A New Approach for Transformer Bushing Monitoring

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Abstract

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 spill. 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 does not lead to a catastrophic failure can harm people due to burst porcelain insulators, catapulted through the air by the force of the breakdown arc.

Today, experience shows that a transformer during his lifetime will have two sets of bushings. As transformer today are expected to last 50 years, bushings are expected to have a lifetime of 25 years. Past experience showed, that there are two major periods where bushings fail. The production/quality related failures take place once the bushings reach an age of 10 to 13 years. The second wave of bushing failures takes place between 20 to 30 years of age, which is considered as their normal life time. Nevertheless, it is true, that bushings fail earlier than 10 years of age but is also true, that there are bushings installed on transformers with an age of more than 50 years.

The two main health indicators for a bushing are the loss factor (tan δ/ power factor) and the capacitance. The loss factor is sensitive to almost all bushing faults, but the capacitance is an important factor to detect partial breakdowns between capacitive layers and also to detect, in combination with the loss factor, contact problems inside the bushing.

On-line monitoring of loss factor and capacitance aims to detect incipient faults and give an early warning as well as using the bushings until its real end of life. In order to have a reliable monitoring system, the accuracy of the acquisition of the monitored parameters needs to be very high. The lost angle, at a quite relevant amount of moisture impregnated into the bushing core, will only show a slight change at ambient temperature. Some bushing monitoring systems today are not able to capture these slight, but important changes. The problem is that standard capacitors as measuring references are no available in the field for online monitoring. Instead sister bushings are used as a reference source to assess the condition of a bushing (balanced current method), but voltage and angle differences between phases as well as different temperatures aging rates are not considered with these methods.

New approaches use stable voltage sources as reference signals, mainly from the same phase of the monitored bushing. The phase shift between the leakage current signal from the bushing and the voltage source is measured, corrected by the phase shift offset and the loss factor calculated directly. Using for example a voltage transformer (VT) as reference source, accuracies up to 0.1mrad in terms of measuring the phase shift can be achieved and small, but relevant changes can be detected.

Failure statistic

Transformers are one of the most critical components within the electrical network and cannot, once they fail, be replaced 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. Also, monitoring solutions were less reliable or not available 10 to 20 years ago. Besides, 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. Additionally, 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 in 2012 an interim report (1) which shows the newest statistic on transformer failures (see Figure 1 and Figure 2).

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

Figure 1: Transformer failure statistics

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,

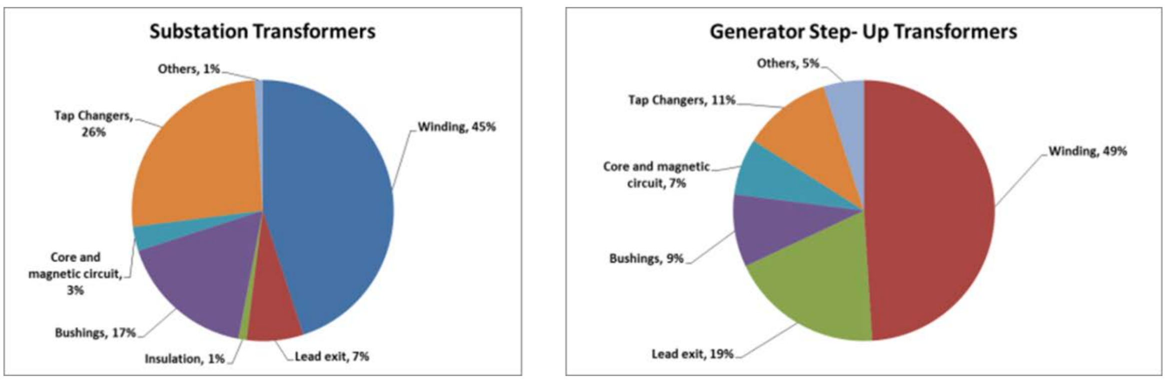

Figure 2: Failed component statistic

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. Failing of a bushing can lead to catastrophic failures and can be going along with environmental disasters or personal fatal accidents. According to a transformer reliability study published in (2), 70% of all transformer fires are cause by bushing failures.
The cause of bushing failures varying from normal aging, moisture, quality issues during manufacturing, repeated thermal and mechanical cycling, transients and external influences like external flashovers. As result a high number of bushing failures develop from partial breakdowns, thermal instabilities or degradations of longitudinal insolation interfaces.
The average lifetime of bushings is estimated in general as half of the life of a transformer (25 years). In reality there are bushing 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

