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STATE OF THE ART TRANSFORMER BUSHING MONITORING

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SUMMARY

Transformer bushings are one of the most critical components of a transformer. Up to 20% of major failures on high voltage transformers today can be related to bushings. Almost half of these failures result in catastrophic failures like explosions, fire or oil spillage. The cost of these damages and the lost opportunity to deliver energy could be several hundred times higher than the price of a bushing. Even a failing bushing which will not lead to a catastrophic failure can harm people due to burst porcelain insulators, catapulted through the air by the force of the arc of the breakdown.

KEYWORDS

**BUSHING
ONLINE MONITORING
CBM
ASSET HEALTH
PHASE SHIFT METHOD
DISSIPATION FACTOR
BUSHING CAPACITANCE**

Bushing monitoring is aiming to detect incipient faults and give an early warning as well as using the bushings till its real end of life. That will demand a high accuracy in determining the dissipation factor of a bushing main insulation.

This paper will give a short overview about the failure statistics and the different parameters, which can be used to access the condition of a bushing and its usability for online monitoring. It will describe different causes for bushing failures and will discuss how these failures can be detected in an early stage by using the dissipation factor and capacitance monitoring.

In order to have a reliable monitoring system, the accuracy of the acquisition of the monitored parameters needs to be very high. For example, even if a quite relevant amount of moisture impregnated into the bushing core, the loss angle will only show a slight change at ambient temperature. Bushing monitoring

systems today are not able to capture these slight, but important changes as they are comparing the three bushings from different phases and due to imbalances in common electrical distribution and transmission networks.

New approaches are using stable voltage sources as reference signals, preferable from the same phase as the monitored bushing and using the phase shift between the leakage current signal from the bushing and the voltage from the reference to measuring the dissipation factor with high accuracy of 0.1mrad to allow detecting small dissipation factor changes.

THE SLOY, WINDYHILL, DUNOON TEED CIRCUIT.

This circuit was constructed in the 1950s as a double 132KV overhead line using a 'light' construction on steel towers. Unexplained fault activity increased from 2006 and was found to originate on the Dunoon tee'd section. The terrain the tee traverses is wooded with hills and valleys with a long span crossing a loch. The maximum elevation is 370m. There are several sections close to the sea. A simplified line diagram of the complete circuit is shown in Figure 1 and one of the towers in Fig 2. The section lengths have been refined using travelling wave measurements over the past year.

FAILURE STATISTIC

Transformers are one of the most critical components within the electrical network and cannot, once one fails, be exchanged easily by a new one. Often transformer failures cause the inability to deliver energy, have high potential to harm people and can cause environmental disasters. Due to all of these, a high financial impact often is connected to transformer failures.

Especially the old economies like Europe, NA and Japan are facing aged key network components. Continuous monitoring solutions were not used extensively in the past, due to n-1 availability of the main equipment. Furthermore, monitoring solutions were less reliable or not available 10 to 20 years ago. Nevertheless, the condition assessment in the utilities of the old economies was carried out under comprehensive periodic measurements and maintenance programs. Nowadays these utilities are seeking more and more for solutions to operate their costly components till its real end of life. Furthermore asset exchange programs will be based on the condition of the equipment. Condition monitoring and condition based maintenance are seen as an important factor to achieve these goals.

The CIGRE WG A2.37 released 2012 an interim report (1) which shows the newest statistic on transformer failures (see Table 1).

Table 1: Transformer failure statistics (1)

FAILURES & POPULATION INFORMATION	69 kV < 100	100 kV < 200	200 kV < 300
Failures	145	212	163
Transformer-Years	15220	48994	47473
FAILURE RATE/ YEAR	0.95%	0.43%	0.34%
FAILURES & POPULATION INFORMATION	300 kV < 500	kV 700	All
Failures	154	11	685
Transformer-Years	41569	959	156186
FAILURE RATE/ YEAR	0.37%	1.15%	0.44%

It can be seen, that over all voltage classes, the failure rate is 0.44%, which means, out of approximately 230 transformers, one will fail per year. Besides the preventions of faults or early detection of upcoming faults, the assessment of the remaining live and the health of the equipment is of immense interest,

especially for aged equipment. In order to assess the asset health a combined set of data from the main transformer and its main components needs to be measured/ monitored. Besides other components parts, bushings are one of the main causes of transformer failures. Its contribution to transformer failures is around 20% of the overall transformer major failures, depending on the type of transformer.

