

# TRANSFORMER ON-LINE BUSHING

# MONITORING SYSTEM EXPERIENCES

Transformers are the most important assets in the power network. Increasing number of electrical vehicles, demand for additional charging stations, installation of heat pumps impact the infrastructure.



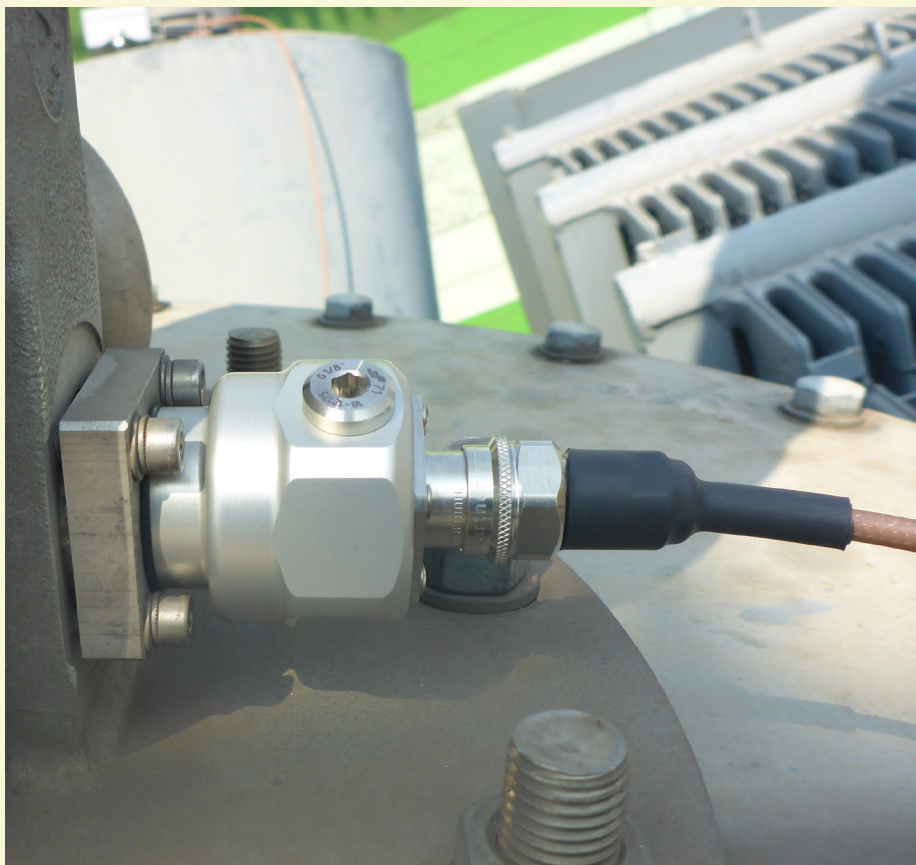
Transformers are the most important assets in the power network. During the last few years, the share of electrical energy generated from photovoltaic and wind power plants was continuously growing. Power network configuration, energy flow and the transformer role change. Increasing number of electrical vehicles, demand for additional charging stations, installation of heat pumps impact the infrastructure. AC inverters used for converting the DC voltage to AC increase the risk of damage to the equipment insulation system. The main negative aspects of the converters are the harmonics (deformation of sinusoidal voltage) and their impact on the degradation of the insulation system.

Based on the CIGRE technical brochure 642, "Transformer Reliability Survey"[1], almost 18% of all failures documented for transformers operated in substation can be tracked down to the malfunction related with transformer bushings. Additionally, it is important to mention that bushing failure leads in most cases to fire or explosion of the transformer (37% of all critical failures with explosion or fire). The above numbers show how critical and important proper maintenance of this transformer component is. To ensure functionality and on time service planning several on-line monitoring systems are used what with periodical testing (specified by the bushing manufacturer) increase system reliability significantly [2].

