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Improving the Reliability of Online Bushing Monitoring

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***Summary* — This paper discusses the common issue of bushing failures in power transformers and presents methods for preventing such failures through online monitoring. The paper presents a method based on the comparison of bushing leakage currents from different transformers connected to the same busbars to overcome problems with unreliable measurement results due to grid voltage imbalance or frequent transformer outages.**

***Keywords* — bushing, online monitoring, insulation diagnostic, capacitance, tan delta.**

I. Introduction

Together with windings and tap changers, bushing-related failures are among the top three major contributors to transformer failures. CIGRE study [1] analyzed 964 major transformer failures and results have shown that bushing failures cause 14.4% of all transformer failures on average. However, the share of bushing-related failures increases significantly with increasing voltage class totaling 27.8% for transformers with the highest system voltage from 500 kV to 700 kV. It is also worth mentioning that failures originating in the bushings most often lead to severe consequences such as fires and explosions (Fig 1).

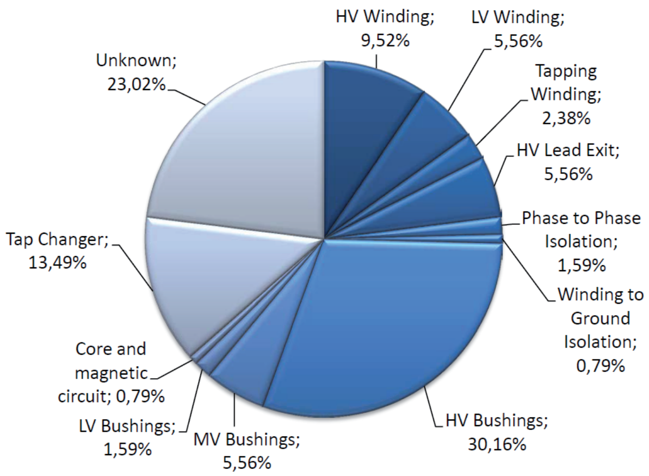

Fig. 1. Failure location where fire or explosion occurred [1].

Deeper analyses on bushing reliability, where bushing failures were analyzed separately from transformer failures and included incipient and non-transformer damaging failures were conducted in another CIGRE study [2]. In case an incipient fault is discovered early enough it allows the user to schedule a transformer outage and replace, or repair, faulty bushing to prevent transformer failure. To discover the incipient fault, several bushing diagnostic techniques have been developed over the past decades and they differ based on the required transformer state (offline or online) and the frequency in which they are performed (periodic or continuous).

Commonly accepted diagnostic methods for assessment of bushing insulation state are capacitance and dissipation factor or power factor measurements. Many utilities perform these procedures on a periodic basis. Since offline measurements are performed with stable environment conditions and controlled and known voltage source, they are very precise and reliable. However, those measurements require trained personnel and equipment and must be performed while the transformer is offline. Over the last three to four decades utilities around the globe started using bushing online monitoring to assess bushing parameters while transformer is online. Online monitoring is performed while operating conditions such as voltage, load and ambient temperature dynamically change, and that has a significant impact on the precision and reliability of those measurements. There are multiple methods developed to minimize that influence and one of them is presented in this paper.

II. Online Bushing Monitoring Methods

Bushings are being monitored by connecting an additional capacitive divider on the bushing test (measuring) tap. The connection to the bushing test tap is established by using specially designed adaptors to fit different designs of test taps of various bushing types and manufacturers. In this way, it is possible to measure the leakage currents that flow through bushing insulation and calculate changes in the bushing's capacitance and power factor. The measuring path of the system is given in Fig 2.