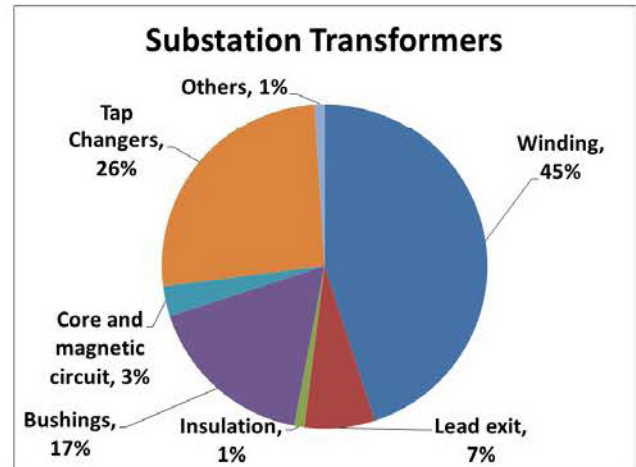


Figure 1: Failed component statistic (1)

Failing of a bushing can lead to catastrophic failures and can be going along with environmental disasters or fatal accidents of personal. According to a transformer reliability study published in (2), 70% of all transformer fires are caused by bushing failures.

The causes of bushing failures are varying from normal aging, moisture, quality issues during manufacturing, repeated thermal and mechanical cycling, transients and external influences like external flashovers. As a result a high number of bushing failures develop from partial breakdowns, thermal instabilities or degradations of longitudinal insulation interfaces.

The average lifetime of bushings are estimated in general as half of the life of a transformer (25 years). In reality there are bushings still working properly which are older than 40 years as well as there are bushings, which are failing already after 10 to 12 years of operation. To improve transformer reliability the demand of reliable bushing monitoring is increasing throughout the industry.

BUSHING MONITORING PARAMETERS

The main bushing parameters, which are used today for bushing online monitoring, are the Power Factor in the IEEE world (or Dissipation Factor in the IEC world), the bushing main capacitance and partial discharge activity. Table 2 is giving an overview about the different bushing parameters and its ability to detect different failures in an early stage of its development.

It can be seen, that Dissipation Factor and Partial discharge are the most powerful parameters, which have the ability to uncover most of the incipient bushing failures. The capacitance monitoring is a good indicator for partial break downs (break down between two or more layers with the result of a short circuit between them) and contact problems (capacitance decreases or is fluctuating heavily). Further each parameter will be discussed regarding the best usage for online assessment of the health condition of capacitive bushings.

Table 2: Parameter Sensitivity for different defects (+ detectable; - not detectable)

Defect	Tan δ	C	PD
Insulation aging	+	-	-/+
Moisture	+	-	-
Void/ Delamination	(+)	-	+
Surface contamination	+	-	+/-
Surface discharges	+/-	-	+
Partial breakdowns	+/-	+	+/-
Contact problems	+	+	+

The Power factor reflects, as property of the insulation material, the condition and the health of the insulation itself. It represents the ratio between capacitive and resistive current, which are giving in their summation the leakage current.

The capacitive current is the result of the capacitive layer design and therewith proving a given value. The resistive current is defined by the resistivity of the insulation material and is a direct parameter of the quality of the insulation system. Each healthy solid and

liquid insulation material has its typical resistive current component. An increasing resistive current will indicate a degradation of the insulation system and will increase the angle δ and decrease the angle ϕ and will result in an increase in Dissipation Factor (see Figure 2).