### Introduction

In the previous years, several monitoring systems based on different measurement and evaluation methods were developed to control capacitance and dissipation factor (power factor) – the two most critical parameters of transformer bushings. Change of these bushing parameters during transformer operation time delivers essential information of the insulation system state and is specified by the manufacturer.

The bushing monitoring evaluation results are important for future decisions related to transformer operation. The correct measurement method and accuracy of the whole bushing monitoring system (C or/and tan delta) is a most important parameter of such a system. Several external parameters such as used bushing coupling units and its internal components (capacitors or/and resistors with temperature dependency), voltage and current signal filters, algorithms performing calculation (air temperature and moisture impact) and evaluation (external reference, voltage comparison etc.) as well as visualization of the results impacting the overall system usability. It is important to mention that the allowed capacitance and dissipation factor change depend on the type and operating voltage of the bushing. One of the most common and sufficient on-line bushing monitoring methods is a voltage measurement (coupling on the test or voltage tap) with or without comparing to external reference signal (voltage transformer) [3].



## Transformer Bushing and On-Line Monitoring

The main function of the transformer bushings is to transfer current at defined potential to the winding through an opening in the transformer tank. Condenser-type bushings are used for higher voltages, reducing radial and axial voltage stresses while minimizing size. Bushings are manufactured by wrapping paper or synthetic material on a central conductor (for example aluminum tube), with separate electrodes (thin metal foil, conductive paper, or paint) of defined length and diameter.

Typically, the last electrode relates to measuring tap (called test or voltage tap depending on the type and function) creates two main capacitances that can be measured:

$C_1$  – is a HV capacitance between the central electrode and the tap,  
 $C_1 = C_{e1} + C_{e2} + \dots + C_{en}$  where the  $C_{e1}$ ,  $C_{e2}$ ,  $C_{en}$  are the serially connected elementary condensers.

$C_2$  – is a LV capacitance between the tap and the flange on ground potential (in operation this capacitance is short-circuited to ground).

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Depending on the insulation material used in manufacturing we can distinguish between the following types:

- RBP – Resin Bonded Paper
- OIP – Oil Impregnated Paper
- RIP – Resin Impregnated Paper

For all the above bushings the paper is used as an insulating material. New development also introduces synthetic materials with higher operating temperatures and lower humidity absorption instead of paper.

- RIS – Resin Impregnated Synthetic
- RIF – Resin Impregnated Fiber

The bushing coating or housing (weather sheds) can be made from porcelain or silicon rubber. Manufacturing technology impacts the importance of the monitored parameters. For example, the capacitance  $C_1$  of the RBP compared to the RIP and OIP is affected by the oil penetration into the main structure of condenser body. Change of  $C_1$  can be observed even if there is no short-circuited elementary condenser situation. RIS bushing can keep dissipation factor on constant level.

The most efficient way to estimate bushing condition based on the on-line monitoring is to control the change of the capacitance  $C_1$  and the associated dielectric dissipation factor ( $\tan\delta$ ) or power factor ( $PF - \sin\delta$ ). It is proven that humidity and the ageing process are impacting capacitance only at higher temperatures. A short circuit between elementary condensers will increase the capacitance independent of temperature. The change in the dissipation factor and power factor is temperature-dependent. Increase of  $\tan\delta$  indicates higher loss in the bushing's insulation system and is often caused by introduction of moisture or ageing process.

Limits for the change of  $C_1$  and  $\tan\delta$  are depending on the system voltage and technology used for bushing construction. The approximate capacitance changes corresponding to short-circuited elementary condensers are shown on the next page in Table 1.

