Dispersing the clouds – gain clear insight into your bushings using advanced diagnostic methods

Abstract:

Bushing diagnosis can include various methods, from a simple visual inspection or a conventional power/dissipation factor measurement, to the latest high-tech broadband dielectric frequency response measurements. This article explains the different bushing insulation types and shows which problems can occur in bushings and which diagnostic methods can be used to detect them. Each measurement has its advantages and disadvantages and some are more suitable for onsite measurements, others for quality control of new bushings. Case studies show the effectiveness of advanced dielectric measurement principles in detecting moisture and aging problems.

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1. Introduction

Bushings are a vital part of power transformers and other assets as they act as insulators and transmit electrical power in or out of a power transformer. No active action or mechanical movement is required, and maintenance measures like the changing of worn parts are also not needed. Compared to the rest of the power transformer they are quite low-priced. All of these facts could lead to the conclusion that condition diagnosis of bushings is not economical as they can just be replaced when any failure occurs.

However, such a conclusion would be very short-sighted. About 41% of all bushing failures on high-voltage power transformers lead to a fire or explosion of the transformer (Figure 1) – this corresponds with a complete loss of the transformer [1]. Also, about 37% of all fires or explosions of power transformers are caused by bushing failures [1]. This shows how important it is to prevent bushing failures, not just in order to avoid unplanned outages but also to avoid the loss of assets in dramatic circumstances.

This paper shows which problems can lead to the failure of bushings and how diagnostic methods can be used to detect those problems at an early stage.

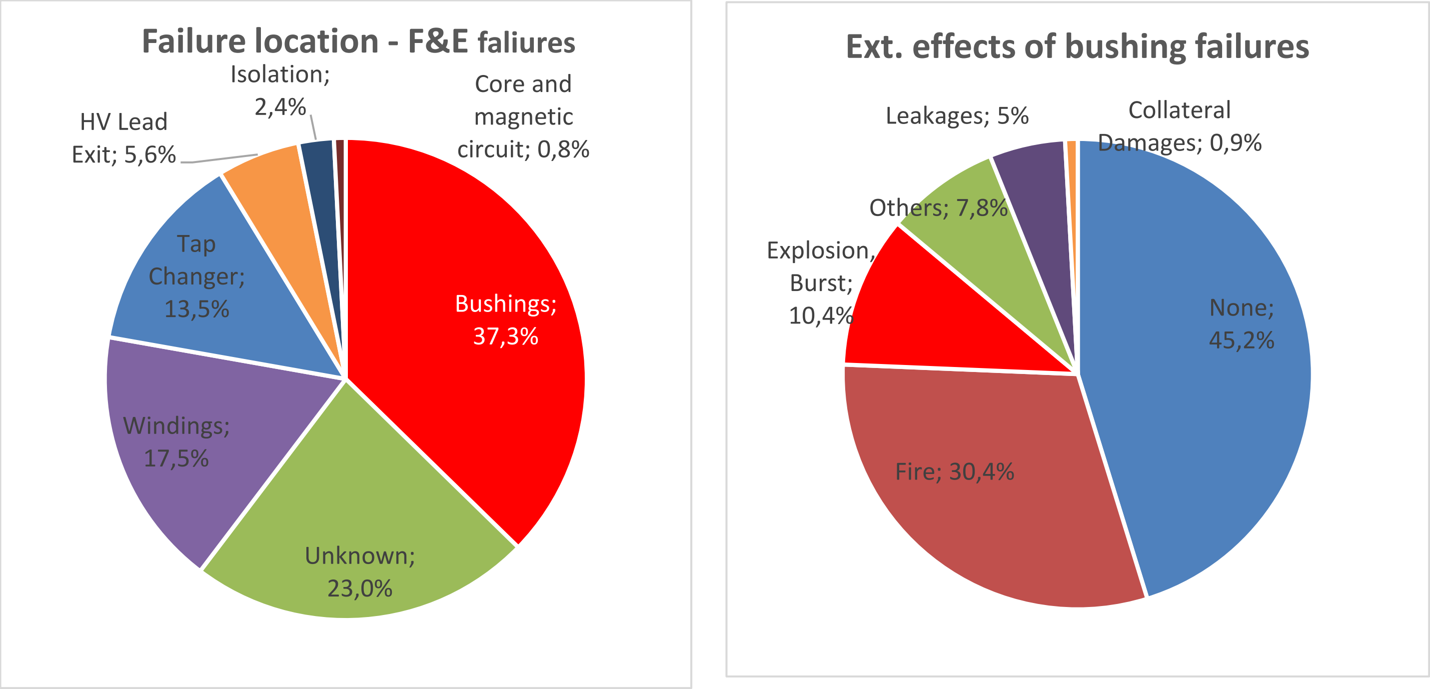


Figure 1. Failure locations of fires and explosions of power transformer failures (left) and external effects of bushing failures (right) [1]