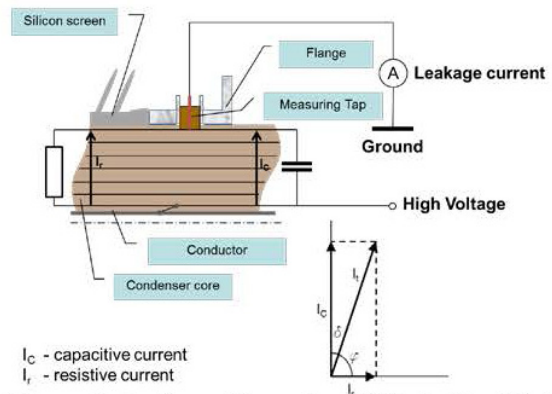


Figure 2: Leakage Current and Dissipation Factor ($\tan \delta$)

The Dissipation Factor measurement under online conditions requires a high accuracy in order to detect already small changes and to guaranty the detection of increasing moisture content in the insulation system, which is difficult to achieve under online condition. External influences like low frequency magnetic fields, external noise and harmonics as well as the lack of stable reference signal sources are the factors, which influence these measurements.

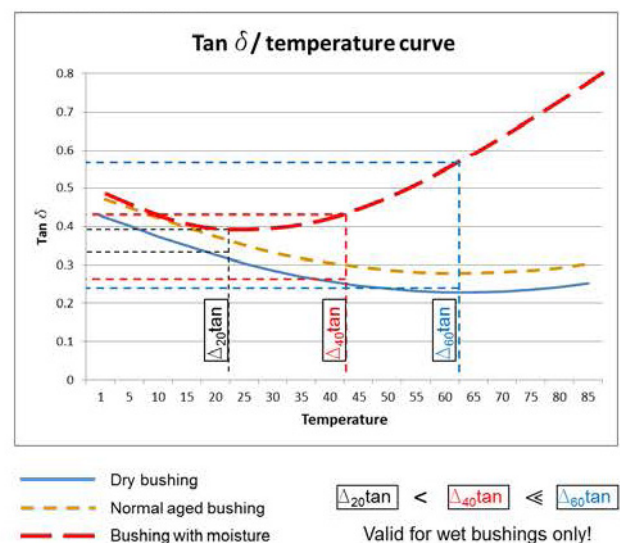


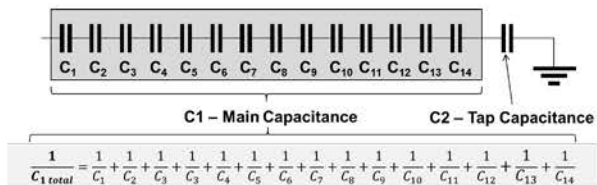
Figure 3: Dissipation Factor depending on temperature and moisture

Figure 3 shows the behavior of the insulation system with increased moisture content. The accuracy of the Dissipation Factor monitoring needs to be highly accurate, considering the Dissipation Factor difference at 20°C for a wet and dry insulation. With the current online methods, this accuracy is hardly to achieve.

The advantage of online Dissipation Factor monitoring is that the Dissipation Factor of a bushing can be seen at different temperatures. Depending on the load of the transformer, the temperature of the bushing will increase or decrease. It can be seen in Figure 3, that the Dissipation Factor gradient of “wet” bushings is much higher at higher temperatures than for dry bushings. Offline measurements without additional active heating of the bushing and low accuracy online monitoring are not able to detect this kind of defects.

Capacitance

As described above for the capacitive current, the capacitance is a parameter which represents the design of the capacitive layers. Figure 4 is showing, how the total capacitance will be calculated. It will increase, if two or more layers of the electrical field control foils are short circuit (see Figure 4). If only two layers are shorted, the capacitance will increase by a percentage equivalent to the total number of layers. For example, if 2 out of total 50 layers will be short circuit, the capacitance will increase by 4%.



Although it is easy to apply for online purposes by simply using a defined secondary capacitor, the number of detectable defects are limited (see Table 2).

Partial Discharge

As it can be seen in Table 2, all bushing defects can be detected by partial discharge but moisture. Therefore partial discharge (PD) measurements are very important

for offline testing at factory or onsite. Nevertheless the detection of the bushing related partial discharge under online conditions is facing major problems.

The measuring principle for online PD bushing monitoring used today is based on the IEC 60270 method. The bushing capacitance will be used as coupling capacitor. Mainly this PD monitoring principle is applied to monitor the transformer but in some cases also to monitor the bushings.