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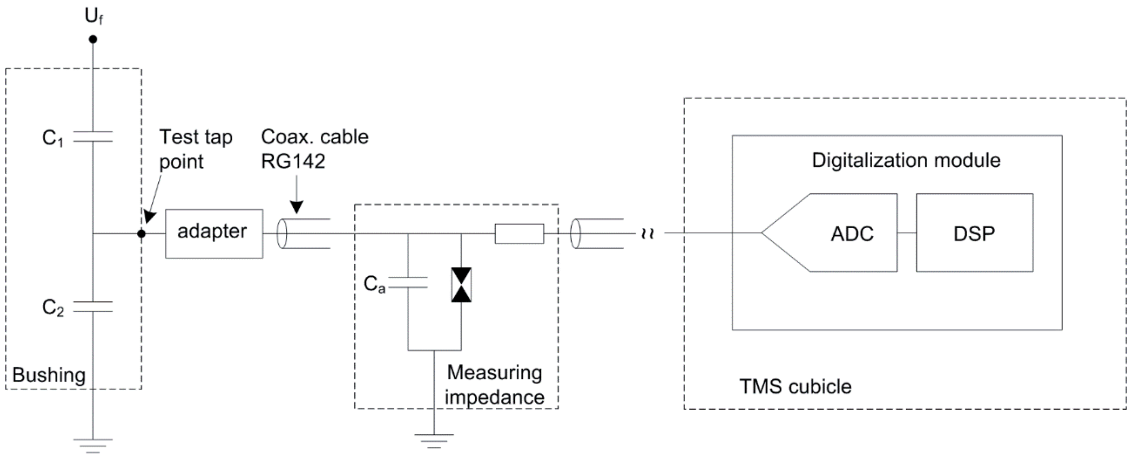

Fig. 2. Bushing and transient overvoltage monitoring measurement path

Currently there are three major methods and topologies used for bushing monitoring and each has its pros and cons speaking in terms of results reliability, complexity, and installation expenses. They are shown in Fig 3. Please note that the naming of methods may differ between different bushing monitoring vendors.

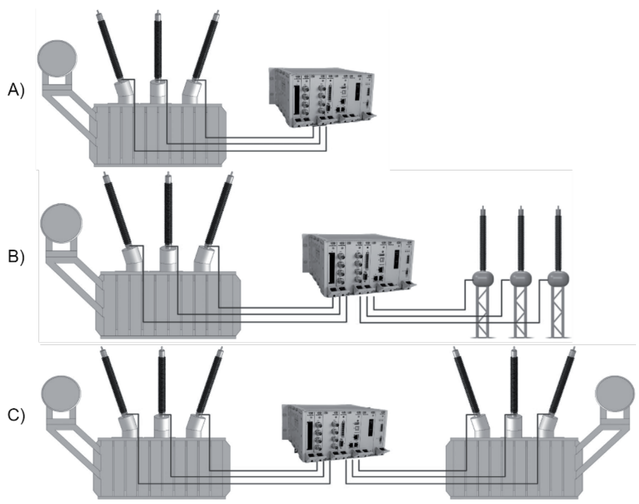

Fig. 3. Bushing monitoring methods
A) Three Phase bank; B) VT reference method; C) Dual transformer method

The simplest and most common method is three phase bank method which uses signals from three bushings connected to the same three phase bank. The most popular algorithms are the sum of currents, adjacent phase to phase, etc. These algorithms are based on comparing initial state or fingerprint data of leakage currents phase angle and amplitude with recent measurements. Using some mathematics, it is possible to calculate capacitance and dissipation factor changes. Capacitance change is expressed as a relative change from the initial state ΔC/C and dissipation factor as an absolute change Δtgδ from the initial state. The algorithms are based on the following assumptions:

- Only one out of three bushings is faulty at the time.
- The voltage level fluctuates on all three bushings similarly at the same rate.
- Angles between phase voltages do not change significantly from the initial state.

The first condition is typically fulfilled. Due to the constant changes in grid voltage levels, load, and phase angles, the latter two conditions are sometimes not fulfilled or are partially fulfilled. The accuracy and reliability of the algorithm depends on how well those conditions are met. Measured values can be expressed as a superposition of real changes in bushing parameters and error caused by grid imbalance.

$$\frac{\Delta C_{measured}}{C_0} = \frac{\Delta C_{real}}{C_0} + CAP\_ERR_{GRID} \quad (1)$$

$$\Delta tg\delta_{measured} = \Delta tg\delta_{real} + TG\_ERROR_{GRID} \quad (2)$$

In case of an unbalanced load or a fault in the grid, false alarms can appear because the angle and amplitude of grid voltage phases can change. To minimize those issues, algorithms use long averaging and other statistical analysis. Long averaging affects the response of the system which can be days or weeks. But even with that, there are cases where those algorithms do not provide satisfactory results and other methods must be used.

