



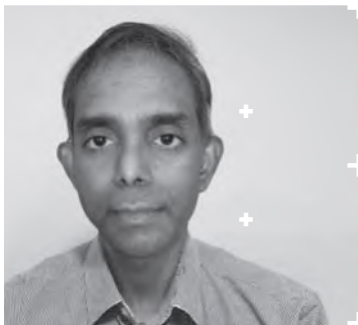
# The Truth About Accuracy in Online Capacitance and Power Factor Measurements on Bushings: Myths vs. Facts

by **Raja Kuppuswamy**

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A recent CIGRE survey shows that over two-thirds of the electrical utilities surveyed use limit criteria to replace bushings, which demands a measurement accuracy far better than the limit. However, it is widely unknown that the industry methods for online power factor and capacitance measurements do not always satisfy this because the accuracy is influenced by several factors that are beyond the realm of the instrument, including power quality, potential transformer usage related issues, practical constraints in implementation, and environmental effects. The focus of this article is to highlight these influences using theory and field observations and quantifying their effects on accuracy.

# An overwhelming percentage of electric utilities surveyed by CIGRE use limit criteria to replace bushings, which demands a measurement accuracy far better than the limit.



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## Introduction

Continuous monitoring of condenser bushings using the signal tapped from their measuring taps is practiced using several methods. The most common is the sum-of-currents method. Additionally, reference (absolute values) or comparison (relative values) methods are increasingly being used because of their perceived higher accuracy.

A recent CIGRE survey [1] shows that over three-quarters of the electrical utilities surveyed use limit criteria of one-percent change in power-factor or a five-percent change in bushing capacitance to replace oil-impregnated-paper (OIP) bushings, or they use both. Two-thirds use the same limit criteria to reject resin-impregnated-paper (RIP) bushings.

When the merits of one measurement method over another

are discussed in the industry, the comparison is primarily restricted to how power quality factors like harmonics and system voltage fluctuations influence the measurement accuracy and are often based on subjective and anecdotal observations. There is hardly any discussion of other factors that significantly influence the measurement accuracy, probably due to the lack of awareness.

Therefore, an attempt is made to focus on the fundamentals of each measurement method, the factors that influence the measurement accuracy, and to use examples to estimate the reduction in accuracy due to these factors. Due to space limitations, the focus is on the measurement methods widely used in the industry and the dominant factors that influence measurement accuracy.

## Concept of the Reference Signal Method

The concept of the reference signal method is shown in Figure 1. This method can be applied when a group of potential transformers (PTs) is available. The reference signal taken from the secondary side of the PT ( $V_S$ ) is compared with the same phase leakage current ( $I_B$ ) measured at the bushing measurement tap. The two signals must be time-synchronous to estimate the phase shift.