2. Bushing types and typical problems

2.1 Modern types of bushings

Over the last few decades, bushings have been manufactured using different types of technology as manufacturing techniques, as well as the available materials, have improved. At present, the following types of bushings are available:

- Oil Impregnated Paper (OIP)
- Resin Bonded Paper (RBP)
- Resin Impregnated Paper (RIP)
- Resin Impregnated Fiber/Synthetic (RIF/RIS)

Oil Impregnated Paper (OIP) bushings are the most common type with a very long history and considerable experience. Their insulation consists of tightly wound paper layers impregnated with oil, making them sensitive to oil leakage. This bushing type requires special transport, storage and mounting positions and shows a higher risk of fire in the event of a failure [2].

Resin Bonded Paper (RBP) bushings are made of wound paper which is glued together by a resin. Trapped air and gaps in the insulation increase the partial discharge (PD) levels during service and limit the maximum voltage level for this bushing type. In addition, RBP bushings are very sensitive to moisture ingress. Despite the low costs of this bushing, most utilities and manufacturers have discontinued this type [2].

The Resin Impregnated Paper (RIP) bushings are an improvement of the RBP technology as the paper is completely impregnated with resin. This eliminates the problem of partial discharges, which typically occurs during service, and thus allows higher voltage levels. Another advantage of RIP bushings is their low dielectric losses. Despite the impregnation, moisture can ingress during transportation and storage and this must, therefore, also be considered [2].

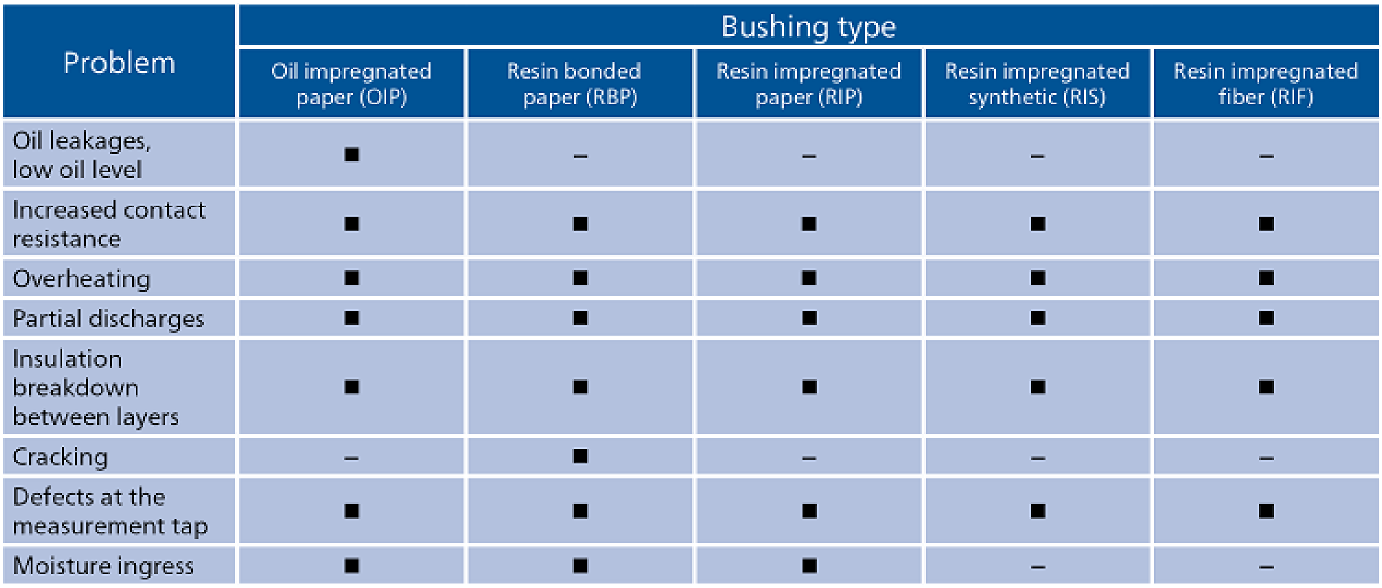
Resin Impregnated Fiber/Synthetic (RIF/RIS) bushings are a further improvement of the RIP technology. Here, synthetic fiber (RIF) or synthetic fabric (RIS) is used instead of paper and is impregnated with epoxy resin. This makes their insulation very robust against moisture ingress. Like RIP bushings, RIF and RIS bushings have a very low PD level and low dielectric losses and can be used and transported in any position [3]. As the RIF/RIS technology is relatively new and not common practice, it is not yet considered in many standards and testing guides.