The other two methods previously mentioned in Fig 3 are reference based. These are VT (voltage transformer) or dual transformer methods. Measurements from a reference object, VT, or another transformer connected on the same busbar, are used to compensate for grid imbalance. Reference methods significantly improve dynamic response, accuracy, and reliability of measurement since previously mentioned conditions are no longer required.

As can be seen in Fig 3 B) and C), all signals from the device under test and reference object are connected to the same acquisition unit. This simplifies the synchronization of measurements from reference object and device under test but at the same time complicates cabling and introduces problems such as ground isolation. Very often there are no free secondary terminals of VT or other transformer in a substation, or they are far away from the device under test. Because of these, in many cases, utilities decide to implement the simplest method (three-phase bank) despite its drawbacks.

III. Novel Monitoring Method

A variant of the reference method was developed that can be used for upgrading existing systems using three phase method without additional expenses and added complexity. The system uses already existing digital infrastructure such as LAN to synchronize distributed acquisition units and share measurement data used for compensating grid imbalance problems. Reference acquisition unit can be another bushing monitoring system or other third-party devices such as a power quality analyzer or SCADA. It is only important that it measures voltages and phase angles on the same busbar and that can provide data digitally.

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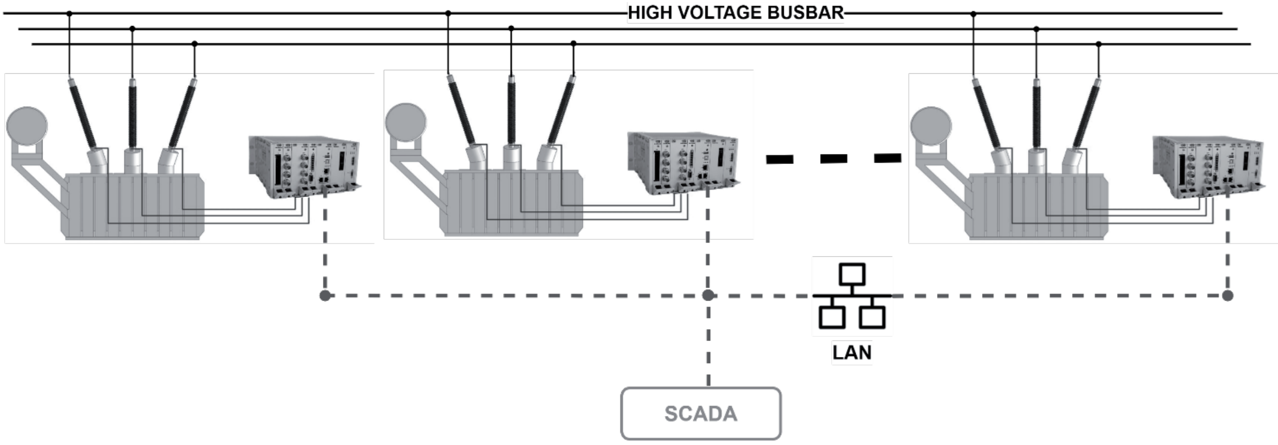

Fig. 4. New variant of the bushing monitoring reference method

Usual communication in monitoring systems is only one way. The monitoring system sends data to SCADA and does not receive any data from SCADA or other monitoring systems connected to SCADA. Existing infrastructure was used to establish bidirectional communication between all interconnected devices. Each monitoring system sends its measurements to other systems in LAN and receives data from them and SCADA.