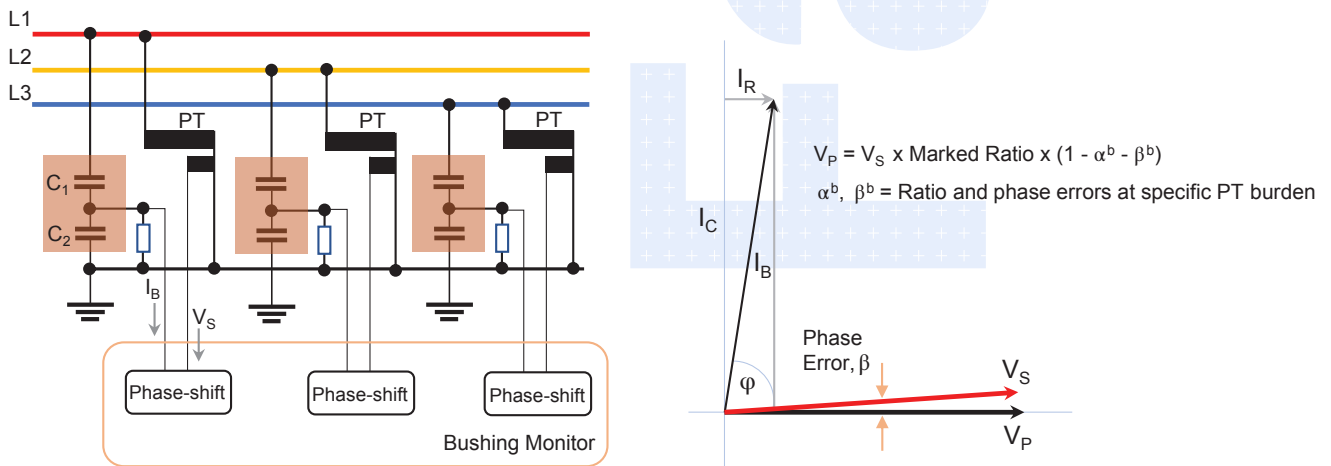


Figure 1. Bushing monitoring: Reference signal method

### Power Factor Calculation

The power factor is the cosine of the angle between the  $V_P$  and  $I_B$ , where  $V_P$  is the primary side voltage on the PT. Since measuring instruments typically handle a few volts as input,  $V_S$  is used instead of  $V_P$ . This compromise results in a small phase shift or phase error ( $\beta$ ) and a ratio error ( $\alpha$ ), as illustrated in Figure 1.

These errors are not fixed but depend on several factors, including the PT accuracy class, the length of the cable connected to the PT's secondary terminals, the temperature difference between the PT and the transformer tanks, and the additional burden on the PT caused by the bushing monitor.

The bushing power factor error can be approximated to  $\cos(\beta_b)$ ,  $\beta_b$  is the phase-error at the specific PT burden.

As an example, according to IEEE C57.113, the maximum permitted phase error for PT of class 0.6 (standard metering) is 30 minutes or 0.5 degrees. A phase error of 0.5 degrees results in a power factor error of +/-0.9%. That is almost twice the factory acceptance test limit of < 0.5% for OIP bushings and closer to the 1% limit criteria used by a very large percentage of utilities surveyed by CIGRE to change OIP or RIP bushings [1]. When absolute limits are used to change bushings, an error of +/-0.9% can cause a good bushing to be rejected and a bad bushing to be accepted.

**The accuracy of the reference signal method is severely limited by the accuracy class of the PT used, wye or open-delta connection, long secondary cables, and temperature.**

### Capacitor Calculation

The capacitance  $C_B$  of an HV bushing is calculated using the equation 1.

$$\left\{ \frac{I_B}{2 \cdot \pi \cdot f \cdot V_P} \right\} = \left\{ \frac{I_B}{2 \cdot \pi \cdot f \cdot V_S \cdot \text{marked PT Ratio} \cdot (1 - \alpha^b - j\beta^b)} \right\} \text{ (Equation 1)}$$

Where  $\alpha^b, \beta^b$  = Ratio, and phase errors with the specific external burden.

As an example, according to IEC C57.113, the limits for ratio correction factor for PT of class 0.6 is between 1.006 and 0.994, which equates to a 1.2% error in  $C_B$  calculation. This is an acceptable error for both OIP and RIP bushings below 550 kV because the change in bushing  $C_1$  capacitance due to a short in adjacent layers is above 1.2%.

A large percentage of utilities surveyed by CIGRE use +5% capacitance change from factory test values to change OIP or RIP bushings. An error of 1.2% can cause a good bushing to be rejected and a bad bushing to be accepted.

phases voltage reference is estimated from the remaining two phases where the PTs are available. The middle phase voltage is the vector sum of the voltages from the two outer phases. That means the magnitude and phase shift of the middle-phase reference voltage depend on the voltage and phase shift variations in the two outer phases. That introduces an additional error in power factor and capacitance calculations that varies dynamically with time.

### Other Factors That Can Influence the Accuracy of Measurements

#### Potential Transformers Available Only in Two Phases

It is common in the United States to use PTs only in two phases, as shown in Figure 2. The missing middle

#### Length of the PT Secondary Cable

If the cable from the PT secondary to the data-acquisition system input is very long, they may have sufficient impedance to introduce additional voltage drop and error. If it is of appreciable magnitude in percent of the secondary voltage, it will introduce other ratio and phase errors. The ratio and phase angle error may be calculated according to the vector diagram in Figure 3 and the equations 2 and 3.

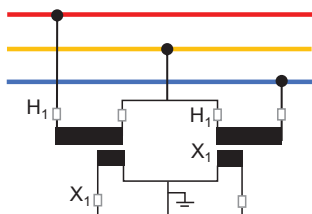


Figure 2. Open delta PT connection

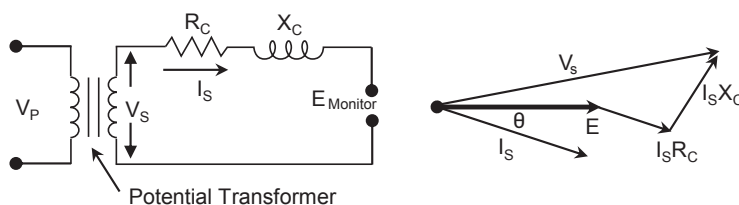


Figure 3. Equivalent circuit and phasor drawing

The percent ratio will be increased by the value in Equation 2, which must be added to the percent ratio of the PT to get the actual ratio.