The PD magnitude of incipient bushing faults is between 5pC up to 100pC. Higher are possible in case of contact issues. Typical values are usually below 50pC. Comparing that with the allowed and possible PD activity on overhead lines (some nC) and inside the transformer the bushing related PD can be hidden. It is further difficult to distinguish between the different possible PD origins as overhead lines, transformers, external discharges and the bushing itself.

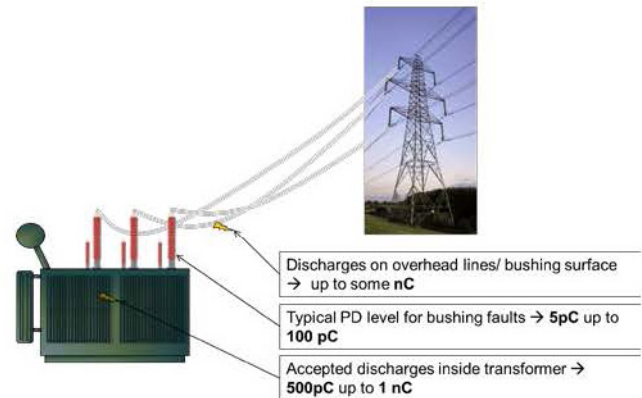


Figure 5: Challenges for Bushing online PD monitoring

Furthermore due to the high capacitance of the test object and the typical inside background noise, the sensitivity of the PD monitoring using the bushing as coupling capacitor is quite limited.

Proposed parameter for online monitoring

It can be concluded that partial discharge online monitoring for bushings will give limited information about the health of a bushing due to the described circumstances.

More promising are the parameters Capacitance and Dissipation Factor. They can be monitored for bushings specifically by the use of different methods, which will be discussed in the next chapter more in detail.

OVERVIEW ABOUT TODAY'S USED BUSHING MONITORING METHODS

The most up to date method used today for bushing monitoring is the reference signal method, where the phase shift of the leakage current of a bushing and its stable reference signal is measured. This method will be discussed, further below more in detail, but first the methods used today and its advantages and disadvantages will be described.

Capacitance monitoring

The capacitance monitoring is one of the most easy to apply method to do online bushing monitoring. It is aiming mainly on detecting partial breakdowns between one or more of the capacitive layers.

A secondary capacitor, mostly called C3 will be added between bushing tap and ground (see Figure 6). The main capacitance C1 and the measuring capacitance C3 in that case are representing a capacitive divider. While it can be assumed, that the primary voltage of the high or medium voltage network is relatively stable a partial breakdown can be detected by an increase of the voltage across the C3. Basically a permanent increase of the secondary voltage (across C3) by 5 to 10% is indicating a partial breakdown already.

The disadvantage of the capacitance method is that only partial breakdowns and contact problems in the measuring path can be detected. Furthermore even for the higher voltage levels (420kV and above) the number of the capacitive layers are between 60 and 100 layers depending on the voltage level and supplier of the bushing. If one layer is short circuit the voltage increase then is only between 1 and 1.6%. With high voltage network fluctuations in the magnitude of the voltage from more than 2% it is difficult to detect even a partial breakdown between two layers solely. To overcome this drawback, a direct comparison of the secondary voltage and the primary voltage can be used, which

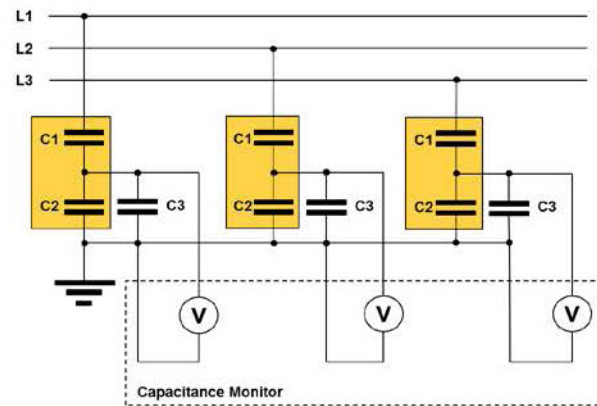


Figure 6: Principle of Capacitance Monitoring

the primary voltage (e.g. VT or CVT) or via digital data from the station control system. Nevertheless, that will then make the system more complex than just a measurement of the secondary voltage across a C3.