2.2 Typical bushing problems

As already mentioned, the different bushing technologies show advantages and disadvantages. It should also be taken into account that some problems are typical for a specific bushing type. For example, some problems just occur in OIP bushings but are not applicable to RIP bushings. Other problems occur in all bushings types. This has to be considered during the establishment of a smart testing and maintenance strategy for bushings and transformers.

Table 1 gives an overview of the most common bushing problems and shows which problem is applicable for which type of bushing.

Table 1. Potential problems for different bushing types



Problem	Bushing type				
	Oil impregnated paper (OIP)	Resin bonded paper (RBP)	Resin impregnated paper (RIP)	Resin impregnated synthetic (RIS)	Resin impregnated fiber (RIF)
Oil leakages, low oil level	■	–	–	–	–
Increased contact resistance	■	■	■	■	■
Overheating	■	■	■	■	■
Partial discharges	■	■	■	■	■
Insulation breakdown between layers	■	■	■	■	■
Cracking	–	■	–	–	–
Defects at the measurement tap	■	■	■	■	■
Moisture ingress	■	■	■	–	–

Oil leakage and low oil levels only occur in OIP bushings. They are critical for two reasons: First of all, if the oil loss is large enough, the insulating medium is at least partially missing which can lead to partial discharges and finally to a breakdown of the whole insulation. Secondly, when oil leaves the bushing via a leak, moisture can enter, which threatens the bushing's insulation.

High contact resistances can occur due to bad contacts on both sides of the bushing conductor and this normally results in overheating. Overheating can also take place when the bushing current is much higher than the specified value. In particular, overheating has further consequences: It can deteriorate contacts or damage the insulation which, in turn, can lead to a thermal breakdown of the insulation.

The bushing design, with its capacitive layers, creates a homogeneous electrical field within the insulation and prevents high local fields. Defects, voids and cracks within the insulation, for example in RBP bushings, can cause local high fields which cause, in turn, partial discharges. Those discharges do have further impacts, such as local damages and carbonizations, which can lead to a breakdown between adjacent capacitive layers. One effect of such a breakdown is the increased field between the other layers. Another effect is the progressive damage which doesn't stop at one layer but advances towards the next layers. Both effects lead to a higher electrical stress at the remaining insulation which, especially in cases of transient over-voltages, can lead to a breakdown of the insulation.

The measurement tap of a bushing is connected to the outer grading layer of the bushing. In service it has to be connected to ground potential. This is often performed by a spring contact which connects the pin of the tap to ground if no measurement equipment is connected to it. The tap is usually closed and sealed by a cap towards outer influences. Typical defects at the measurement tap are:

- Leaky seal at the cap (or loss of cap) which can lead to moisture ingress and corrosion of the grounding spring.
- Bad or open contact of the grounding spring which can lead to discharges and arcs.
- Bad or insufficient contact of the tap to the last grading layer. As transient voltages cause very high capacitive currents in this path, this can lead to partial defects and discharges. This is a particular problem near gas insulated switchgear (GIS) where transients occur frequently.

Moisture ingress is a problem for all conventional types of bushings (OIP, RBP, and RIP) as they are based on cellulose which absorbs water. Moisture ingress is a typical problem for "spare" bushings which have been inadequately stored for a long time. Moisture is, in general, critical as it increases the dielectric losses. This can lead to a thermal runaway and reduce the dielectric strength, which in turn can lead to partial discharges and breakdown.