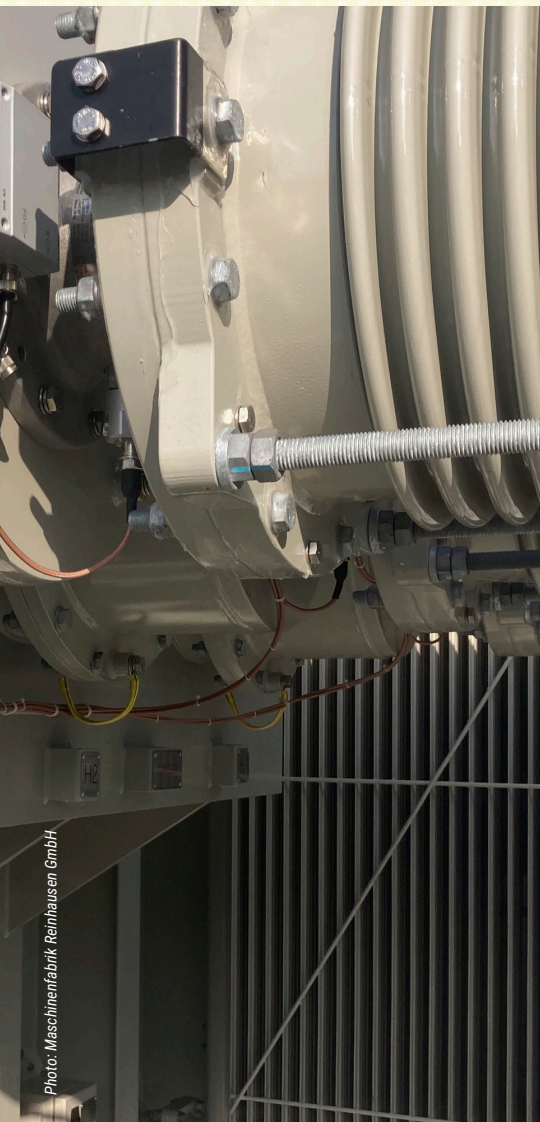


Table 1: Examples of approximate capacitance change of the  $C_1$  for short-circuited elementary condensers [4].

Um [kV]	RIP capacitance change [%]	OIP capacitance change [%]
72,5	12	8,8
123	7,1	4,8
145	6,3	3,9
170	5,3	3,4
245	4,2	2,7
300	2,9	2,4
362	2,4	2,1
420	2,2	1,7
550	1,9	1,3
800	1,3	0,9

Um – maximum operating voltage

More accurate information regarding the number of elementary condensers needed for better calculation of the capacitance change should be provided by a bushing manufacturer. The information is essential to set warnings and alarms limits to the correct level.



Compared to the capacitance the  $\tan\delta$  measurement is much more sensitive to external factors (temperature, weather condition) due to the small value of angle  $\delta$ . Bushing condition evaluation based on  $\tan\delta$  measurement depends on the bushing insulation type and construction. Two evaluation methods can be applied: based on the specified  $\tan\delta$  value or a relative  $\tan\delta$  change.

Table 2: Limits for the evaluation of the power factor for bushings depending on technology used [4].

Standards	RIP	OIP	RBP
Tan Delta (IEC 60137)	< 0.7 %	< 0.7 %	< 1.5 %
Power Factor (IEEE C57.19.01)	< 0.85 %	< 0.5 %	< 2 %
Typical values aged 50/60 Hz (according to CIGRE Brochure 445)	< 0.5 %	< 0.5 %	1.0 %

Table 3: Accuracy for capacitance and  $\tan\delta$  measurement for different systems [5].

Accuracy	Tan Delta or Power factor	Capacitance	Leakage current	Phase
System A	$\pm 0.035 \%$	$\pm 0.2 \%$	0,1 %	$\pm 0.01^\circ$
System B	1 %	0,1 %	0,1 %	$0.01^\circ$
System C	0,05 %	1 %	1,5 %	$0.1^\circ$
System D	n.a.	0,20 %	0,1 %	n.a.
System E	$\Delta\tan\delta \pm 0.01 \%$	$\pm 0.04 \%$	n.a.	n.a.
System F	$\Delta\tan\delta: < 0.001$ (0.01 %; $\pm 0.1$ mrad)	< 0.7 %	< 0.7 %	< 1.5 %
System G	0.05 % + VT error	$\pm 2$ pF + VT error	$\pm 1$ mA	n.a.