$$\frac{I_s (R_C \cos \theta + X_C \sin \theta)}{V_s} \times 100 \text{ (Equation 2)}$$

The phase angle will be increased by the value in Equation 3, which must be algebraically added to the phase angle of the PT to get the actual phase angle.

$$\frac{I_s (R_C \sin \theta - X_C \cos \theta)}{V_s} \times 3438 \text{ minutes (Equation 3)}$$

The standard industry practice uses a coax cable of type RG58 [2] to run the PT's secondary voltage to the data-acquisition system. For example, let us estimate the different ratio and phase angle errors introduced by a 50 feet RG58 cable using only its dc resistance of 0.5 ohms and ignoring the inductance, which is negligible.

According to IEEE C57.113, the metering burden of 200 VA has a burden impedance of 72 ohms ( $I_s = 1.67 \text{ A}$ ). Considering only the resistive drop across the cable, per revised Equations 2 and 3, this translates to an additional ratio error of 0.7% and phase angle error of 0.4°. That causes an additional error of 0.69% on the power factor and 1.4% on the capacitance calculations.

The voltage drop across the secondary lead in percent of the secondary voltage is 0.7%. This value would violate the recommended total voltage drop in the secondary circuit, which must not exceed 0.1% for revenue metering.

### PT Burden

The ratio and phase errors of the PT vary with the external burden value connected to the PT's secondary terminals. It is very common in the industry to operate PTs at burdens different from the ANSI or IEC calibrated values. Therefore, the ratio and phase error values at a random burden ( $\alpha_b, \beta_b$ ) necessary to correct the measured capacitance and power factor are unavailable to the user which may lead to unpredictable errors in the power factor and capacitance calculations.

### The Temperature Difference Between Units

The reference signal method requires that the temperature inside the PT and the transformer tank is the same; otherwise, other errors in power factor and capacitance calculations will occur. Unfortunately, the temperature difference is unavoidable as PT operates at a fixed load, and the load on the transformer can fluctuate. During the transformer's operating range, the variation of capacitance for commonly used insulating materials in healthy bushings is between 0.03% and 0.05% per degree Celsius, and power factor variation is >0.1% per 20°C [1]. If the bushing is wet or aged, then the variations in capacitance and power factor with temperature are unpredictable.

Assuming the bushing is healthy and the relative temperature difference between the PT and the transformer tanks is 25°C, the capacitance and power factor changes are respectively >1% and >0.1%.

The summary of all the dominant influences on the accuracy is shown in Table 1. The total measurement error is a summation of the errors in columns 2 to 4, which can easily exceed 2%.

### Concept of the Sum-of-currents Method

The concept of the sum-of-current method is shown as a block diagram in Figure 4. During commissioning, the indicator is balanced to zero. The balancing circuit's purpose is to balance out the minor variations in bushing capacitance and power factor, which can be present if they are of the same type and manufacturer. As the insulation ages, one bushing will eventually begin to age faster than the other two. The leakage current and the phase angle in one of the phases will also change, and the indicator will no longer read zero. The amplitude of the change reflects the severity of the problem, and the phase angles indicate which phase is experiencing the problem.

Diagnostic parameter	OIP & RIP bushing replacement limit per survey [1]	PT on all 3 phases (wye connection)	For PT with 50 ft secondary lead	The temperature difference between the PT & transformer tank
	[Col. 1]	[Col. 2]	[Col. 3]	[Col. 4]
Power-factor / Tan delta in %	> 1%	Min. ± 0.9%	0.70%	~0.3 to 0.5% / 10°C
Capacitance	> +5% of FAT	Min. ± 1.2%	1.40%	>0.1% / 20°C

Table 1. Summary of dominant influences on the reference signal method accuracy

**Temperature difference of 25°C between the PT and the transformer tank causes a significant error in power factor measurements.**

The change can be approximately represented by the Equation 4 under the assumption of a single defective phase.

$$\gamma = \frac{\Delta I}{I_0} \approx \sqrt{(\Delta \tan \delta)^2 + \left(\frac{\Delta C}{C_0}\right)^2} \quad (\text{Equation 4})$$

$\gamma$  - parameter Gamma or imbalance  
 $\Delta \tan \delta$  - tangent delta change  
 $\Delta C/C_0$  - relative change in bushing capacitance

Equation 4 tracks relative changes in power factor and capacitor from a base value, typically their offline test values.