Each unit has an operating three phase bank method used for bushing monitoring and calculates capacitance and dissipation change. Systems share calculated values, voltages, phase angles and top oil temperature readings with other systems in the same LAN. Grid imbalance compensation is performed as simple subtraction between monitored bushing and its reference bushing on another object operating on the same busbar. As the error produced by grid imbalance is the same on both the device under test and the reference object, it is canceled in subtraction. The example below explains that calculation in detail for dissipation factor measurements.

$$\Delta tg\delta_{measured,DUT} = \Delta tg\delta_{real,DUT} + TG\_ERROR_{GRID} \tag{3}$$

$$\Delta tg\delta_{measured,REF} = TG\_ERROR_{GRID}\,, \qquad \text{where } \Delta tg\delta_{real,REF} = 0 \tag{4}$$

Since it is very unlikely that bushings on both reference and device under tests, have elevated dissipation factor for same value and at the same time, one of measured values consists only of error generated by grid imbalance and other consist of error generated by grid and real change of bushing dissipation factor. This is shown by equations 3 and 4.

$$\Delta tg\delta_{real} = \Delta tg\delta_{measured,DUT} - \Delta tg\delta_{measured,REF} \tag{5}$$

Subtraction of those two equations gives final equation 5 where error produced by grid is canceled. The same principle is applied for capacitance measurements and gives the following equation.

$$\frac{\Delta C_{real}}{C_0} = \frac{\Delta C_{measured,DUT}}{C_0} - \frac{\Delta C_{measured,REF}}{C_0} \tag{6}$$

However, the key factor for subtraction is that measurements are synchronized and that bushing temperatures are more or less equal or different but stable. Different temperatures between objects can be compensated using thermal compensation curves retrieved from bushing manufacturers [3] but keep in mind that those curves are valid only for static temperature, where all insulation in bushing is at the same temperature. Bushings typically have big thermal capacitance, and in laboratory conditions will equalize to their ambient temperature after 3 – 5 hours. This is a reason why using those curves while bushing temperature is dynamically changing introduces some error.

IV. Case Study

A hydropower plant in Croatia, commonly used during peak loading, has three generators and step-up transformers. The low voltage side of each transformer is connected to its generator, and the high voltage side of transformers is connected to 110 kV busbar. A single line diagram is given in Fig. 5.

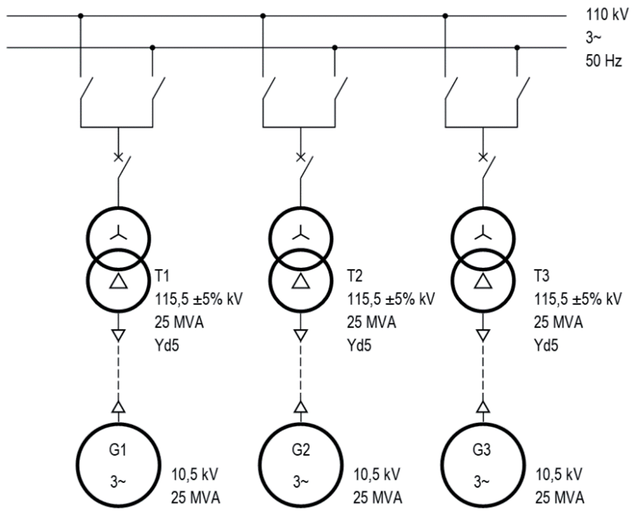

Fig. 5. Simplified single line diagram of powerplant

All three transformers were manufactured by the same company and equipped with OIP bushings of the same type and manufacturer. Transformer T1 was manufactured and commissioned in the year 2000 and transformers T2 and T3 in year 2004. Transformers T2 and T3 still have originally installed OIP bushings, while the bushing in phase U on T1 was replaced in the year 2017 (due to elevated dissipation factor) with a bushing manufactured in the year 2004 supplied as a spare one.

Table I

Production Years of Bushings

Phase	Transformer T1	Transformer T2	Transformer T3
U	2004	2004	2004
V	1999	2004	2004
W	1999	2004	2004

Considering the age of the installed bushings, the utility decided to install a bushing and transient overvoltages monitoring system in 2020. Since transformers are usually switched on only for several hours a day, and rarely more than one-week, bushing

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Fig. 6. Transformer Monitoring Installation

monitoring three phase bank method was not an appropriate choice due to the slow response time.

