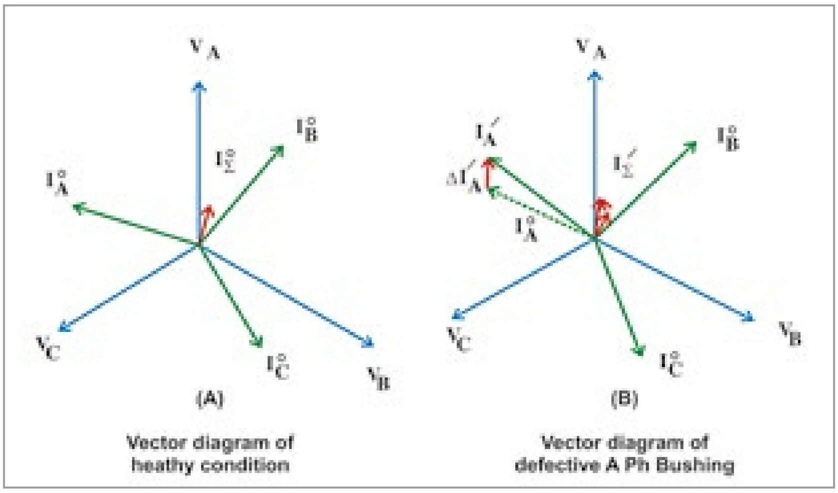

Figure 6. A phasor diagram showing drifted location of the current vector with reference to the voltage vector of the A phase, indicating deterioration of insulation of the A phase bushing in (B)

> The hot spots in the bushings can only be detected by infrared thermography carried out remotely while the transformers are on load

Although the recorded load was only 20 MW, the transformer had met the load demand to the extent of 85-87 MW during irrigation season (the irrigation season is between November and February of the following year).

Ingress of moisture must have taken place through:

a. the cracked cementing which couples the porcelain portion of the bushing to the metallic dome, and/or
b. the deteriorated gasket of the oil level indicator, Fig. 5a

This phenomenon is due to contraction of the bushing core at low load periods and at cool night hours. Location of ingress of moisture is encircled in white, Fig. 5a. Non-bursting and non-shattering of the splinters of the outer porcelain of the OIP bushing at the air end indicate that the failure did not take place due to any violent conditions, such as heavy lightning impulse stroke/switching surges, etc., but resulted from the pressure that had developed inside it at a very slow pace – which is also confirmed by the bursting at the lower oil end side, Fig. 5b.

The development of excessive pressure inside the ill-fated bushing appears to have taken place due to a failure/shorting of some of capacitances caused by ingress of moisture, increase in tan δ value and also occurrence of low intensity partial discharge over the five-month period after the last offline tan δ and capacitance measurements were performed.

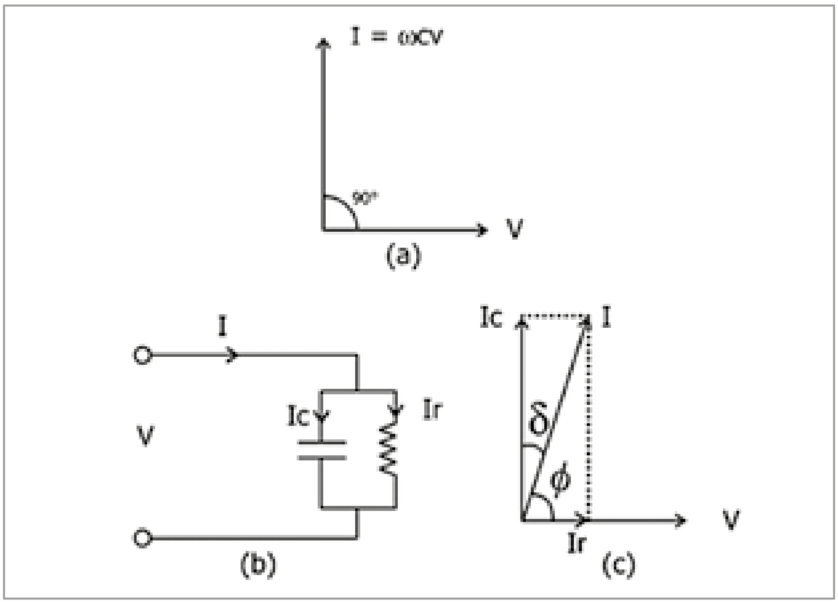

Figure 7. The loss angle shown ($\delta = 90 - \phi$) developed as the angle between the phasors I_C and I: (a) current leading voltage in a capacitor; (b) moisture and other impurities offer parallel resistance and I gets two parallel paths, being divided into I_C and I_r; (c) vector diagram of the circuit in (b) wherein $\delta = 90 - \phi$ is called loss angle; (d) tan $\delta = I_r / I_C$