### Influence of Voltage Unbalance

System voltage unbalance is one of the main contributors to the method accuracy. Voltage unbalance is a condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120° phase relationship or both.

A variation in system voltage creates an unbalance and may be interpreted as capacitance or power factor change. Magnitude variation may be interpreted as capacitance change and phase shift changes as power factor.

Accounting for the influence of the voltage unbalance effects on the capacitance and power factor, Gamma's equation can be rewritten as Equation 5, assuming a change in one phase again.

$$\gamma = \frac{\Delta I}{I_0} \approx \sqrt{(\Delta \tan \delta + \Delta \phi)^2 + \left(\frac{\Delta C}{C_0} + \frac{\Delta V}{V_0}\right)^2} \quad (\text{Equation 5})$$

$\Delta \phi$  - change in phase shift  
 $\Delta V/V_0$  - relative change in system voltage

**Field measurements across multiple U.S. sites reveal that errors in power factor and capacitance measurements due to asymmetric voltage variations are <1%.**

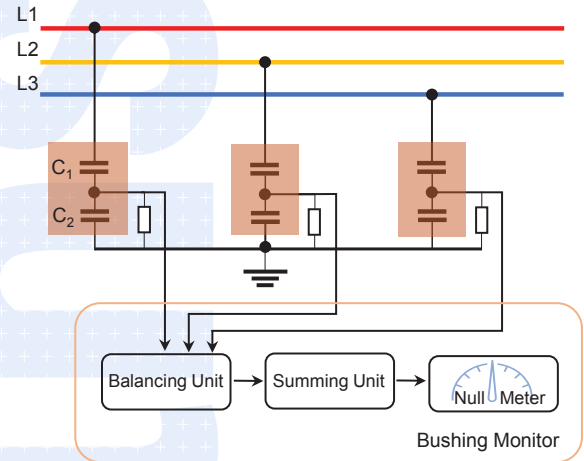


Figure 4. Bushing monitoring: Sum-of-currents method

For changes in all phases, the equation must use vector summations. Gamma reacts only to asymmetric changes in the system voltage. All symmetric voltage changes will compensate each other (the same increase of all voltage magnitudes, for example, will not disturb the balance).

Therefore, the method's accuracy depends on the statistics of the asymmetric voltage variations in the location.

### Field Study on the Effects of Voltage Unbalance

To study voltage unbalance effects, continuous measurements were performed at four locations across the United States for 6 to 8 weeks. At Location 1, three single-phase

transformers were in a three-phase bank with the bushing in each phase of different make and age. The initial power factor difference between the bushings was about ten percent. This example represents the worst-case scenario for any bushing monitoring method. At the remaining locations, the transformer type and bushing voltage ratings were chosen to represent normal configurations.

Table 2 is a statistical summary of the phase shifts estimated from units in four locations. Due to space limitations, the nameplate information of the transformers and bushings are not shown but can be found in [3].

During the field studies [2], the gamma value was <0.5% for Locations 2 to 4 and <0.8% for Location 1.

### Estimating the Accuracy of Power Factor and Capacitance Measurements

Assuming the dataset follows the normal distribution, the mean plus two standard deviations represent 95<sup>th</sup> percentile values. 95<sup>th</sup> percentile for phase shift was <0.4°. This means 95% of data points are below 0.4°.

An exception was Location 1, a particular case where the unit was installed on a bank of three single-phase transformers where the make, model, and age of the bushings on all the three phases were different: for example, the bushing nameplate capacitance of phases A and C were 470 and 543 picofarads, respectively.

	Unit #1 Loc. #1		Unit #2 Loc. #2		Unit #3 Loc. #3		Unit #4 Loc. #4	
Phase-pair	A - B	A - C	A - B	A - C	A - B	A - C	A - B	A - C
Average	0.10°	0.41°	-0.24°	-0.04°	-0.02°	-0.12°	-0.10°	-0.10°
Standard deviation	0.06°	0.06°	0.04°	0.04°	0.12°	0.11°	0.11°	0.10°

Table 2. Statistical summary of a field study on the effects of voltage unbalance