The installed monitoring system (Končar TMS) was upgraded with the previously mentioned algorithm without the need for any hardware upgrade. The algorithm enabled canceling grid imbalance impact and provided a much faster response than commonly used algorithms with long averaging buffers and slower responses.

V. Monitoring Results

Since the monitoring system was installed on three transformers, a total of three pairs (as presented in TABLE II) of devices under test and reference objects were able to be monitored. In that way, each bushing monitoring has two reference objects for canceling grid imbalance.

Table II

Dual transformer compensation pairs

Pair	Device under test	Reference object
T1 vs. T3	T1	T3
T2 vs. T3	T2	T3
T1 vs. T2	T1	T2

Theoretically, it is possible to create 6 pairs, for example, T1 vs T3 pair can also be presented as T3 vs T1 where the device under test and reference object source swap places. In that case, the result is the same but with the opposite sign. Considering that dissipation factor and capacitance can only increase over time, negative result points that monitored parameters of the reference object have changed while positive result points that parameters of the device under test have changed. Having two references for each object is not mandatory but in this case it is important because it can be used to prove that the algorithm is effectively canceling grid imbalance and is not generating false positive alarms. For example, the pair of reference and device under test objects, whose bushings are in good condition, should have constant values of capacitance and dissipation factor over time.

Fig. 7 shows dissipation factor measurements for bushing on phase V for all pairs of DUT and reference objects. Over the displayed period, the top oil temperature was changing in the same manner on all three units. However, the bushing dissipation factor showed elevated levels and dependency versus temperature for T1 vs. T3 and T1 vs. T2 pair. The maximum measured dissipation factor change was 0.4%. That indicated that something was going wrong with the bushing on phase V on transformer T1. Values for pair T2 vs. T3, marked red on the chart above, did not change at all, which points that bushings on T2 and T3 are in good condition and proves that the algorithm effectively cancels grid imbalance impact and is not generating false alarms as previously explained.