Defect	Power Factor	Capacitance	Partial Discharge
Insulation aging	+	-	-/+ Detectable if discharges are the cause of the degradation/ aging
Moisture	+	-	-
Void/ Delamination	(+) After a certain time once the dielectric material starts to corrode	-	+
Surface contamination	+	-	+/- If the surface contaminations are creating surface discharges
Surface discharges	+/- Surface discharges with a high intensity can be seen by a unstable tan δ	-	+
Partial breakdowns	+/- If it is combined with erosion of insulating material	+	+/-
Contact problems	+ Shows up as an increased or unstable tan δ	+ Shows up as decreased or unstable capacitance	+

Table 1: Detectability of different bushing failures

in the IEEE world (or Dissipation Factor in the IEC world), the bushing main capacitance and partial discharge activity. Table 1 gives an overview of the different bushing parameters and its ability to detect different failures in an early stage of its development. it can be seen, that Power 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.

Power Factor

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 d and decrease the angle f and will result in an increase in Power Factor (see Figure 3).

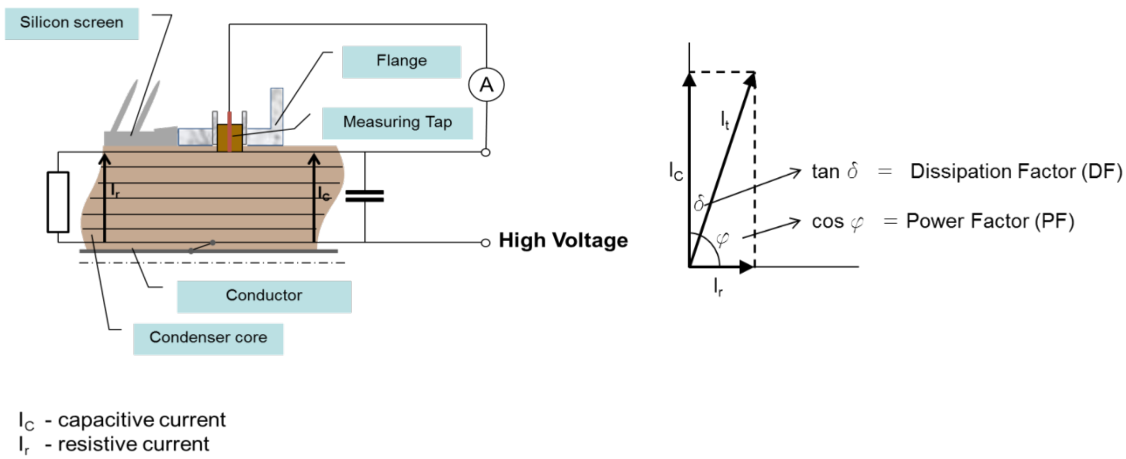

Figure 3: Leakage current and Power Factor

The Power 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.