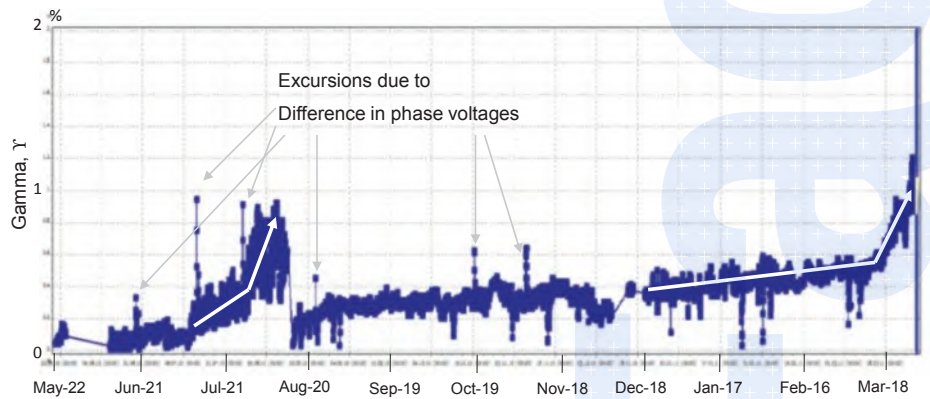


Figure 5. Illustration of the influence of system voltage fluctuations while monitoring a 230 kV bushing

A phase shift of 0.4° represents an error of +/-0.7% in power factor calculation. If Location 1 is excluded, the phase shift drops to <0.2°, and the error in power factor calculation reduces to +/-0.35%. That is well below the 1% limit used in the industry to replace OIP and RIP bushings.

During the field studies [2], the gamma value was <0.5% for Locations 2 to 4 and <0.8% for Location 1. 95<sup>th</sup> in Figure 5, which confirms this observation. During the entire 11-month period, the asymmetric changes in the system voltage were less than 0.85 (γ<1).

For a hypothetical case of a purely capacitive type defect (short-circuited adjacent layers for capacitively graded bushings), Equation 5 can be rewritten as

$$\gamma^2 = 1 = \left( \frac{\Delta C}{C_0} + \frac{\Delta V}{V_0} \right) \quad (\text{Equation 6})$$

For ΔV/V<sub>0</sub> of 0.01 or 1%, the relative change in bushing capacitance from

the initial value (ΔC/C<sub>0</sub>) is 1%. In other words, a one percent asymmetrical change in system voltage causes a one percent change in relative capacitance calculation. The results are summarized in Table 3.

### Influence of Temperature

The temperature has minimal effect on the results because, on a three-phase transformer, all the bushings are affected nearly the same way by the heat source, which is the top oil of the transformer.

It is worth mentioning that when evaluating changes in the bushing power factor and capacitance, using the bushing nameplate values must be avoided. This applies to all online methods of bushing capacitance and power factor. Nameplate values are established during the factory acceptance testing of bushings with the bushings tested in a tank different from the transformer tank's size and geometry. A recent report published by HSP [4] reports a variation of 5% to 7% between the nameplate bushing

Diagnostic parameter	OIP & RIP Bushing replacement limit per [1]	All three bushings inside the same transformer tank	Influence of temperature
Power factor / Tan delta (%)	> 1%	± 0.70%	Negligible
Capacitance	> +5% of FAT	± 1.00%	Negligible

Table 3. Summary of dominant influences on sum-of-current method measurement accuracy

capacitance and the capacitance measured after the bushing was mounted on the transformer. This means it is more prudent to use offline capacitance test values from the bushing or transformer site commissioning report as a reference when diagnosing the bushing condition.

### Comparison Method – Transformer to Transformer Comparison

This method can be applied when two twin transformers are close to each other and connected in parallel, as shown in Figure 6.

HV bushings installed on the same phase are compared against each other using the capacitive leakage currents,  $I_{A1}$  and  $I_{A2}$ , measured at their taps. Before starting the test, offline test values of power factor and capacitance must be available for all bushings.

### Power Factor Calculation

At the start of the test, both bushings' online power factor is assumed to be the

same as their offline values,  $\cos \phi'_1(\text{online}) = \cos \phi_1(\text{offline})$ . It is worth mentioning that the bushing power factor depends heavily on temperature, and this assumption may not always be valid.

Next, the online power factor angles for the two bushings are estimated and the difference is established, as in Equation 7.

$$\Delta\theta = \phi'_2 - \phi'_1 \text{ (Equation 7)}$$

As the bushings are not identical, the angle  $\Delta\theta$  will not be zero. Furthermore, if the two bushings age similarly,  $\Delta\theta$  will remain constant. This means that if the rate of aging is the same for both bushings, aging effects cannot be detected.

