

# On-line Monitoring System for Dielectric Loss of Capacitive Bushing Considering Harmonic Effects

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**Abstract.** The existence of harmonic waves may cause some errors during measurement of dielectric loss, thus hindering accurate evaluation of insulation. By taking the influence caused by harmonic waves into consideration, this article introduces an approach which may achieve higher accuracy in the calculation of dielectric loss. Calculation results show that harmonic components and orders of harmonic waves may have big impact on dielectric loss. This article also develops a dielectric loss on-line monitoring system based on bus, which can fulfill tasks including signal conditioning, data acquisition and conversion, upper computer communication and data transmission. This system uses A/D conversion controlled by industrial computer to implement remote communication and synchronous sampling of harmonic waves and is able to improve accuracy of dielectric loss under the influence of high order harmonics, therefore, make accurate on-line evaluation of equipment's insulative conditions.

## 1. Introduction

As important electrical equipment in power systems, transformers' insulation performance is directly related to the reliability and security of power supply. As an important part of transformer, capacitive bushing failure accounts for more than 40% of transformer faults [1]. Dielectric loss could show insulative conditions of capacitive equipment with high sensitivity. Therefore, on-line monitoring of dielectric loss for capacitive bushing could identify potential insulative defects and could be of great significance in ensuring secure and stable operation of electrical equipment.

The increasing number of nonlinear devices may generate great amount of harmonic waves which may cause additive power loss during transmission and reduce power transmission capacity of power transmission lines. The existence of harmonic waves could result in large errors in dielectric loss on-line monitoring, thus rendering it invalid to use dielectric loss factor as a comprehensive index to reflect the insulative performance of capacitive equipment [2-3]. This article therefore purposes a method which can measure dielectric loss on-line and find potential defects of electrical equipment by improving the measurement accuracy in the case of large amount of harmonic waves.

## 2. Considering the effect of harmonic on dielectric loss

In this paper, a method for calculating dielectric loss of capacitive bushings under the influence of harmonics is proposed and applied, which could improve the accuracy of the on-line monitoring system for dielectric loss under the influence of harmonics. Normally, harmonics in the power system



can be regarded as a series of harmonic components composed of sinusoidal waves of different frequencies, that is, the fundamental wave at 50Hz superimposed with integer multiples of 50Hz.

In a balanced three-phase system, even harmonics have been eliminated due to the symmetry, leaving only odd harmonics like the 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup> to exist. Taking the system containing only the 3<sup>rd</sup> harmonic as an example, this paper introduces the calculation method of dielectric loss of capacitive bushing considering the influence of harmonic. The dielectric loss of the insulating medium includes conduction loss and polarization loss. Conduction current is excited under both DC and AC electric field [4]. If a sinusoidal alternating electric field  $E = E_m e^{i\omega t}$  is applied, the total current density through the relaxing medium is shown in (1):

$$j = j_a + j_c = \left( \gamma + \frac{\omega^2 \tau \Delta \varepsilon}{1 + \omega^2 \tau^2} \right) E_m e^{i\omega t} + i\omega \left( \varepsilon_\infty + \frac{\Delta \varepsilon}{1 + \omega^2 \tau^2} \right) E_m e^{i\omega t} \quad (1)$$

$j_a$ —Active power component of current density;

$j_c$ —Reactive power component of current density;

When the frequency of the alternating electric field applied to the medium increases to a level where the change of the relaxation polarization lags behind the change of the electric field, the electrical displacement of the dielectric lags the electrical field by a phase angle  $\delta$ . At this point  $\varepsilon$  needs to use the plural form, that is, the complex permittivity  $\varepsilon^*$ :

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \quad (2)$$

$$\varepsilon' = \varepsilon_\infty + \frac{\Delta \varepsilon}{1 + (\omega \tau)^2} \quad (3)$$

$$\varepsilon'' = \frac{\gamma}{\omega} + \frac{\omega \tau \Delta \varepsilon}{1 + (\omega \tau)^2} \quad (4)$$