Since neither the transformer nor any of the other bushings or auxiliaries/components were adversely affected, it was obvious that the fault was not of a violent and serious nature. It was confined to the failure of one 245 kV bushing only.

10. Remedial measures

The practical remedial measure is to switch to the online monitoring system of the bushing tan δ for high value transformers (power utilities may weigh the advantages/gains of this in relation to the cost investment, Table 5).

It has already been mentioned that the tan δ value of the insulation (in this case, the bushings) increases with a rise in temperature and moisture contents.

The online monitoring system of tan δ will not only record the tan δ value on a real-time basis on actual voltage, at different loading conditions, different oil temperatures and different winding temperatures, but also it will identify the bushing getting red-hot consequent to loose lead connections, loose terminal clamp connections, etc. The heat generated by the loose lead connections and terminal clamp connections can be verified further with the thermovision infrared scanning.

In addition, with the online monitoring system, the tan δ of the bushing is being monitored at the system voltage level and at actual temperature of the bushing (i.e. at dynamic real-time conditions), whereas in case of offline tan δ monitoring the applied voltage is typically 10 kV only.

11. Online monitoring of the bushings tan δ and capacitances: Theories and methodologies

The methods used in the online monitoring of the bushings tan δ and capacitance values include the following:

- Sum-of-currents method
- Absolute measurement – voltage transformer reference method
- Dual transformer comparison method

11.1 Sum-of-currents method

The voltages in a three-phase transformer are assumed to be almost equal and to have a phase displacement of 120° between them sequentially. The bushings of these transformers are considered to have almost equal insulation level. Since insulation is capacitive in nature, with the application of the three-phase balanced voltage the leakage capacitive currents will flow between the respective phase and the ground through capacitances C_1, leading the applied driving voltage by little less than 90°, but maintaining the phase displacement of three phase balanced voltage. The vector sum of all three capacitive leakage currents should be zero ideally, considering them equal in magnitude and angle of displacement (which is 120° between them sequentially). However, in practice, the vector sum of the leakage capacitive current will not be zero, but a very small value making a very small angle, for example with the A phase voltage phasor, Fig. 6 (a red coloured phasor).

The deterioration of insulation means an increase in the resistive component (i.e. contaminant/impurity) in the bushing, making the resistive current flow in parallel to the capacitive current, Fig. 7.

The resistive current component is in phase with the driving voltage, while the total resultant current through the capacitance of the bushing is leading the driving voltage by the angle ø less than 90° (i.e. the resultant current is lagging the original capacitive current vector by the angle δ). Thus, the tan δ is the dielectric dissipation factor of the A phase bushing, which means that the vector sum of the capacitive currents of all three phases will deviate from the original value having a slightly increased value, Fig. 6(b) (red coloured increased vector).

The change in sum of the currents can approximately be estimated using the equation (3), with the assumption that only one bushing (A phase) has developed a fault [10]:

$$\Sigma I = \frac{\Delta I}{I^{o}} \approx \sqrt{(\Delta \tan \delta)^2 + (\Delta C/C_o)^2} \qquad (3)$$

where

ΣI = sum of currents
$\Delta \tan\delta$ = small change in tan δ
$\Delta C/C_o$ = relative change in bushing capacitance
C_o = initial capacitance reading
I_o = Initial sum of current value

Following the concept outlined above, many manufacturers have developed their online monitoring system. The basic block diagram of the bushing monitoring scheme is shown in Figure 8.

In this scheme the sum of the bushing currents is considered. In practice, the capacitances of the bushings might not be exactly the same. During commissioning the null meter is balanced to zero.

The purpose of balancing is to take into account the system voltage, phase fluctuations and bushing characteristics and thus fix an initial reference mark. With the development of a fault, the current and the phase angle change and the null meter will no longer show the null position.

With the change in amplitude and phase angle, the bushing losing its dielectric property can be identified.