The angle  $\Delta\theta$  is calculated during the initial learning phase and is taken as a reference value. This value is compared with the online values determined throughout the lifetime of the bushings,  $\Delta\theta'$ . Considering that the power factor angles,  $\phi'_1$  and  $\phi'_2$ , get worse with time, we can state the following:

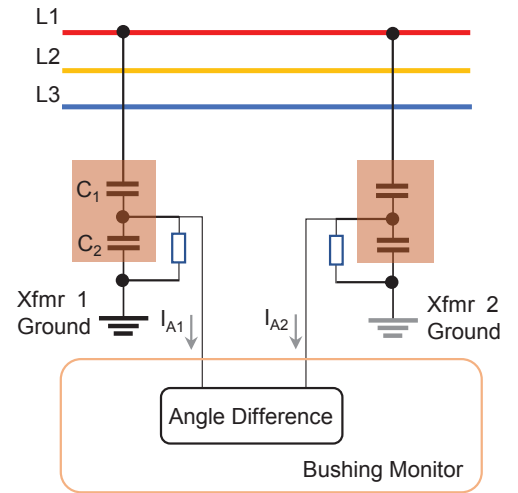


Figure 6. Bushing monitoring: Comparative signal method (two bushings in two separate tanks)

$\Delta\theta > \Delta\theta'$  - showing the degradation of the Bushing 1  
 $\Delta\theta < \Delta\theta'$  - showing the degradation of the Bushing 2



**The comparison method of bushing monitoring assumes that the online power factor and capacitance test values are the same as their offline values at the start of the test.**

## Capacitor Calculation

The capacitance of HV bushings is calculated with the Equations 8 and 9.

$$I_{A1} = 2 \cdot \pi \cdot f \cdot C_{A1 \text{ offline}} \cdot V_1 \equiv V_1 = \frac{I_{A1}}{2 \cdot \pi \cdot f \cdot C_{A1 \text{ offline}}} \quad (\text{Equation 8})$$

$$C_{A1 \text{ online}} = \frac{I_{A1}}{2 \cdot \pi \cdot f \cdot V_1} \quad (\text{Equation 9})$$

$V_1$  is the voltage on the terminals of the two-phase A bushings connected in parallel.  $C_{A1 \text{ offline}}$  is the capacitance of the bushing A from transformer 1. Similarly, using Equations 8 and 9, the online capacitance values for all remaining bushings are calculated.

A change in the capacitive leakage currents measured at the taps indicates a change in the bushings' capacitance. The system voltage variations do not affect the

measurement since both bushings are affected in the same way by these variations. The bushings diagnosis is made based on the difference between the capacitance values determined in the offline and online mode,  $\Delta C$ . This quantity ( $\Delta C$ ) must remain within certain limits.

## Influence of the Ground Potential

The bushing monitor is usually mounted on one of the two twin

transformers, separately grounded, and the bushing monitor shares one of the grounds. If there is a difference in the grounding potential between the two transformer grounds, it will cause an additional noise current to flow, as shown in Figure 7, and can cause unpredictable phase errors.

The primary cause for the difference in the ground potential is the electromagnetic field interference from the overhead electric power lines that produce induced voltages on the metal structures like transformers. These are unavoidable and unstable situations that can change by the minute.

During monitoring a bank of three single-phase transformers, our field measurement shows that a typical difference in the ground potential between two transformer grounds is in the range of 100 mV to 300 mV. If the grounding is defective or electromagnetic interference is higher than usual due to the transformer's proximity to the overhead power lines, the differences can be higher. We had one such case on two 100 MVA autotransformers standing next to each other at a 230 kV substation (outside North America), where the difference was a little over a volt.

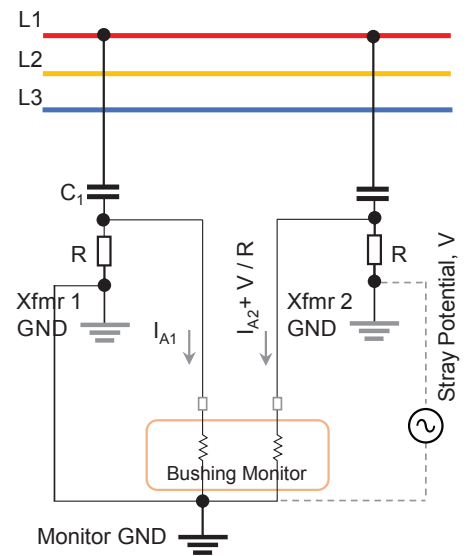


Figure 7. Influence of the ground potential

For a bushing  $C_1$  capacitance of 500 pF, the terminal voltage of 345 kV, and sensor impedance of 2000 ohms, the noise current would be 0.3% of the test-tap current. According to Equation 9, this would result in an error of 0.3% in the capacitance measurements. Assuming that an amplitude change of 0.3% causes a phase shift of 0.3 degrees, the error in power factor measurements would be 0.5%.