Monitoring systems offered on the market provide technical information regarding accuracy of the capacitance and  $\tan\delta$  measurement. Examples of an accuracy for different monitoring systems can be found in Table 3.

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Understanding of the basic parameters makes the comparison and preparation of monitoring system specification simple and clearer. The focus should be put on the essential parameters like power factor and capacitance. These two parameters are well described and the limits for different bushing technology are known.

The accuracy of capacitance should be defined as percentage change of the measured capacitance what correspond to the change if one conducting layer will be short-circuited what is depending on the system voltage and bushing type. For example, accuracy of 1% for the capacitance change can be not enough for the higher voltages > 400 kV in case of OIP bushing type but sufficient for < 170 kV for RIP bushing type.

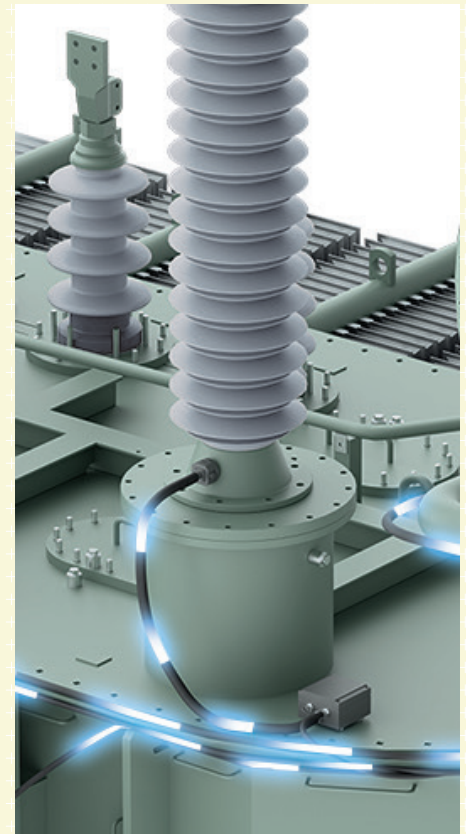
The power factor or  $\tan\delta$  should also be defined as accuracy of the percentage change. For example, the new OIP bushing with  $\tan\delta = 0,5\%$  shows starting aging process if the values go to the 0,7% [5].

### Bushing On-Line Monitoring Challenges

Transformer on-line bushing monitoring system can be installed from the beginning of operation or as a retrofit. In many cases, based on experience, bushing failures appear during the first years or after many years in service. Such failures can be triggered by bad condition of insulation because of moisture ingression or oil leakage, incorrect handling, or lack of regular service.

On-Line Monitoring constantly delivers necessary information allowing proper operation and on-time maintenance (if necessary) of a transformer bushing. It is important that such a system can work in each environmental condition and is not affected by external noise providing measured data with sufficient accuracy.

Figure 1: Visualization of the on-line bushing monitoring.