Balanced current method

The balanced current method, also called sum of currents method is the today's most used method for bushing monitoring. The principle is that the summation of the leakage currents of the three bushings of the different phases under consideration of its phase angles is zero (see Figure 7). The perfect circumstances mean that the magnitude of the voltage is absolutely the same, the phase shift between the phases is exactly 120 degree, and the bushings are all from the same type and having all the same temperature.

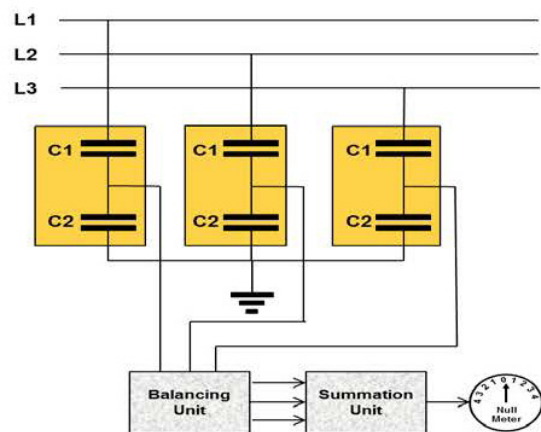


Figure 7: Principle overview Balanced current method

In real world the electrical networks are carrying a more or less imbalanced load. Phase asymmetries regarding voltage magnitude of 1 to 1.5% and 0.2 degree in phase angle variations are very common for stable networks know in the 'old economies'. Much higher asymmetries can be seen in more unstable networks in other parts of the world. The asymmetries are changing with the load conditions in a daily, seasonal and unpredictable manner. Changes of capacitance of a bushing (partial breakdowns) can be more accurate detected because the general fluctuations of the voltage magnitude across all the three phase is being better compensated due to the principle of the method compared to a pure capacity monitoring describe above. But still the clear detection of a partial breakdown for voltage levels 500kV and above remains a challenge, even if the voltage magnitude asymmetry is only 1.5%. If the asymmetry is even higher it will be even more difficult to get a reliable result also for lower voltage levels.

Another challenge for this method is the phase asymmetry regarding the phase angle. If the phase angle unbalance is only 0.2 degree, it would mean that the deviation of the Dissipation Factor is already (cos f, where f is $90^\circ - 0.2^\circ = 89.8^\circ$) 0.349%. The Dissipation factor of a health OIP (Oil Impregnated Paper) bushing will be around 0.250%! The small changes of the Power Factor, used for detecting moisture (compare Figure 3), cannot be detected.

Modern systems today are using self-learning systems, which are recording the typical daily und seasonal behavior of the bushings to predict the load conditions. Nevertheless, the achievable accuracy in regards to the measured Dissipation Factor is limited.

Due to the above described facts the usability of this method for single phase transformer is also limited.

A NEW APPROACH FOR ONLINE BUSHING MONITORING

Today the biggest drawback to increase the accuracy in Power Factor and Capacitance monitoring is that the bushing either will be compared to each other across the phases and the unbalances between the phases are not stable and far from being neglect able.

The only approach to overcome this drawback is to find a load independent reference signal source within the same phase as the monitored bushing.

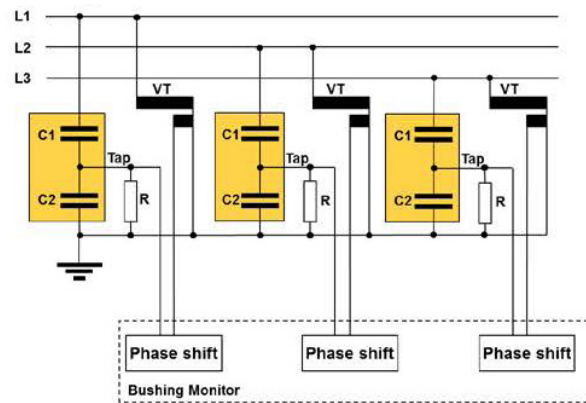


Figure 8: Principle of Reference signal method

The installation of a standard capacitor (gas filled) as used for offline measurement and during routine testing is far too expensive and would increase for EHV installations the size of a switchyard. Another possibility is the usage of a voltage transformer. A voltage transformer (VT) always has a stable load on its secondary winding. Furthermore the VT's are not changing their transfer behavior according to the load of the network. As pure measurement principle the phase shift measurement between leakage current and reference signal reduces the needed hardware to a minimum, due to the circumstance, that after digitizing the signal, all signal processing will be done by software algorithms. Figure 8 is showing the principles of the reference signal method by the use of VT's from the same phase.