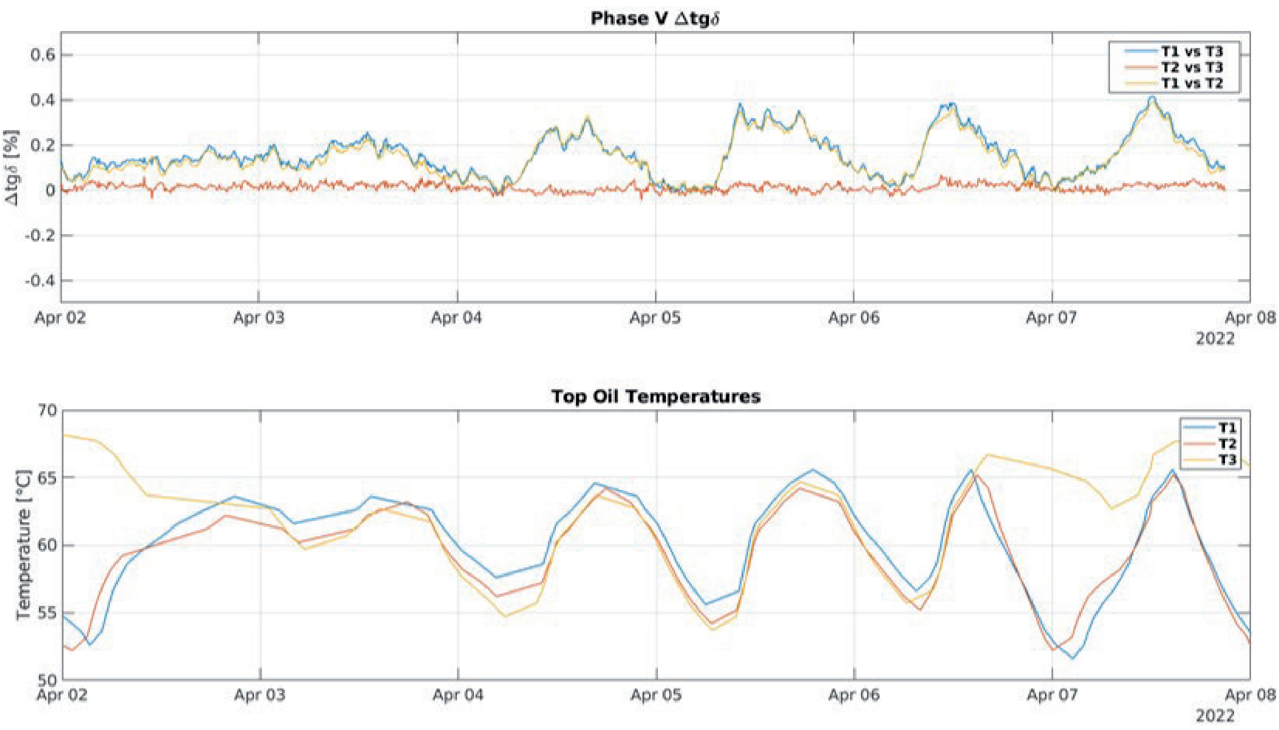

Fig. 7. Dissipation factor and temperature trend chart

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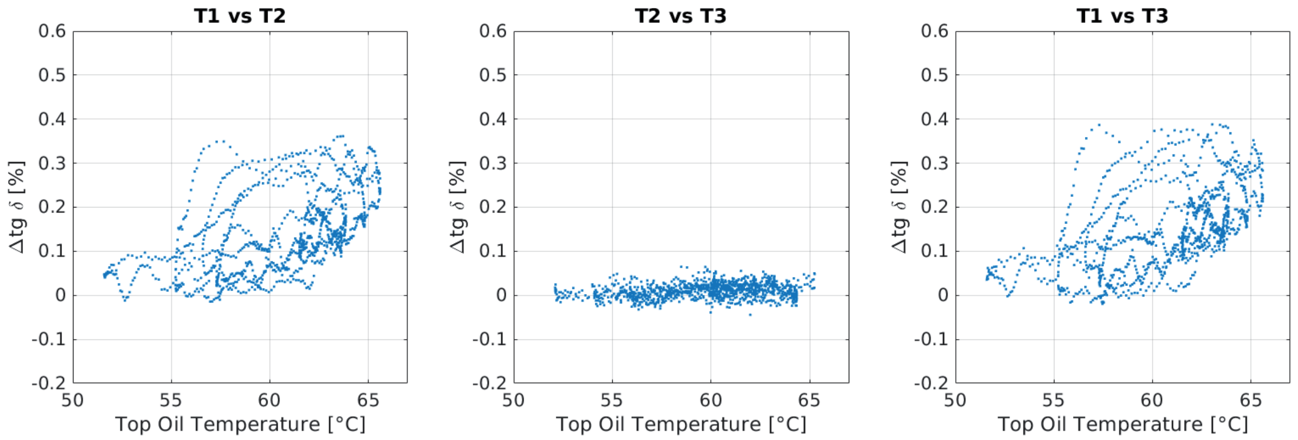

Fig. 8. Dissipation factor change versus temperature

Dissipation factor change is plotted against the top oil temperature for all three pairs and is shown in Fig. 8. It is now clear that bushing has altered dissipation factor thermal dependency which can point to moisture ingress. Dissipation factor temperature dependency is usually proven using offline measurements on low frequencies or by thermal cycling in laboratory conditions. In the summer of 2022, all bushings were checked using an offline method which proved the results obtained by the monitoring system. The bushing on phase V of the T1 transformer had a dissipation factor of 0.85% and it was immediately replaced with a new spare bushing. The utility provided faulty bushing for further postmortem analysis to prove our assumptions.

Additionally, over two years of operation, the system recorded multiple transient overvoltage and disturbance events including lightning strikes in overhead lines. This adds value to monitoring systems by enabling maintenance personnel insight into real operating conditions of bushings and transformer itself and provides valuable data for grid modelling.

Fig. 9 shows waveforms recorded during a lightning strike in the overhead line which caused 3 pole short circuit. After approximately 60 ms, automatic recloser reenergized the line. The event correlates with SCADA and LLS (lightning location system) records.