The tangent of the dielectric loss angle can be expressed as below (5):

$$\tan \delta_k = \frac{\varepsilon''}{\varepsilon'} \quad (5)$$

Equations (3)-(5) above are called Debye Equation.

$$\varepsilon_\infty = \varepsilon_0 n^2 \quad (6)$$

$$\Delta \varepsilon = \varepsilon_s - \varepsilon_\infty \quad (7)$$

$\tan \delta_k$  indicates the dielectric loss corresponding to the k-th harmonic alone.  $\varepsilon^*$  is a function of frequency and temperature. To simplify calculation, this article assumes the temperature to be constant at 20°C and focuses only on the relationship between dielectric loss factor and frequency. In (2)-(7),  $\varepsilon'$  is the real part of the complex permittivity, which is related to the reactive component of the current density  $j_c$ .  $\varepsilon''$  is the imaginary part of the complex permittivity and is related to the active component of the current density  $j_a$ .  $\gamma$  is the conductivity of the dielectric,  $\tau$  is the relaxation time of the insulating medium, and  $\varepsilon_\infty$  is the dielectric constant of the dielectric when the frequency verges to infinity. It is close to the dielectric constant under the optical frequency.  $n$  is the refractive index of the material.  $\varepsilon_s$  is the static dielectric constant and is taken as a relative dielectric constant value.

The two frequencies  $\omega$ ,  $3\omega$  are substituted into the Debye equation, respectively. Then the values of the two dielectric loss factors  $\tan \delta_1$ ,  $\tan \delta_3$  under the decomposition of the fundamental and 3rd harmonics are calculated respectively. The refractive index  $n$ , vacuum dielectric constant  $\varepsilon_0$ , relative dielectric constant  $\varepsilon_r$ , conductivity  $\gamma$  and relaxation time  $\tau$  of the insulating medium can be obtained by consulting related literatures. it is also assumed that the phases of the fundamental wave and the third harmonic are both zero. Consider the 3rd harmonic content to be 5%, that is,  $U_3 = 0.05 U_1$ .

The expression of the dielectric loss of the dielectric at the fundamental voltage is given by (8):

$$P_1 = \omega U_1^2 C \tan \delta_1 \quad (8)$$

For the circumstance of the 3rd harmonic voltage, the dielectric loss of the dielectric expression is shown in (9):

$$P_3 = 3\omega U_3^2 C \tan \delta_3 \quad (9)$$

Considering the 3<sup>rd</sup> harmonic only, the total dielectric loss ( $P_{to}$ ) expression of the capacitive device is shown in (10):

$$P_{to} = P_1 + P_3 \quad (10)$$

Therefore, the sum of the dielectric loss  $P_1$  and  $P_3$  indicates the total dielectric loss under the combined influence of the fundamental wave and the third harmonic. According to the fact that total dielectric loss is equal,  $P_{to}$  can be taken into (11) to obtain an equivalent dielectric loss factor  $\tan \delta'$  when harmonics are present. In (11) the frequency is the fundamental frequency, and the voltage is calculated using the effective value  $U_{eq}$  of the harmonic voltage, which can be obtained by (12). Figure. 1 shows the flow chart for calculating the dielectric loss factor considering the effect of harmonics.