3. Methods for diagnostic testing

A set of different methods can be carried out for assessing the condition of bushings. As well as periodic diagnostic measurements, visual inspections can be performed on a regular basis and – in some cases – on-line systems can be installed for continuous monitoring. Over the last few decades, new approaches for periodic diagnostic measurements have been developed – accordingly, they are separated here in conventional and advanced diagnostic methods.

3.1 Conventional diagnostic methods

For condition assessment of bushings, various conventional diagnostic methods exist which use visual, thermal, chemical and dielectric methods. Table 2 shows their applicability and effectiveness in relation to the typical bushing problems listed in Table 1.

Table 2. Effectiveness of different methods to detect specific bushing problems

Problem	Conventional methods				Advanced methods			
	Visual inspection	Thermovision	Oil analysis (OIP bushings only)	C and tan (δ) at line frequency	C and tan (δ) at different voltages	C and tan (δ) from 15 Hz ... 400 Hz	Dielectric frequency response	Partial discharge measurement
Oil leakages, low oil level	++	+++						
Increased contact resistance		+++	+					
Overheating		+++	+					
Partial discharges			+++					+++
Insulation breakdown between layers				+		++	+++	+++
Cracking				+		++	+++	+++
Defects at the measurement tap	++				+++			
Moisture ingress				+		++	+++	

\+ Low effectiveness ++ Medium effectiveness +++ High effectiveness

Dielectric capacitance and power/dissipation factor measurements at a single frequency are usually performed at the line frequency of the system. This measurement has been a common procedure for many decades. Whereas a change in capacitance indicates a breakdown between capacitive layers, an increase of the power/dissipation factor can also indicate problems such as water, aging, carbonized parts or bad contacts. Both IEEE and IEC bushing standards require the measurement of the power/dissipation factor at room temperature as a routine test for new bushings and to set limits for the losses (Table 3).

Table 3. Limits and typical dissipation factor (DF or tan(δ)) and power factor (PF) values at line frequency according to IEC 60137 and IEEE C57.19.01 at 1.05 Um√3 and 20 °C / 70 °F [3], [4]

	Oil impregnated paper (OIP)	Resin bonded paper (RBP)	Resin impregnated paper (RIP)
Tan δ (source IEC 60137)	< 0.7 %	< 1.5 %	< 0.7 %
PF (source IEEE C57.10.01)	< 0.5 %	< 2 %	< 0.85 %
Typical values for new bushings	0.2 % - 0.4 %	0.5 % - 0.6 %	0.3 % - 0.4 %

Another common practice is performing thermography inspections of bushings [5]. This procedure helps identify areas of the bushings which carry current and have a poor contact resistance – for example, the connection of the bushing terminal to the busbars of the substation. An additional benefit of thermography for OIP bushings is that low oil levels can also be detected.

Particularly for OIP bushings, the dissolved gas analysis (DGA) is an alternative conventional diagnostic method. It can detect various problems such as discharges and overheating. The small oil volume of the bushing requires special sampling techniques and the results interpretation also has to be adapted. Further information about DGA, especially for bushings, can be found in [6].

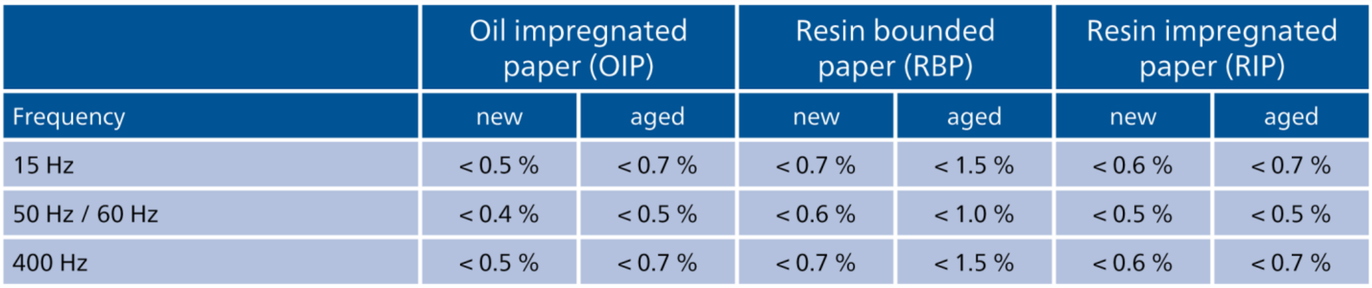
3.2 Advanced diagnosis methods

Based on the conventional diagnostic methods, different advanced measurement approaches have been developed. Table 2 also shows their applicability and effectiveness in relation to the different bushing problems.