VI. Postmortem Analysis

The faulty bushing was taken to a laboratory for postmortem analysis. It was suspected that moisture in the insulation caused a dissipation factor increase and altered temperature dependency. Bushing was tested using offline method and thermally cycled in the climatic chamber from 20 to 80 °C in steps of 10°C. The bushing temperature was measured using a thermocouple on the bushing flange. After each step or increase in ambient temperature, the bushing was left for four to five hours till its temperature reached stagnation. After that bushing dissipation factor and capacitance were tested with 2 – 12 kV voltage at 50Hz frequency and by 15 – 400 Hz frequency at voltage level of 2kV.

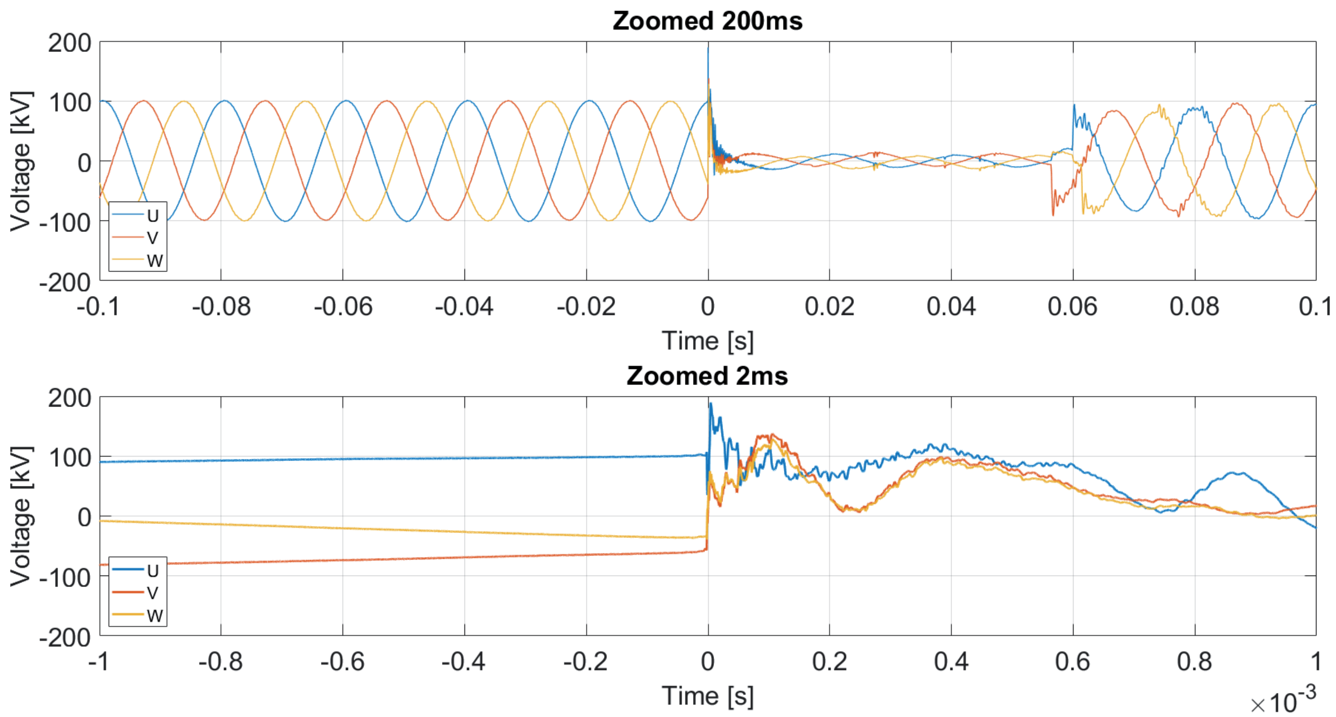

Fig. 9. Three pole short circuit caused by a lightning strike

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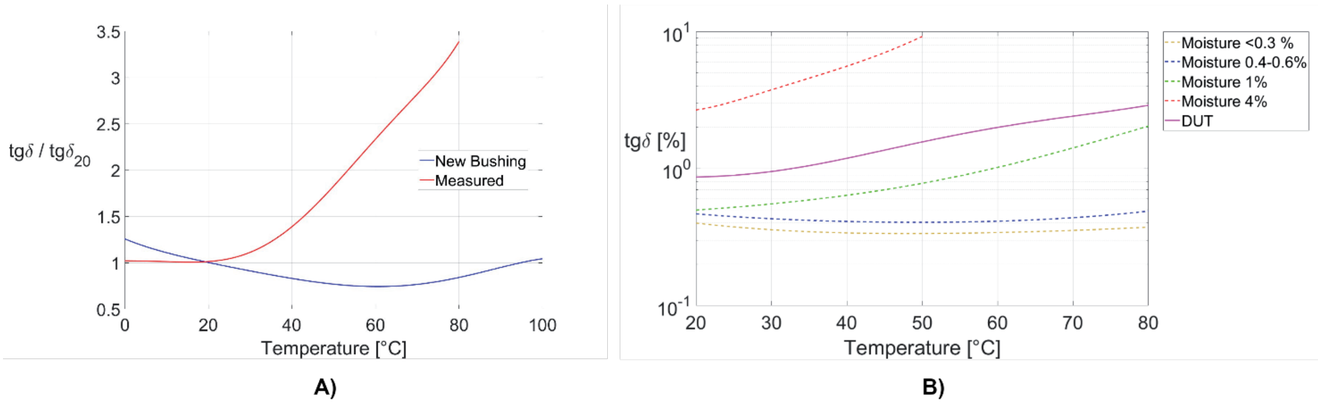

Fig. 10. Dissipation factor temperature dependency vs moisture [4]

Fig. 10 B) shows dissipation factor temperature dependency for various levels of moisture content [4] in comparison with measurements on faulty bushing (DUT). As moisture increases, the dissipation factor rises, and the saddle of the curve tends to shift to lower temperatures. Dashed curves are taken from bushing OEM datasheets and a solid pink curve was measured on faulty bushing. That proves the elevated level of moisture content. Fig. 10.A) displays the compensation factor for thermal compensation of dissipation factor measurements. The blue curve is taken from the manufacturer's datasheet and is valid only for healthy bushing. The red curve shows measurements for faulty bushing.