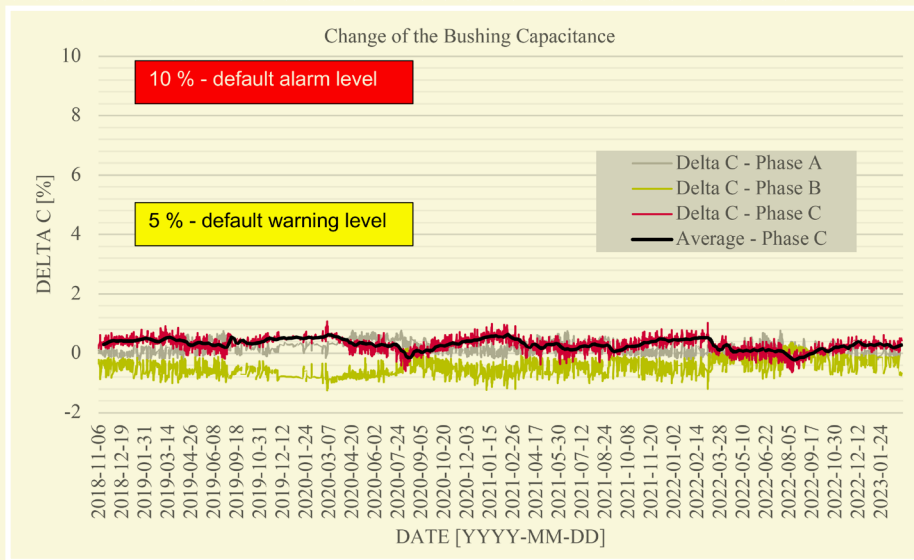


Based on experience, Maschinenfabrik Reinhausen GmbH has developed a product that meets this fundamental principle. MSENSE®BM uses a dual reference voltage method. The bushing voltage signal is compared with voltage reference from the same phase measured on the voltage transformer. The second comparison, based on the patented method, is made with the signal from the adjacent phase (phase A with B, B with C and C with A). The influence of the network fluctuation in amplitude and phase shift, as well as external interference (sun, rain, etc.), can therefore be effectively eliminated while maintaining the required measurement accuracy.

**Example 1 – Stable installation.**

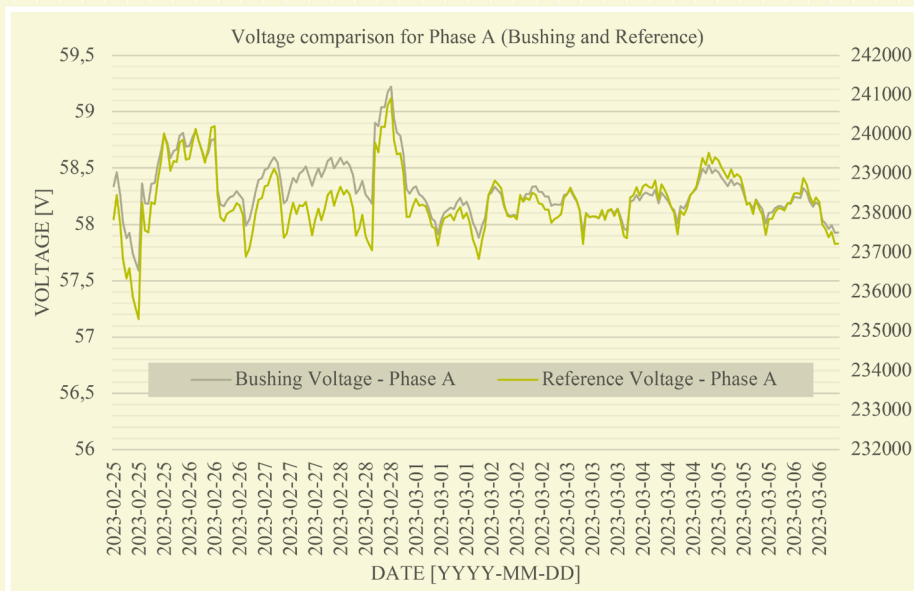
In the figure below an example of bushing monitoring signals evaluation recorded during four years in operation is shown. No significant deviation in measured of the capacitance were observed. The signals remain stable (approx. 0,5% oscillation) and do not cross the warning and alarm level which was set respectively for 5 and 10%.

Figure 2: Change of the bushing capacitance over long installation period.



Looking more closely at the voltage measurement for bushing and reference signals, it is easy to observe that the fluctuation of the voltage is identical. The same amplitude of both voltages indicates no change in the bushing capacitance. Signal accuracy is sufficient and stable.