An improved version of the measurement at line frequency is the measurement over a frequency range including line frequency. A typical frequency range is from 15 Hz to 400 Hz. Due to the increased frequency range, the frequency dependency of dielectric properties can be analyzed. Moisture ingress in particular influences lower frequencies: For example, a measurement at 15 Hz is more sensitive to moisture ingress than a measurement at line frequency.

Table 4 shows the indicative limits at different frequencies of the Cigre power transformer maintenance guide [7].

Table 4. Indicative values of tan(δ) limits for bushings at 20 °C [7]



	Oil impregnated paper (OIP)		Resin bounded paper (RBP)		Resin impregnated paper (RIP)	
Frequency	new	aged	new	aged	new	aged
15 Hz	< 0.5 %	< 0.7 %	< 0.7 %	< 1.5 %	< 0.6 %	< 0.7 %
50 Hz / 60 Hz	< 0.4 %	< 0.5 %	< 0.6 %	< 1.0 %	< 0.5 %	< 0.5 %
400 Hz	< 0.5 %	< 0.7 %	< 0.7 %	< 1.5 %	< 0.6 %	< 0.7 %

The commonly called “tip up test” is a measurement at a single frequency where the voltage is increased and the dielectric parameters are measured in a voltage range, mostly at line frequency. Measurements of bushings at different voltages can reveal problems like bad contacts of measurement taps, PD or an emerging breakdown between capacitive layers. If a contact problem exists, the power/dissipation factor usually decreases towards higher voltages as at higher voltage level arcing bridges paths. High PD activity which occurs only above the inception voltage can increase the power/dissipation factor due to ionization losses. Therefore, any change of the power/dissipation factor is a sign for a potential problem.

Broadband dielectric measurements are used to measure the dielectric property of an asset in a very wide frequency range, usually from the lower kHz region to a few mHz or even µHz. The big advantage of using a very broad frequency range is the high sensitivity for different influence factors, especially moisture [6]. This method is also capable of determining an absolute amount of the water content in oil-paper insulations, for example in power transformers and OIP bushings [8]. This measurement detects small differences in water content and can, therefore, also be used for quality control of new bushings. As the database is only valid for pure oil-cellulose insulations, the water content determination is not possible for other bushing types such as RBP and RIP [9]. However, as the water content also influences the dielectric properties of those insulation systems, small changes can also be detected by comparing different measurements.

Another advanced diagnostic method is partial discharge measurements on bushings. A high-voltage source is required in order to provide the test voltage, which is in the area of the nominal voltage. Due to the high effort of the test, partial discharge measurements on bushings are mainly performed by the manufacturer or in special cases. Alternatively, a monitoring system can be installed for on-line partial discharge measurements.

4. Case studies for bushing condition diagnosis

The following case studies are examples how different failures might be detected using the advanced dielectric diagnosis methods described in this publication. The data had to be anonymized so no details about the specific model or manufacturer can be shown here; for the same reason, no photos can be shown.

4.1 Wet RIP bushing

The first case study shows a set of measurements on 123 kV RIP bushings. The measurements were performed using OMICRON’s CPC 100 combined with the CP TD1 booster which can apply up to 12 kV at line frequency and up to 2 kV from 15 Hz to 400 Hz. The measurements were done at 2 kV with the high-voltage output at the conductor, the measurement at the tap and guarding the flange and tank (UST). All five measured bushings are of similar age and type. Dielectric capacitance and power/dissipation factor measurements were performed from 15 Hz to 400 Hz on all bushings (Figure 2). Particularly at low frequencies, which are more sensitive to moisture influence, the deviation of the losses of bushing 1N to the other bushings is quite significant. It was speculated that the bushing got wet during storage, which is one of the typical problems of RIP bushings. Therefore, it was recommended replacing this bushing before putting the transformer into service. This example shows the advantage of a measurement at various frequencies compared to a single measurement at line frequency where the deviation is also visible but significantly smaller.