11.1.1 Features of the online tan δ monitoring

The online tan δ monitoring devices are presently manufactured by reputed manufactures. They are supplied to transformer OEMs to be incorporated as per the requirement of customers.

Online tan δ monitoring using the sum-of-currents method includes the following features [7]:

- Monitoring of bushings/CTs at a time: 2x3 bushings/CTs can be monitored
- Monitoring of 1-phase units: it is possible to monitor 4x1-phase transformers with three units in service and one spare unit; the spare unit gets automatically grounded through its sensor in a kiosk provided
- Defective bushings: a specific software depicts the imbalance of the current vector position on a polar plot, which in turns affects the power factor and capacitances of the defective bushing
- Effect of temperature/voltage: changes in tan δ and capacitance can be identified in relation to the temperature and voltage, as well as the deteriorating condition of such bushings
- False alerts: special algorithms eliminate false alert due to noise and other atmospheric conditions
- Communication protocol: it can be locally accessed through RS 232 and remotely for SCADA, etc. through Ethernet /RS 485 or similar
- Data storage period: five years on an hourly basis
- Self-diagnostic feature
- Change in PF and capacitances: change in A phase can be detected, as shown in yellow on polar diagrams in Fig. 9

11.2 Absolute measurement – voltage transformers reference method

To overcome the variation in the tan δ values due to imbalance of system voltages, the absolute measurement (voltage transformer reference method) has been introduced [9, 11]. Imbalance voltages in the system occur due to unequal loading of the phases, system faults or due to asymmetric induction from high currents in the nearby overhead lines. It has been observed that the tan δ value of the oil-impregnated bushing with the original tan δ of 0.25 % increases to 0.5 %.This could be alarming, but misleading too.

In the absolute measurement method, absolute values are taken from the voltage transformers of respective phases.

> **With the online monitoring, the tan δ of the bushing is being monitored at the system voltage level and at actual temperature of the bushing, i.e. at dynamic real-time conditions**

Online monitoring of the bushings tan δ and capacitance includes the following methods: sum-of-currents, absolute measurement, and dual transformer comparison

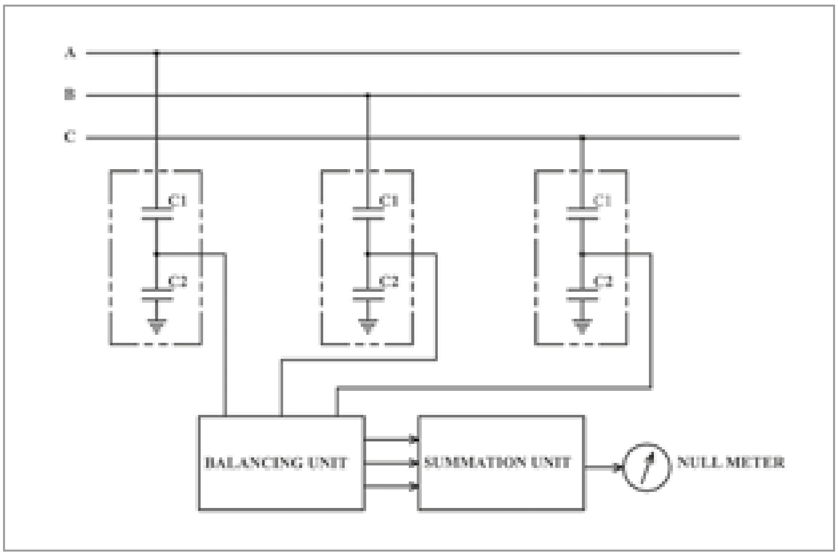

Figure 8. A schematic diagram of the sum-of-currents method [10]

The schematic diagram of connections is shown in Fig. 10.

The equipment and set-up for the absolute measurement – voltage transformer reference method is presented in Fig. 11.