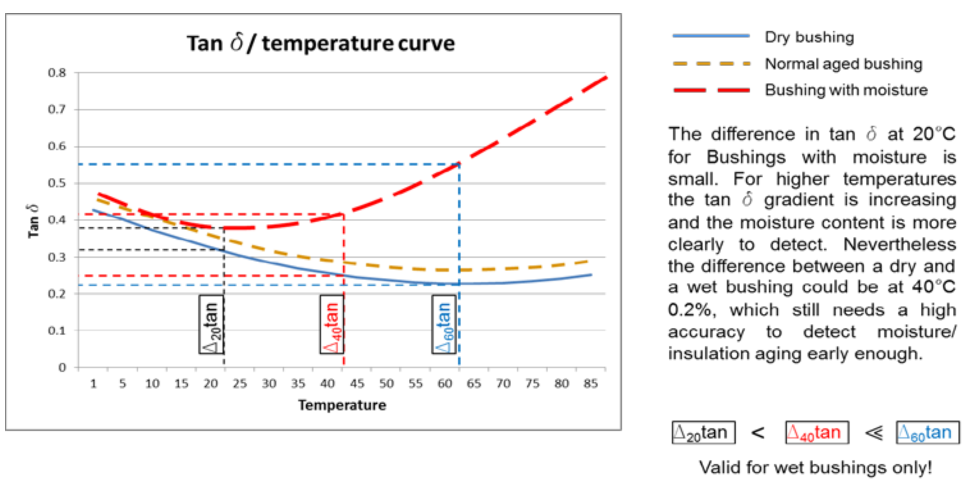

Figure 4: Power factor behavior over temperature due to increased moisture

Figure 4 shows the behavior of the insulation system with increased moisture content. The accuracy of the Power Factor monitoring needs to be very accurate, considering the Power 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 Power Factor monitoring is that the Power Factor of a bushing can be seen at different temperatures. Depending on the load of the transformer, the temperature of the bushing will increase of decrease. It can be seen in Figure 4, that the Power 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. 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 2%.

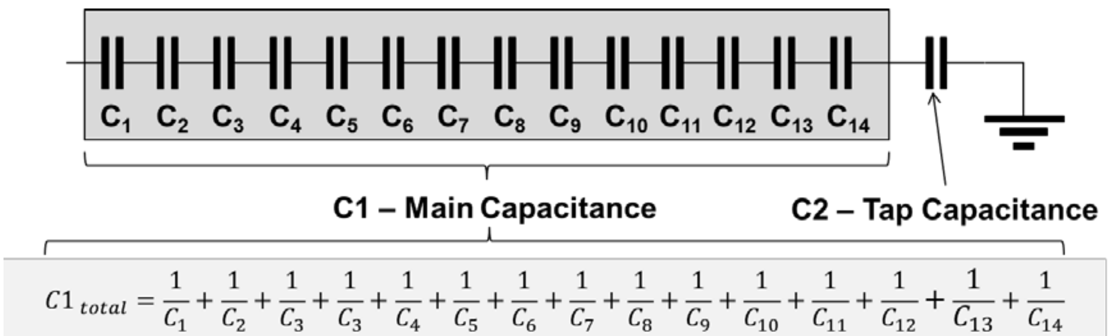

Figure 5: Bushing series capacitances

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 1).

Partial Discharge

As it can be seen in Table 1, all bushing defects can be detected by partial discharge but moisture. Therefore, partial discharge (PD) measurements are very important for routine and re-testing at factory or on site. 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 is used as coupling capacitor. 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 (typically 500pC up to 1nC allowed (see Figure 6), most likely the bushing PD will be hided due to the higher ‘external’ signals. Additionally, due to the high capacitance of the test object and the typical onside background noise, the sensitivity of the PD monitoring using the bushing as coupling capacitor is quite limited. If a PD signal is detected, it is difficult or even in some cases impossible to find the origin of the PD (overhead line/ line connectors/ transformer/ high current duct or maybe even the bushing) without any additional measurements, which might require an outage of the transformer.