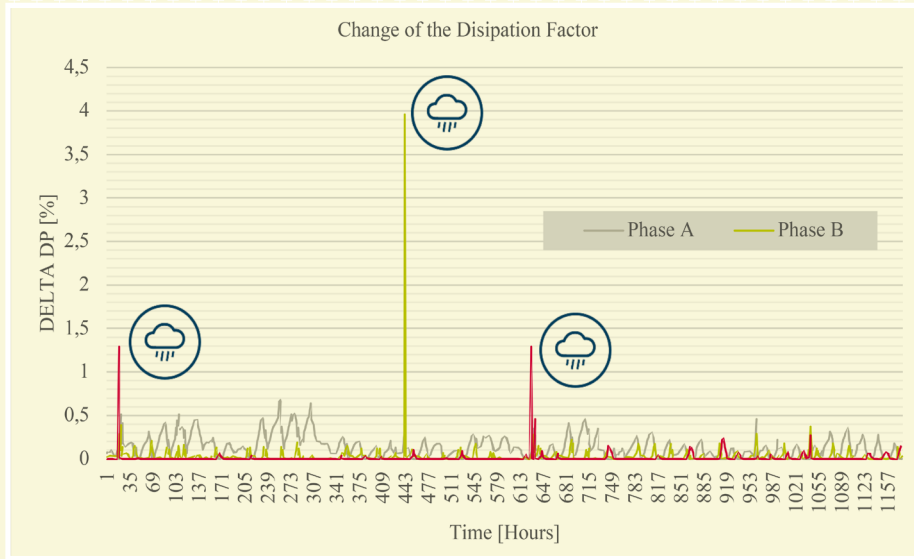
Figure 3: Voltage comparison for phase A (bushing and reference signal).



**Example 2 – Impact of the pollution of the bushing surface**

If the bushing monitoring installation site is impacted by high pollution, the system can record short “spikes”. This behavior can be observed especially for dissipation factor measurement and is caused by discharges on the bushing housing surface. The correlation of the measured signal with historical information regarding weather conditions can be easily observed. Signal with “Spikes” was detected only during raining season and back to previous level after short time. In that case different mechanical construction of the bushing housing is negatively impacting the signal recording. To avoid false alarms additional algorithms in MSENSE®BM for signal evaluation are implemented.