The most important features and duties of the main equipment in the absolute measurement method are as follows [11]:

- UHF sensor:
  - highly sensitive PD measurements in the winding insulation
  - wide frequency response
  - results can be correlated to the PD signals detected at the bushing
- Acquisition unit/transformer:
  - synchronous acquisition of data from the bushing tap adopters and UHF sensors
  - advanced signal processing system for capacitance, dissipation/power factor, transient overvoltages and partial discharge, etc.
- Acquisition unit/VT reference:
  - synchronously acquires reference signals from the VTs for absolute capacitance and dissipation/power factor measurements
  - It can be used with three voltage transformers reference scheme or three power transformer bushings reference scheme of a similar power transformer on the same bus
- MCU fiber optic bus controller:
  - It is used for connecting each acquisition unit to the central computer
  - maintains galvanic isolation eliminating interference and ensures personal safety
- Central computer with compatible user friendly monitoring software:
  - state-of-the-art data base system ensures long term data storage and retrieval
  - processing of the data is performed intelligently to provide useful information of status/condition of the bushings
  - parameters are monitored to give signal, alarm and warning of limiting levels/defined thresholds
  - accessible via web browser interface
  - specimen graphs/curves of dissipation factor and capacitance of the bushings in this system, Fig. 12

11.3 Dual transformer comparison method

In the dual transformer comparison method [11], the concept of comparison is similar to the absolute measurement method. Instead of three voltage transformers, the respective phase bushings of a transformer with similar rating connected in parallel are used for reference. The test setup is similar to that in the absolute measurement method.

12. A sample cost-benefits analysis of an online tan δ monitoring system for bushings

The following analysis aims to show the benefits of installing an online tan *δ* monitoring system for power transformer bushings. The online tan *δ* monitoring system monitors the condition of the condenser bushings while the transformer is in service. The analysis is based on a sample case of the failure of the 245 kV OIP bushing of the 220/132 kV, 160 MVA power transformer presented in section 9.

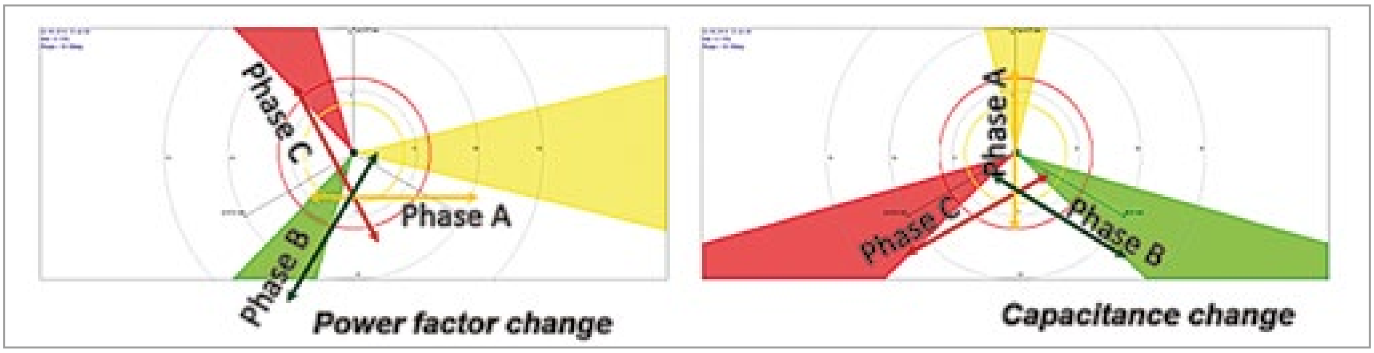

Figure 9. Phasor diagrams showing change in PF and capacitance

12.1 Assumptions

- Season: peak irrigation season for the agricultural fields (Nov 2015)
- Date of failure: 15 November 2015
- Load: 164 MW fed by two 160 MVA, 220/132 kV power transformers of equal impedances and tap position variations
- Load on the affected transformer prior to failure: 82 MW
- Location of the site: the 220 kV substation is 150 km away from the headquarters of the executive engineer, testing division and the utility's material and equipment stores
- Extent of failure: a failure of one 245 kV 1250 A OIP bushing
- Parameter values recorded at the last offline bushing testing prior to its failure: $\tan\delta = 0.0053$; capacitance = 394 pF
- Period elapsed between the failure and the last offline $\tan\delta$ measurement: five months after the last $\tan\delta$ measurement with a portable 10 kV kit
- Intervals of $\tan\delta$ and capacitance testing: six-monthly
- Duration of down time after failure: 72 hours (assumed)