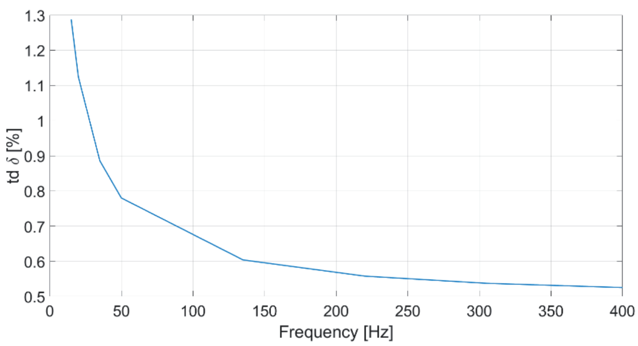

Fig. 11. Dissipation factor versus frequency

Since the dissipation factor measured at low frequencies is more dependent on moisture, those measurements are used to prove moisture ingress. Fig. 11 shows elevated values of dissipation factor at low frequencies which also points out that the bushing dissipation factor increase was caused by moisture ingress.

VII. Conclusions

The presented method provided several improvements over the simplest three phase bank method. It improved its reliability and provided up to a hundred times faster response. The faster response of the system enabled measurement of power factor temperature dependency which can be the earliest sign of moisture ingress in bushing and was not seen with other bushing monitoring algorithms. When compared with other reference methods, it has lower complexity and cost of implementation. It also provides a possibility for simple upgrades of existing monitoring systems using three phase bank method. Nevertheless, please note that even with these upgrades, the results of an online system cannot be literally compared with offline measurements since operating conditions during measurements differ significantly. Online and offline measurements should be considered as complementary methods. A reliable monitoring system should be used to trigger bushing offline measurements and enable true condition-based maintenance.

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