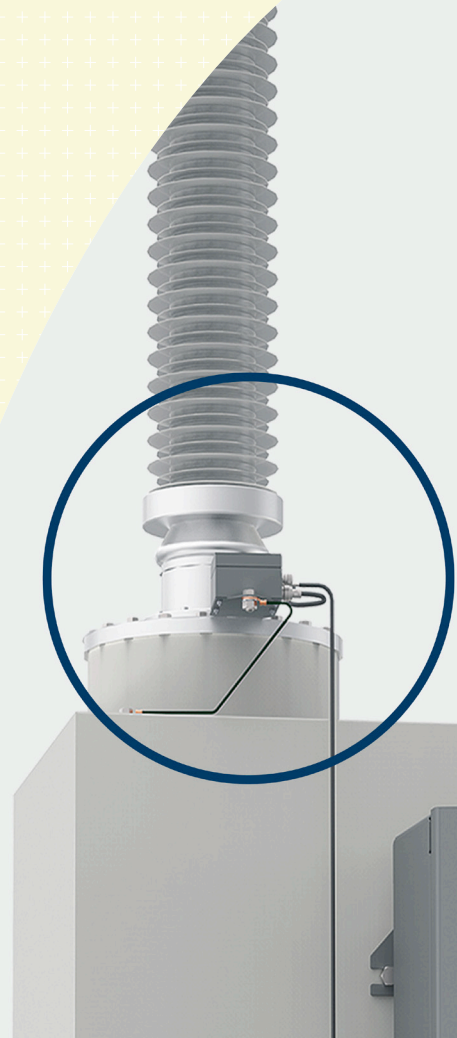
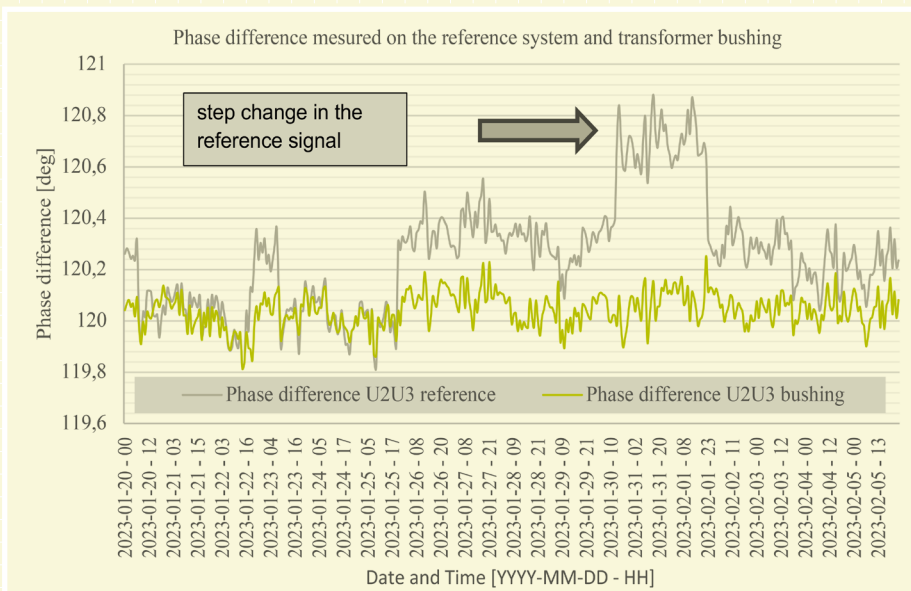
Figure 4: Change of dissipation factor due to weather condition.



**Example 3 – Reference signal**

Simple comparison of the reference voltage or phase shift measurement with the bushing reading can also impact signal evaluation. In the case below, a simple monitoring system can generate false alarms during changing of the busbar connection in the substation. For that special configuration, the signal from the voltage transformer was distorted for phase shift which was confirmed with external measurement. Evaluation of the recorded signals shows stable signal for bushing phase displacement and step changes in signal measured on voltage transformer. Implementation of additional algorithm in MSENSE®BM allow to detect that change to avoid generation of the false alarms.

Figure 5: Phase shift difference for unstable voltage transformer.



**The on-line bushing monitoring systems help maintain safe transformer operation and schedule of maintenance activities on demand. By choosing the most suitable measurement method in combination with implementation of evaluation algorithms, MSENSE®BM provides constantly correct information with the required accuracy.**

**Conclusion**

The on-line bushing monitoring systems help maintain safe transformer operation and schedule of maintenance activities on demand. Depending on the measurement method used, different accuracy can be achieved in estimating changes in capacitance and dissipation factor. Information about the type of bushing installed on the transformer, system voltage, network stability and location are essential to correctly evaluate the measured signal.

By choosing the most suitable measurement method in combination with the implementation of evaluation algorithms, MSENSE®BM provides constantly correct information with the required accuracy. Integration with ETOS® (Embedded Transformer Operating System) makes it easy to install and use this precise and cost-effective solution for on-line bushing monitoring system.

**References**

- [1] "Transformer reliability survey", CIGRE TB 642, December 2015
- [2] "Guide for Application for Monitoring Equipment to Liquid-Immersed Transformers and Components", IEEE PC57.143/D21, 2010
- [3] "State of the Art Transformer Bushing Monitoring", Thomas Linn, Qualitrol – Switzerland, power generation, August 2020
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- [5] "Experiences with Bushing Monitoring System - Proposal of Unified Benchmark Process", J.M. Szczechowski, Dr.-Ing. J. Wu; CEPSI 2021



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