12.2 Activities required and costs

a. Availability of heavy duty crane at site: not available. Therefore, the works were carried out manually

b. Personnel required:
  - for removal of the failed bushing and transformer testing
  - for testing and energizing the transformer at the time of installation

c. Testing of the transformer, HV and LV bushings after the incident; acquisition of a new 245 kV bushing, pre-commissioning tests and energization of the transformer: 150,000 INR (2,266.14 USD)

d. Travel costs for testing engineers and staff for two journeys from the headquarters to the site (150 km away) and back: 15 INR per km multiplied by two

e. Light motor vehicles and transportation of testing staff: $2 \cdot 2 \cdot 2 \cdot 150 \cdot 15 = 18{,}000$ INR (271.92 USD)

f. Cost of the 245 kV, 1250 Amp OIP bushing: 600,000 INR (9,064.57 USD)

g. Inventory and other miscellaneous charges towards storing the bushing (charged as 25 % of the cost of the bushing): 2,266.14 USD

h. Expenditure towards transportation of the bushing:
  - By road (truck) – freight: 18,000 INR (271.94 USD)
  - Transit insurance, charged at 5 % of the cost of the bushing: 453.23 USD
  - Loading/unloading charges: 8,000 INR (120.86 USD)

  Summing up the above, the total transportation costs came to: 846.03 USD

The costs incurred by replacing the failed 245 kV OIP bushing with a new one, taking into account the realistic assumptions listed above, is shown in Table 4. The amounts in USD have been calculated applying the exchange rate of 15 November 2015: 1 USD = 66.1918 INR.

12.3 Loss of revenue

The loss of revenue due to the outage of the transformer can be calculated based on the assumed outage of 50 MW during the assumed down time of 72 hours. With the price of the unit at 132 kV level equalling 5.29 INR (0.0799 USD), according to the prevailing tariff for 2015-16 in M.P. (India), and assuming the load factor of 85 %, the following calculation ensues:

$50{,}000 \cdot 0.85 \cdot 72 \cdot 5.29$ INR=16,187,400 INR (244,552.95 USD)

Note:

Since there was a similar transformer running in parallel on the common bus, the outage of 50 MW is considered for the calculation of the revenue loss. The other portion of the load was shared by nearby 132 kV substations.

12.4 The cost-benefit analysis

The cost-benefit analysis for the replacement of the 245 kV OIP bushing including the loss of revenue to the utility resulting from the failure is shown in Table 5.

From this analysis it can be concluded that the cost of replacement of one 245 kV OIP

Sum-of-currents method is based on the fact that the vector sum of all three capacitive leakage currents should ideally be zero

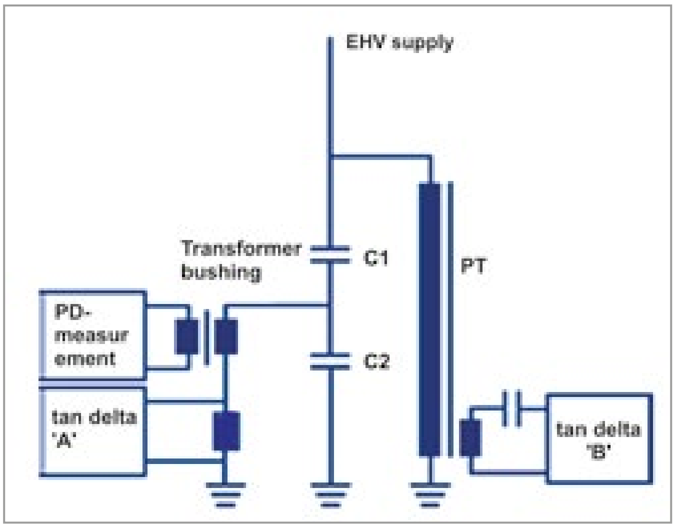

Figure 10. A schematic diagram of the absolute measurement – voltage transformer reference method