## Influence of Harmonics

In our discussions, odd harmonics alone are relevant as even harmonics only appear when there is no half-wave symmetry in the power frequency cycle. Harmonics affect all measurement methods, and the measurement accuracy is heavily dependent on the technology used in the instrument for suppressing them. That also applies to offline bushing power factor and capacitance measurements, and its measurement accuracy is also questionable.

The traditional definition of power factor, which holds only for a pure sine wave, is the cosine of the phase difference between fundamental frequencies of voltage and current and calculation based on the time

displacement of current and voltage waveforms. The actual power factor is the ratio of active power used and apparent power, and higher than the power factor calculated using the time displacement method. This underestimation of the power factor results in accuracy loss.

Capacitance calculation uses frequency (see Equation 1), typically estimated from the bushing leakage current waveform using the principle of zero cross detection, as illustrated in Figure 8.

Suppose the sine wave has several high-frequency harmonics. In this case there will be multiple zero crossings near the actual zero crossings of the AC signal, and the error in frequency calculation will directly influence the measurement accuracy.

## Closing Notes

Over two-thirds of electrical utilities surveyed by CIGRE replace OIP and RIP bushings when their power factor exceeds an absolute limit of one percent. This demands a measurement accuracy below half a percent to avoid false positive or negative results.

The review of the three popular practices for the online bushing power factor and capacitance measurements shows that none of the three can guarantee accuracy under half a percent for all situations. Therefore, the industry must use alternate metrics to evaluate power factor changes in bushings.

The extent of the change in bushing  $C_1$  capacitance reflects the number of short-circuited layers in the total number of grading layers in the bushing core. Most bushing manufacturers recommend at least a 3% change in the  $C_1$  capacitance value from the factory acceptance test even to start an investigation. That demands a minimum measurement accuracy of  $\pm 1.5\%$  in the bushing  $C_1$  capacitance, and only some methods can meet this condition under certain situations. A study by HSP [4] reports that stray capacitance can significantly influence the bushing  $C_1$  measurements, which must be accounted for when investigating the capacitance changes in a bushing.

Using a potential transformer in the reference signal method leads to additional loss in the measurement accuracy. In certain conditions, as elaborated in the article, the measurement accuracy can be even worse than with other methods.

The field measurements across multiple sites in the United States show that the system voltage variations between phases are less than one percent. Its effect on the accuracy of the power factor and capacitance measurements using the sum-of-currents method is within one percent. Even if these variations were to double, the accuracy is within the accuracy of the other methods.

In sum, multiple factors influence the accuracy of bushing capacitance and power factor measurements, and no discussed method has a specific advantage over another.

Our experience in monitoring RIP and RIS bushings shows that their time to failure is relatively shorter than that of OIP bushings after a