$$\tan \delta' = \frac{P_{to}}{\omega U_{eq}^2 C} \quad (11)$$

$$U_{eq} = \sqrt{U_1^2 + U_3^2} \quad (12)$$

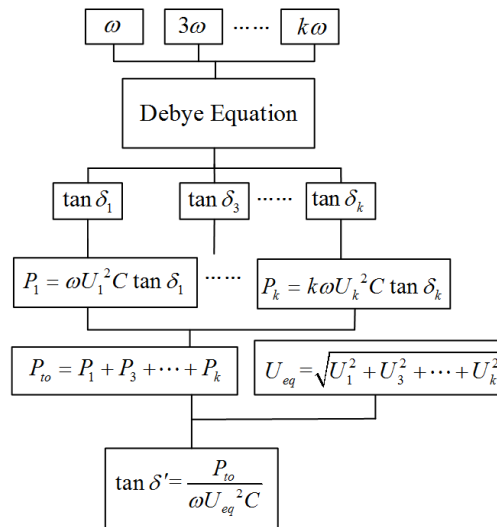


Figure 1. Flow chart for calculating dielectric loss factor under harmonic conditions.

Taking resin impregnated paper bushing as an example, the electrical parameters related to epoxy resin are shown in Table 1. The values of  $\tan \delta'$  under the circumstances of various single harmonics (that is, for the waveform that only contains fundamental and 3rd or 5th or 7th harmonic) are calculated respectively. The calculated value of  $\tan \delta_1$  without any harmonic is  $4.4008 \times 10^{-3}$ .

Table 1. Related electrical parameters of epoxy resin.

Physical quantity /symbol	Parameter (units)
refractive index /n	1.55
vacuum dielectric constant / $\epsilon_0$	8.854e-12 (F/m)
relative dielectric constant / $\epsilon_r$	4.5
conductivity / $\gamma$	1e-13 (S/m)
relaxation time / $\tau$	3e <sup>-5</sup> (s)

Table 2. Calculation results of  $\tan\delta'$  under different harmonic content.

Harmonic content	3rd harmonic $\tan\delta' (\times 10^{-3})$	5th harmonic $\tan\delta' (\times 10^{-3})$	7th harmonic $\tan\delta' (\times 10^{-3})$
1%	4.404	4.411	4.422
2%	4.415	4.443	4.485
3%	4.432	4.496	4.590
4%	4.457	4.569	4.737
5%	4.488	4.663	4.925

It can be seen from Table 2 that the presence of harmonics may have some negative influence on measurement of dielectric loss. To be more specific, the error increases with higher content of harmonics. Table 2 also suggests that the harmonic frequencies have more obvious effect on the dielectric loss than the harmonic content—a large amount of high harmonics could seriously affect the accuracy of on-line monitoring of dielectric loss of capacitive bushing. The error of dielectric loss caused by harmonics cannot be ignored. Therefore, the influence of harmonic voltage must be considered, especially for higher harmonics.

### 3. Applications of the on-line monitoring system

For the on-line monitoring system for dielectric loss of capacitive bushing considering harmonic effects, a bus-based on-line monitoring device of dielectric loss is developed. The on-line monitoring device includes signal conditioning, data acquisition and conversion, upper computer communication and data transmission [5-6]. This device could also be compatible in on-line monitoring system of power station insulation based on bus.

Based on the above research method, we developed an on-line monitoring system for dielectric losses based on bus-module that considers harmonic effects. Figure 2 shows the composition of the dielectric loss online monitoring system. Terminal unit converts the current signals and voltage signals into digital signals. Device SC is the signal converter between RS485 and RS232. Industrial computer serves as the head of system. The on-line dielectric loss monitoring system can comprehensively process the state data collected from the front end, display the value for dielectric loss, and provide human-computer interface. The monitoring system can improve the accuracy of dielectric loss measurement under the influence of harmonics, and conduct accurate on-line assessment of the insulation status of electrical equipment.

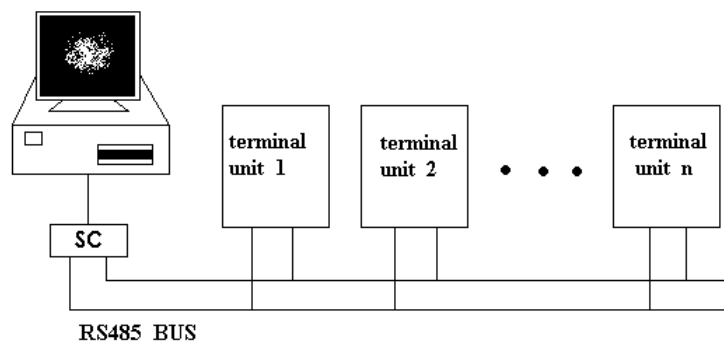


Figure 2. Dielectric loss on-line monitoring system.