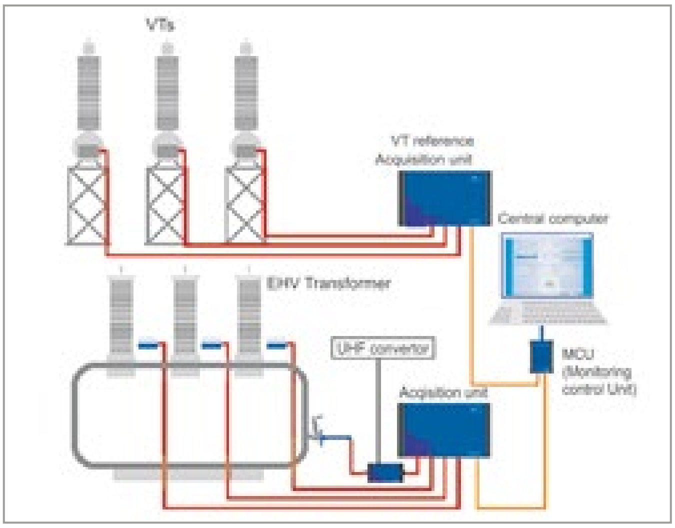

Figure 11. Absolute measurement – voltage transformer reference method

To overcome the variation in the tan δ values due to imbalance of system voltages, the absolute measurement method has been introduced

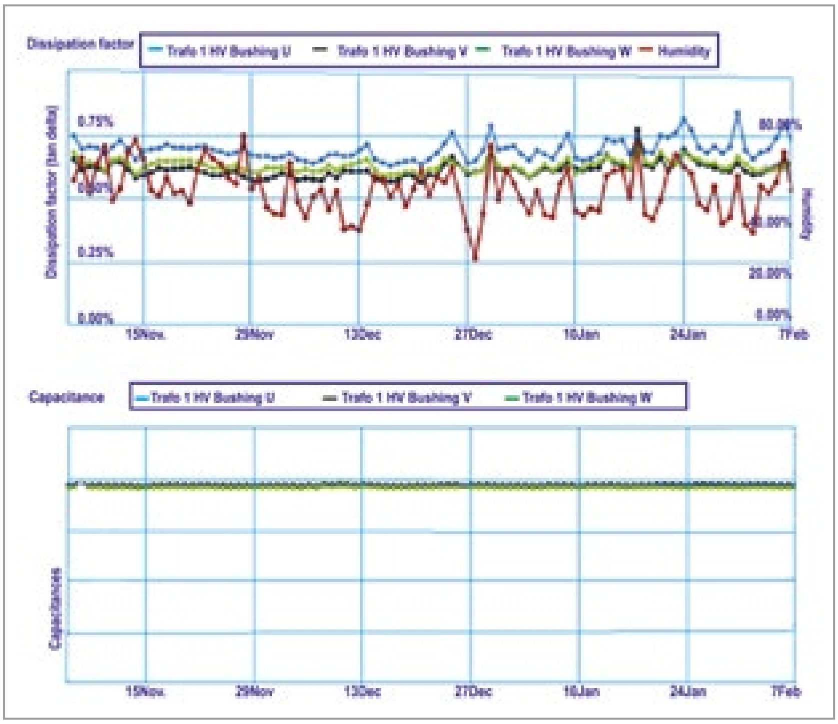

Figure 12. Specimen curves of the tan *δ* and capacitances of all three-phase bushings

bushing, together with the loss of revenue incurred by the failure, is:

- more than 8.28 times higher than the approximate cost of the online tan *δ* monitoring system based on the sum-of- currents method, including its commissioning at site
- more than 3.21 times higher than the approximate cost of the online tan *δ* monitoring system based on the absolute measurement method, including its commissioning at site

The above example has been cited as a sample case of a failure of one 245 kV OIP bushing. Had this incident led to a catastrophic failure of the transformer, an enormous loss would have been incurred to the power utility and the down time would be approximately four to six weeks.

The cost of a new 220/132/33 kV, 160 MVA transformer would have been approximately 5.13 crores INR, i.e. 775,020.47 USD according to the exchange rate at the time of the incident.

Conclusions

This article has explored the condition monitoring of the capacitive graded bushings with particular emphasis on the online monitoring systems for the condenser bushings, designating them as superior methodologies for monitoring of condenser bushings at dynamic conditions on a real-time basis, when compared to the offline monitoring system.

These online monitoring systems are cost effective and able to give a caution signal well before the utility might suffer a catastrophic failure of the transformer.

In view of the above discussion and considering the sample cost benefit analysis, utilities can resort to the online tan *δ* monitoring system for condenser bushings of their 220 kV, 400 kV and 765 kV power transformers and the 420 kV and 800 kV reactors.