Due to the circumstance that the reference signal from the same phase is used, the achievable accuracy is not depending on phase asymmetries.

The major challenges in using that method are the elimination or limitation of noise and the availability of a stable reference source. Especially the second is not always given. Sometimes there are now VT's/ CVT's at the high voltage side or far away in a separate switchyard (especially in Power Plants) or VT's/ CVT's existing only for one phase (mostly the middle phase). Alternative methods are under development.

Signal processing

- Noise and harmonics needs to be eliminated by advanced software algorithms
- The accuracy of the phase measurement is better then 0.1mrad (0.0057 Degree)
- The accuracy enables to detect changes in $\tan \delta$ form e.g. 0.325% to 0.340%
- That enables to detect moisture increase, insulation system aging and degradation early enough
- Temperature compensation will be necessary to achieve this accuracy

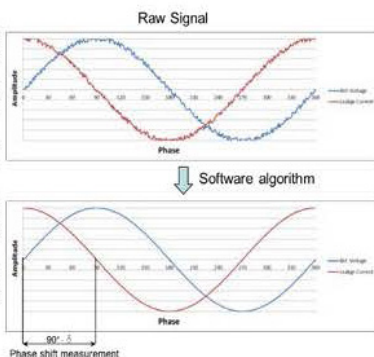


Figure 9: Example for effective noise elimination

The elimination or limitation of noise is one of the major requirements to achieve the necessary accuracy in the phase shift measurement of 0.0057 degree (or 0.1mrad).

Figure 9 is showing a noisy signal before and after signal processing which is illustrating the efficiency of the noise elimination algorithm.

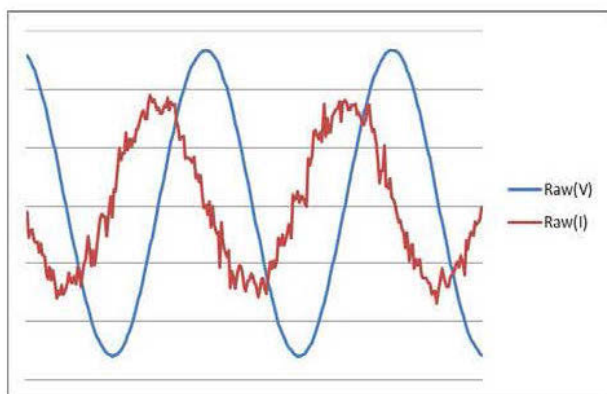


Figure 10: Raw data example from site

Furthermore Figure 10 shows another example for recorded raw data. Due to the relatively high amplitude the signal from the reference source (blue curve) is

almost not disturbed, while the signal coming from the bushing tap has a noise component of about 15 to 20%.

CONCLUSION

Measurements in lab and in a high voltage lab of a bushing manufacturer with real bushings and results from installations showing, that the accuracy of the Power Factor values are measured/ monitored by using this method is far better compared to the methods which comparing bushing from different phase to each other. The results achieved in the lab where showing even better results in stability and accuracy of the measured data than mentioned above (less than 0.0057 degree failure). This needs to be further verified over time also for onsite installations too.

Extensive tests and first applications of this method for bushing monitoring showed, that by using the reference method and having a reference source from the same phase has the ability to detect also already small changes in Dissipation Factor and is able to detect also capacitance changes due to partial breakdowns between two capacitive layers only, even for bushings with rated voltage levels up to 1MV. Furthermore this method can be used also for single phase transformers/ reactors without limitations.

A further field of development is to develop and test an easy device to generate a reliable reference signal for those installations, where no VT or CVT or only in one phase is available.

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