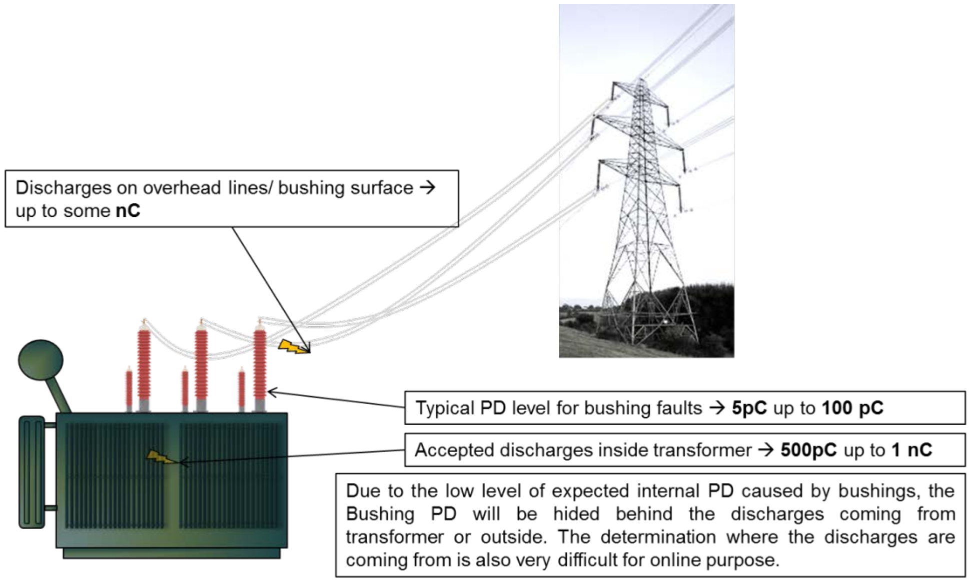

Figure 6: Challenges for online bushing PD monitoring

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. The partial discharge from a bushing will be hidden by 'external' discharges/disturbances. The sensitivity is limited and it is difficult to allocate detected discharges to a certain component or even to distinguish between internal and external discharges.

More promising are the parameters Capacitance and Power Factor which can be monitored for bushings specifically using different methods that will be discussed in more in detail right away.

Overview about today's used Bushing monitoring methods

The newest 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 is discussed further below more in detail, but first, the methods used today and its advantages and disadvantages are described.

Capacitance monitoring

The capacitance monitoring is one of the easiest method to apply to do online bushing monitoring. This method is aiming mainly on detecting partial breakdowns between one or more of the capacitive layers. A secondary capacitor C3 is added between bushing tap and ground (see Figure 7). The main capacitance C1 and the measuring capacitance C3 in that case represent a capacitive divider. A partial breakdown can be detected by an increase of the voltage across the C3, assuming that the primary voltage of the high or medium voltage network is relatively stable. A permanent increase of the secondary voltage across C3 of 5 to 10% will be an indication of a partial breakdown.

The disadvantage of the capacitance method is that only partial breakdowns and contact problems in the main current path can be detected. Furthermore, for the bushings for the higher voltage levels (420kV and above) the number of the capacitive layers are between 60 and 100 depending on the voltage level and supplier of the bushing. If one layer is missing the voltage increase, then is only between 1.6 and 1%. 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 would demand to have access to the measurement of the primary voltage (e.g. VT or CVT) or via digital data within an ECS system. Nevertheless, that will then make the system more complex than just a measurement of the secondary voltage across a C3.