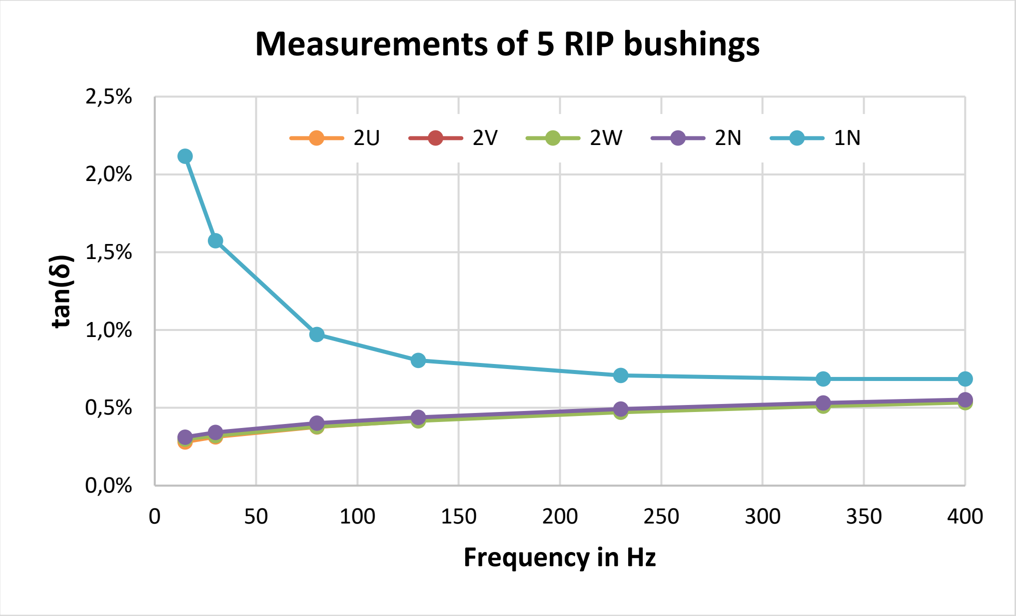


Figure 2. Dielectric loss measurement performed on 123 kV RIP bushings

4.2 Aged RBP bushings

The second case study shows tan(δ)-measurements using also OMICRON's CPC 100 combined with the CP TD1 booster in a frequency range from 15 Hz to 400 Hz of three 245 kV RBP bushings. The measurements were performed at 2 kV with the high-voltage output at the conductor, the measurement at the tap and guarding the flange and tank (UST). Reference measurements were taken eight years earlier using the same test system. They allow the change of the losses to be seen during this time (Figure 3). Although none of the measured values exceeds the limit according to the standards (Table 3), aging is indicated by an increased tan(δ), especially at lower frequencies – this is clearly visible for all bushings. In particular, the bushing on phase V shows significant aging, whereas the worst bushing at the time of the reference measurement on phase W shows the smallest changes.