Acknowledgement

The author expresses his gratitude and sincere thanks to the Managing Director of M.P. Power Transmission Co. Ltd. Jabalpur (India) for permitting him to use the relevant data and photographs of the 220 kV substation in Narsinghpur. He would also like to express his gratitude to Chief Engineer (Testing & Communication) and other testing engineers in the department whose help

In the dual transformer comparison method, the respective phase bushings of a transformer with similar rating connected in parallel are used for reference

Table 4. Expenditure towards the engineers, and skilled and unskilled personnel carrying out the works at the substation

Personnel	Number of engineers/ man-days	Rate per engineer / man-days in USD	Amount in USD*
Maintenance and testing engineers	3·3=9	67.98	611.86
Skilled maintenance technicians and testing personnel	5·3=15	37.77	566.54
Unskilled personnel	8·3=24	7.55	181.29
Total			1,359.68

Table 5. The cost-benefits analysis

Particulars	Investment (USD)	Investment (USD)	Cost incurred to the utility (USD)
Cost of the online tan δ monitoring equipment based on the sum-of-currents method at site after loading, all taxes, duties, export-import formalities, shipment and transit insurance, including erection and commissioning at site (approximately)	30,215.22		
Cost of the online tan δ monitoring equipment and accessories based on the absolute measurement method at site after loading, all taxes, duties, export-import formalities, shipment and transit insurance, including erection and commissioning charges at site (approximately)		77,909.09	
Cost of the OIP bushing			9,064.57
Costs towards inventory and other miscellaneous charges towards storing the bushing etc.			2,266.14
Transportation of the bushing to the site			846.03
Charges towards testing of the transformer, HV and LV bushings after the incident and costs of the new 245 kV bushing and pre-commissioning tests prior to re-energization of the transformer			2,266.14
Cost of the journeys to and from the site for the testing and commissioning engineers and testing team			271.92
Charges towards works on site by engineers, testing technicians and the maintenance staff			1,359.68
Estimated loss of revenue due to down time			244,552.95
Total (in USD)	30,215.22	77,909.09	250,429.43

and support made the writing of this article possible.

References

[1] Er.K.K. Murty, *Fundamentals of condenser bushings,* Transformers Magazine, Special Edition Bushings, Nov. 2017

[2] S.Tenbohlen, J Jagers et al., *Development and results of a worldwide transformer reliability survey*, presented at CIGRE A2 Colloquium 2015, China, 20-25 Sept 2015, on behalf of CIGRE WG A2.37

[3] IEC – 60137, Edition 6.0 2008-07, *International Electrotechnical Commission Standard for Insulated bushings for Alternating Voltages Above 1000 V*

[4] ABB, Publication No. 2750 515-142 en, Rev. 3 on bushing diagnostics and conditioning

[5] BHEL's Presentation on Bushings – 6645329

[6] IS: 2099 - 1986 (Reaffirmed 2003), *Indian Standard Specification for Bushings for Alternating Voltage Above 1000 Volts*

[7] IEEE C57.19.01-2000 (R2005), *IEEE Standard Performance Characteristics & Dimensions for Outdoor Apparatus Bushings*

[8] HAEFLEY TEST AG's Midas 228x, Operating instructions

[9] C. Kane and A.Golubev, *Bushing monitoring methods*, presented at PdMSA conference, Sept 2010

[10] http://www.irinfo.org/articleofmonth/images/2_1_2009_james_16.gif of IRINFO.ORG, Burlington NJ08016

[11] C. Kane, *Online bushing monitoring and comparison of offline testing*

Author

K.K. Murty holds a Bachelor's degree (Hons) in Electrical Engineering obtained from the University of Jabalpur, India. He was a former Chief Engineer and Head of Department at M.P. Power Transmission Co. Ltd. Jabalpur (India), he was a member of the panel of expert professionals at the Central Power Research Institute (CPRI), Bangalore, from 2008 to 2012. Previous to this, he worked as an Advisor (Testing) at SOUTHCO, a discom in the state of Odisha, a Metering Consultant to M. P. Electricity Regulatory Commission and a Course Director for the graduate electrical engineering trainees at the Training Institute of MPPTCL, Jabalpur. He has published a few technical articles in national and international journals and presented some technical papers at various national and international conferences pertaining to power transformers, other power equipment and power systems, etc. Mr. Murty is a Member of India's Society of Power Engineers (MSPE), a Fellow of Institution of Engineers, India (FIE) and is a Chartered Engineer (CE). In October 2015 he was awarded a plaque in recognition of his eminence and contribution to the profession of electrical engineering at the national level by the Institution of Engineers (India).