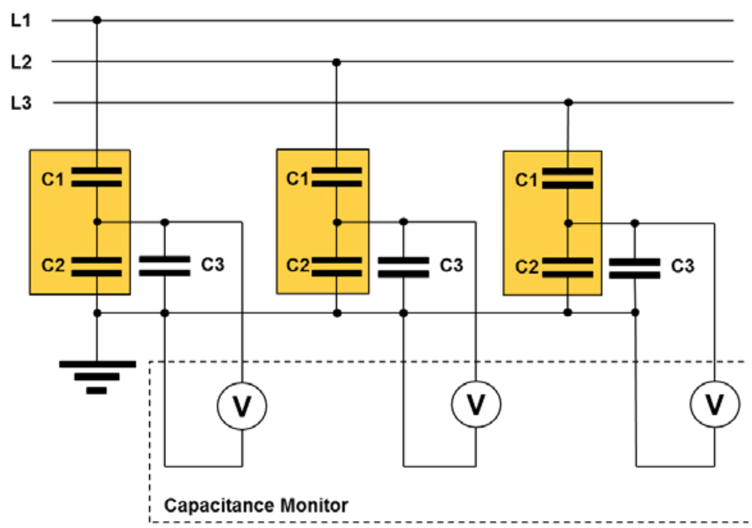

Figure 7: Principle of capacitance method

Balanced current method

The balanced current method, also called sum of currents method is the today's most used method for bushing monitoring (see Figure 8). The principle is that under perfect circumstances the summation of the leakage currents of the three bushing of the different phases under consideration of its phase angles is zero. The perfect circumstances mean that the magnitude of the voltage is absolutely the same, the phase shift between the phases is exactly 120 degrees, and the bushings are all from the same type and having all the same temperature.

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.

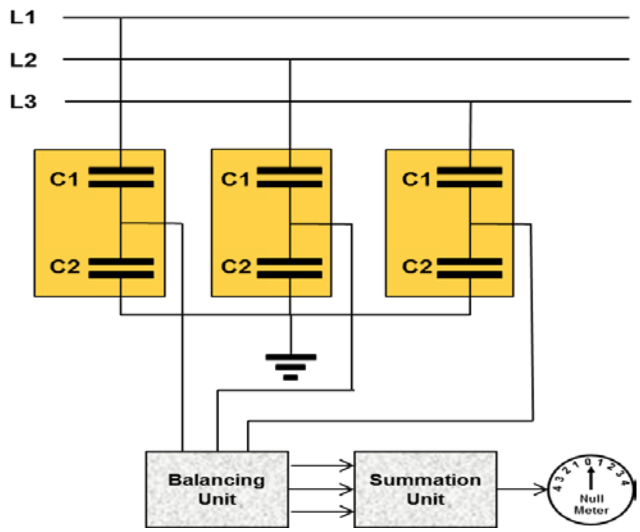

Figure 8: Principle of balanced current method

Another challenges for that method is the phase asymmetry regarding the phase angle. If the phase angle unbalance is only 0.2 degree, it would mean in deviation of the Power Factor already (cos Ɵ, where Ɵ is 90° - 0.2° = 89.8°) 0.349%. The Power Factor of a health OIP (Oil Impregnated Paper) bushing is about 0.25%. Small changes of the Power Factor, used for detecting moisture (compare Figure 4), cannot be detected.

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

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 the switchyard. Another possibility is the usage of a voltage transformer. A voltage transformer (VT) always has a stable load on its secondary winding. VT's don't change their transfer behavior according to the load of the network. Figure 9 shows the principles of the reference signal method by the use of VT's from the same phase. As pure measurement principle, the phase shift measurement between leakage current and reference signal reduces the needed hardware to a minimum, due to after digitizing the signal, all signal processing will be done by software algorithms. Due to the reference signal from the same phase is used, the achievable accuracy is not depending on phase asymmetries any more. Existing phase constant shifts from VT, cables etc. can be compensated.