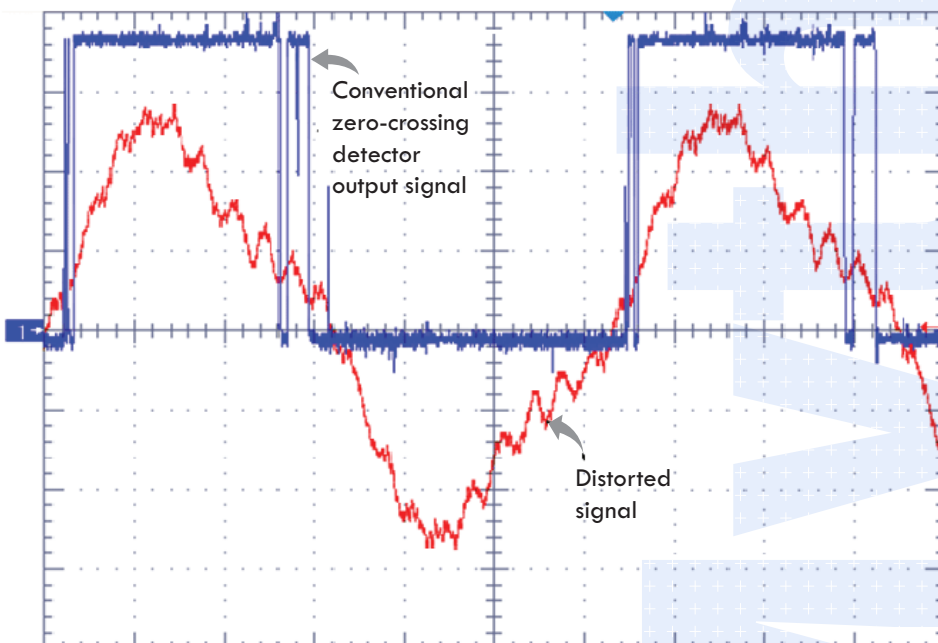
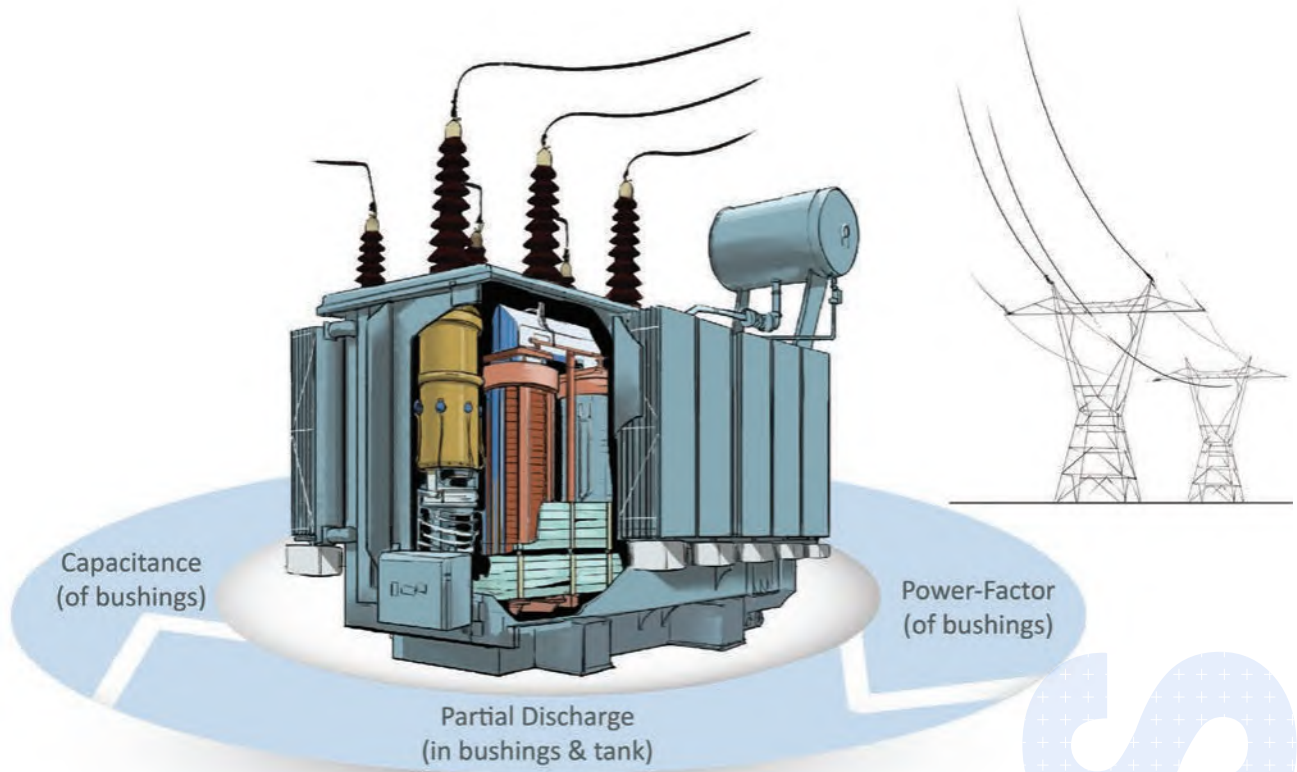


Figure 8. Influence of harmonics (used with a written permission from the authors [5])

measurable increase in  $C_1$  capacitance has occurred. Therefore, it would be beneficial to invest in complementary techniques to monitor bushings. Also, our experience in monitoring bushings using the traditional partial discharge (PD) measurement method shows

that this method identifies developing problems in the bushing core relatively earlier than the bushing  $C_1$  capacitance measurement method. A common misconception is that sensitive online PD measurements cannot be performed, and incorrectly based on

comparison to PD levels measured in the factory. Our experience in PD monitoring, having monitored over a thousand of bushings, reveals that defects inside bushings have PD amplitudes in hundredths and thousands of pico-coulombs.



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**Multiple factors influence the accuracy of the bushing capacitance and power factor measurements, and no method has a specific advantage over any other. Therefore, it would be beneficial to invest in complementary techniques to monitor bushings.**