During the application of dielectric loss on-line monitoring system and fault diagnosis, not only characteristic values of harmonic parameters need to be extracted, but the synchronized relationships between frequency, harmonic content and dielectric loss of different harmonics also need to be ensured to guarantee the accuracy of dielectric loss calculation. In a distributed control system, the front data

acquisition units are separated from each other, which makes it difficult to ensure synchronization of collected data, thus making the following data processing complicated and inaccurate. In the light of this problem, the upper computer is used to control the start time of each data acquisition units' A/D and interval between each samples, which may ensure the synchronization of each front data acquisition unit. In order to solve the synchronization problem, industrial computer control the A/D conversion were applied [7-8]. This system therefore has remote signals simultaneous measurement, remote adjustment, remote communication, real time data showing, data analysing and storage functions. Terminal unit's software flow chart is shown in Figure 3.

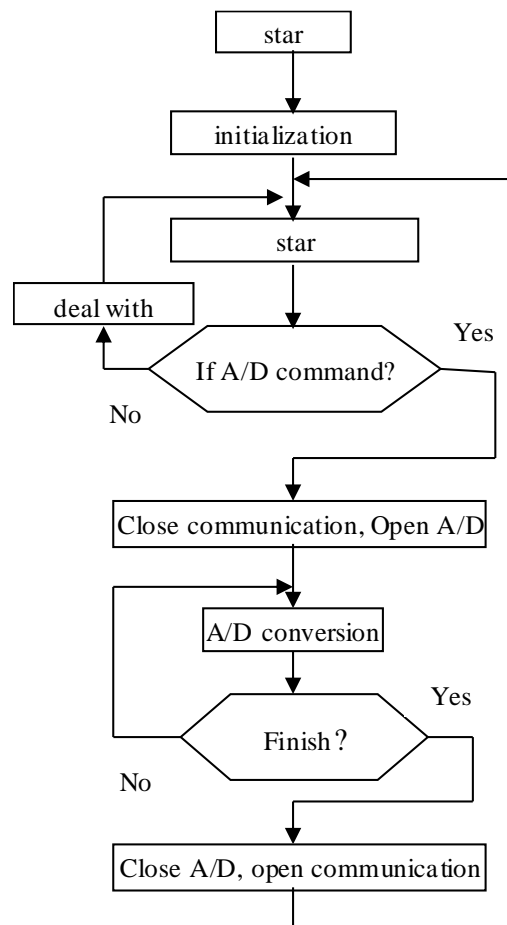


Figure 3. Terminal unit's software flow chart.

#### 4. Conclusion

In this paper, a method for calculation of dielectric loss considering the influence of harmonics is proposed, which can effectively avoid the error of measuring the loss of medium caused by harmonics and improve the accuracy of measurement. Calculation shows the existence of harmonics may have important influence on the measurement of dielectric loss. It has been found that error increases with higher harmonic contents. Compared with harmonic contents, the influence caused by the frequency of harmonics is of greater significance, thus large amount of higher harmonics may have major impact on the accuracy of the dielectric on-line monitoring system. This article also presents a bus-based dielectric loss on-line monitoring system which can complete various functions including remote signals simultaneous measurement, remote adjustment, remote communication, real time data showing, data analyzing and storage. This monitoring system can improve accuracy of measurement for dielectric loss and conduct accurate evaluation of insulative statues of equipment.

### Acknowledgments

The authors would like to acknowledge gratefully the financial support of the technology project of State Grid Corporation of China (No.520101180007).

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