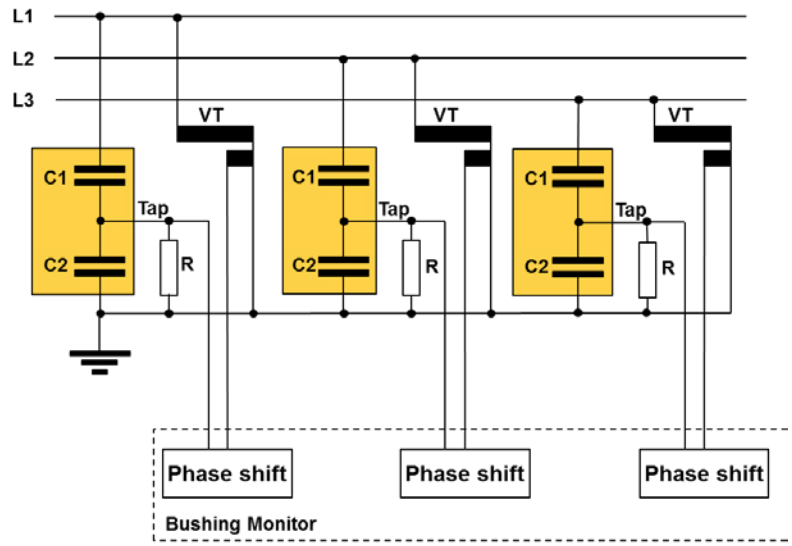

Figure 9: Principle of Reference signal method

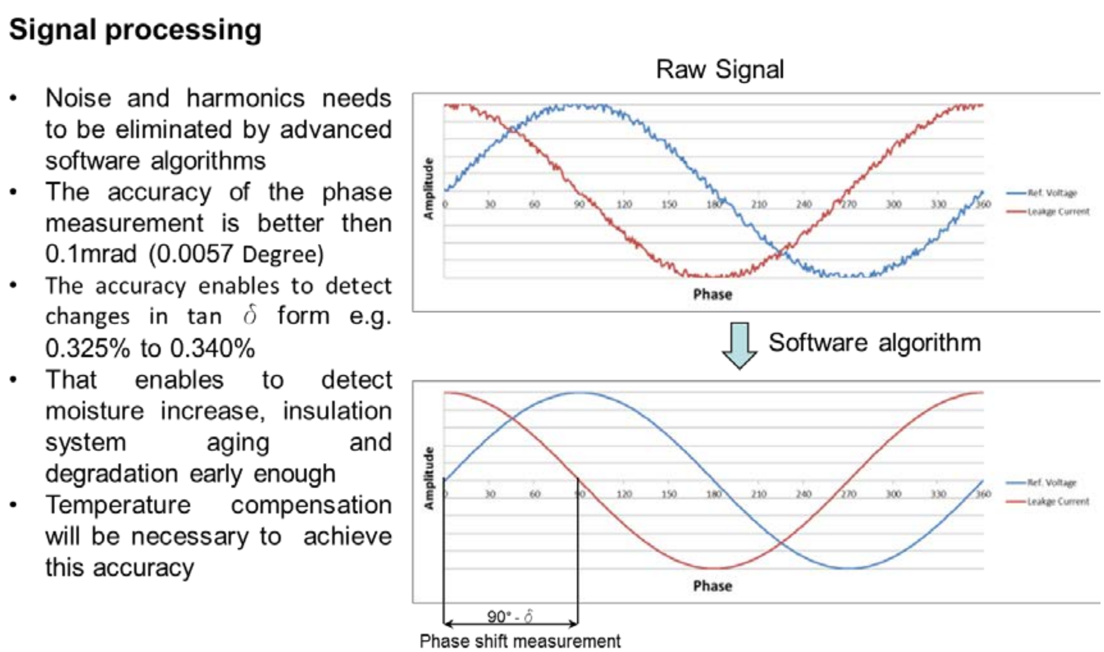

Figure 10: Example for effective noise elimination

The major challenges in using this 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 no VT's/CVT's at the high voltage side or they are far away in a separate switchyard (especially in Power Plants) or VT's/CVT's existing only for one phase (mostly the middle phase). A comparative monitoring in this cases can be applied, which then increases the inaccuracy of the system due to the comparison of different phases as described above. Alternative methods are under development.
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 10 shows a noisy signal before and after signal processing which is illustrating the efficiency of the noise elimination algorithm.

Conclusion

Measurements in utility lab, in a high voltage lab of a bushing manufacturer with real bushings and first results from onsite show that the accuracy of the Power Factor values measured/ monitored using this method are far better compared to the methods which compare bushing from different phase to each other. The results achieved in the lab showed even better results in stability and accuracy of the measured data than expected (less than 0.0057degree). This needs to be further verified over time for onsite installations.
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 small changes in Power Factor and also capacitance changes due to partial breakdowns between two capacitive layers even for bushings with voltage levels up to 1MV. This method can be used also for single phase transformers/reactors without limitations.
A further development will be a 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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