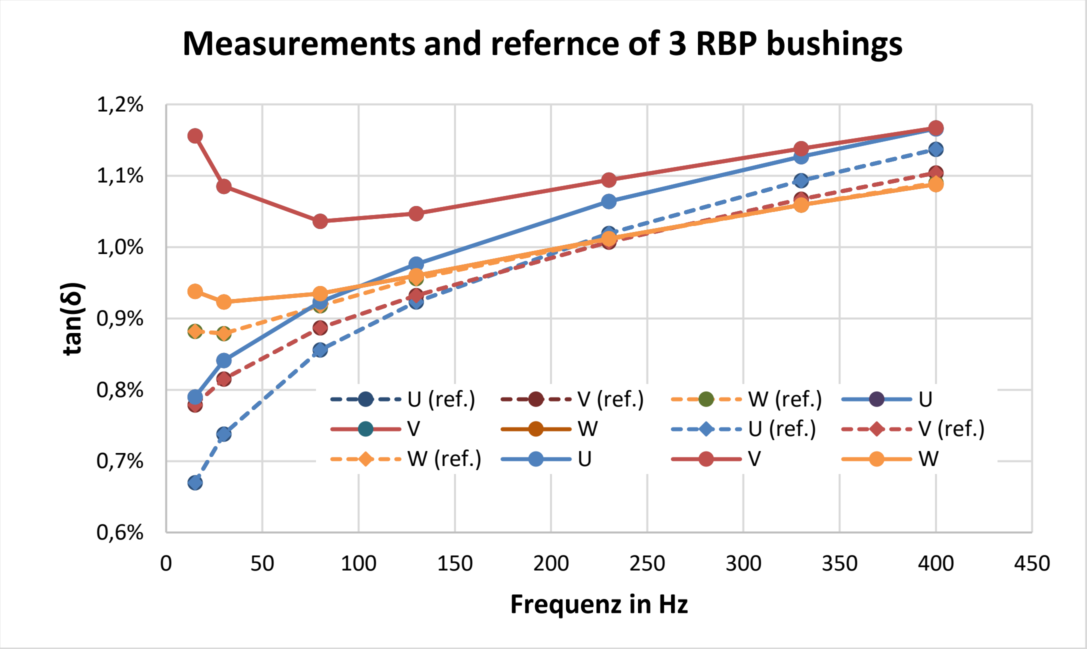


Figure 3. Dielectric measurements and reference measurements of three RBP bushings

4.3 Contact problem at the measurement tap

Tan(δ) measurements of two 123 kV RBP bushings of the same type were performed with OMICRON's CPC 100 combined with the CP TD1 using different voltages at 50 Hz. The measurements were done with the high-voltage output at the conductor, the measurement at the tap and guarding the flange and tank (UST). The result shows a decreasing tan(δ) at higher voltages for bushing C(data from [8]). This could be associated with contact problems at the measurement tap [8] which might be caused by a defect sealing or a missing, defect or not correctly placed cap. A measurement at a single voltage level, for example at 10 kV, would have shown only a sight deviation of the values.

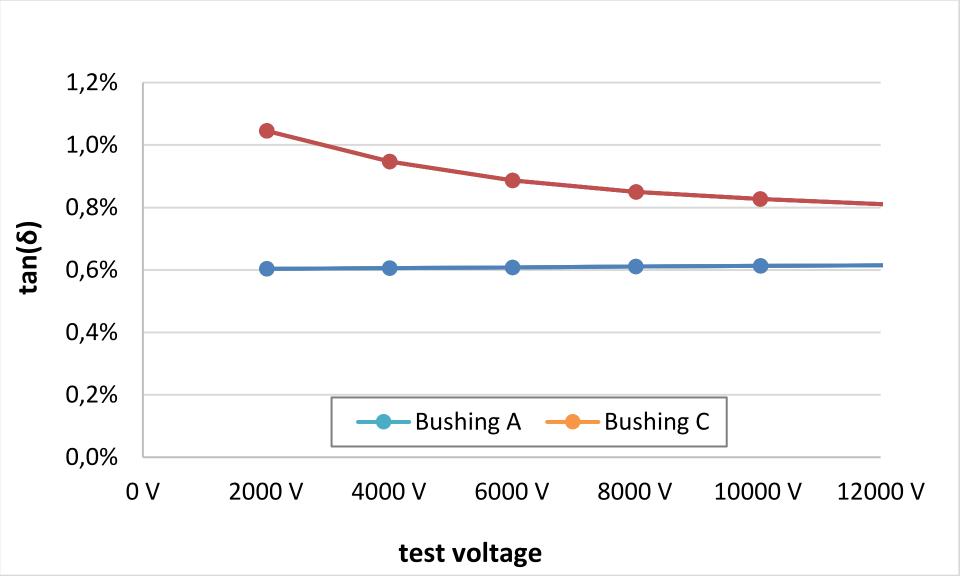


Figure 4. Tan(δ) measurements of two 123 kV RBP bushings at different voltage levels (data from [8])

Conclusion

Condition assessment of bushings is an important task to be carried out by operators of high-voltage assets with the aim of reducing the risks of bushing failures. The outcome of a comprehensive condition assessment is that the most critical bushings can be identified. This is helpful for prioritizing maintenance and refurbishment measures, such as replacement of bushings with new ones, in a systematic and economically attractive way.

For a complete condition assessment, all possible problems need to be considered. Therefore, a set of diagnostic methods can be applied. Conventional methods have been successfully applied in the past and are still the standard method for most network operators. Advanced methods are mostly an improvement of the conventional methods and can detect specific problems more effectively. They do not exclude each other – most advanced methods even include the traditionally measured values. Thus, users with experience in conventional methods can easily profit from the advantages which are possible with current measurement and signal processing technologies.

The case studies presented in this contribution illustrate the enhanced sensitiveness of these advanced methods with respect to the conventional capacitance and power/dissipation factor measurement at single frequencies.

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