Effects of Spike Voltages Coupling With High $dV/dt$ Square Wave on Dielectric Loss and Electric-Thermal Field of High-Frequency Transformer

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ABSTRACT The insulation of high-frequency transformers (HFTs) has a significant impact on the safety and reliability of high voltage power electronic transformers (PETs). The transient voltages from the rapid turn-off and turn-on of the high voltage power semiconducting device increase the insulation stress and loss, resulting in thermal stress distortion. However, few studies have presented an accurate evaluation of the dielectric loss, especially under high $dV/dt$ square waves. This paper focuses on the dielectric loss calculation in HFT insulation by analyzing the loss from a high-frequency square wave with spike voltages. A step function that is equivalent to spike voltage superposition is proposed for the quantitative calculation of the dielectric loss of epoxy resin. A cutoff frequency ($f_c$) is defined to indicate high $dV/dt$ characteristics. A similar narrow step function is used for simulating spike voltage at the rising/falling edge. The additional dielectric loss increases with the spike voltage and the duration. The electric field and temperature distributions are simulated in a 10 kW, 10 kHz HFT by considering the calculation of dielectric loss. The spike voltages enhance the electric field and temperature in the insulation. The increase in the external temperature (close to the glass transition temperature ($T_g$) of epoxy resin) causes a significant increase in the insulation temperature. This paper is of great importance to the design and application of HFT insulation.

INDEX TERMS High-frequency transformer, dielectric loss, square wave, spike voltage, cutoff frequency, FEM.

I. INTRODUCTION

A high-frequency transformer (HFT) is a key component in power electronic transformers (PETs) [1], [2], which can be used for power transfer, electrical isolation, voltage conversion, and impedance matching. The typical working stresses in HFTs are dominated by the PET structure and external conditions [3], [4]. The transient voltages with a square waveform in the windings of the HFT are caused by the fast turn-off and turn-on of the power semiconducting device. In addition, a high spike voltage occurs at the rising edge of a square waveform (high $dV/dt$) because of stray parameters, such as leakage inductance and distributed capacitance [5]. Moreover, high orders of harmonics are also superposed on the transient winding voltages, causing mix-frequency electric stresses in the HFTs [4]. These multi frequencies and high $dV/dt$ voltages increase the electric and thermal stress of the insulation system in the HFTs [6]. It is reported that the insulation system of the HFTs under spike voltages with high $dV/dt$ voltage could be degraded significantly compared with that of power frequency transformers [7]. High-frequency voltage can decrease the breakdown strength ($E_b$) of the insulating material, and the $E_b$ (8 kHz) can be reduced by 17% compared with that of low frequency (500 Hz) [8]. Furthermore, the high temperature from the magnetic core and winding losses under multi-frequency stress by high
$dV/dt$ and spike voltages can enhance the partial discharges of the insulation in the HFT. Consequently, it leads to the degradation of the insulation system of the HFTs [9].

Compared with the losses of the magnetic core and winding, the dielectric loss of the HFT usually has a low proportion. However, it increases significantly under high electric stress, high frequency, and high temperature [10]. Consequently, the lifetime of the insulation system can be reduced [11]. The insulating material, voltage waveform, and working temperature affect the dielectric loss. It has been reported that insulation loss mainly depends on voltage amplitude, switching frequency, and material parameters [12]. An impact on the dielectric loss was obtained by the duty cycle and the modulation index of PWM voltages. Furthermore, multilevel inverters present a low dielectric loss. When considering the harmonics and PWM voltages, the dielectric loss can reach a significant share (17%) of the total transformer losses [2].

It is accepted that the magnetic loss depends on the waveform and frequency of the electric stress [3], [13]. It is similar to dielectric loss. Currently, a dielectric polarization effect under high frequency with non-sinusoidal voltage has been discussed in HFT insulation [2]. The simulation of multiphysical fields in an HFT considering parasitic parameters was studied in previous works [2], [14]–[16]. The results indicated that the loss calculation of the transformer is more accurate when considering the distribution of multiphysical fields in the transformer. However, the calculation of dielectric loss under a square wave with high $dV/dt$ peak voltages is still lacking. The focus should be on the electric-thermal field under such types of stresses.

Improvements in the dielectric and thermal performance of epoxy resin have been studied by incorporating nanofillers [17]. Incorporating a slight amount of graphene fillers ($<0.3$ wt%) enhanced the thermal stability and the dielectric properties of epoxy materials [18]. The PVC/TiO$_2$ nanocomposites indicated that the dielectric loss ranging from 20 to 1.0 MHz can be decreased by surface modification of TiO$_2$ nanofillers [19]. These studies play important roles in the dielectric and thermal performance of epoxy insulation for application in HFTs.

In this article, the analysis and calculation of the dielectric loss in HFTs and the resulting electric field and temperature distribution are discussed. The contribution of this paper focuses on the evaluation of the dielectric loss and electrothermal properties of epoxy insulation used in HFTs. A new method is proposed for calculating the dielectric loss under square wave voltage with spike voltages, which includes a step function with a rapid rise time to simulate the high $dV/dt$ behavior. This method takes into account the handling of spike voltages and the combination of physical field analysis to better estimate the electric and thermal distribution in HFTs. Then, the dielectric loss of the epoxy resin was calculated. The electrical and thermal field model of an HFT insulation structure was also calculated using the FEM method. The influence of spike voltages on the electric field and the temperature in the HFT insulation structure is discussed.

## II. CALCULATION OF DIELECTRIC LOSS

### A. COMPLEX PERMITTIVITY AND DIELECTRIC LOSS OF INSULATING MATERIALS

The dielectric loss mainly contains the effects of polarization and electric conduction. The former is similar to the Joule loss of resistance. The formed current is called the conduction current, which is determined by the conductivity and electric field in the insulation. The latter originates from the relaxation polarization process in dielectrics, particularly under high-frequency alternating fields. It is accepted that the dipole and interface polarization mainly contribute to the relaxation loss. The complex permittivity characteristics of dielectrics are useful to discuss dielectric relaxation and dielectric loss. It can be expressed by $\varepsilon^* = \varepsilon' - j\varepsilon''$, where $\varepsilon'$ is the real part of the complex dielectric constant. It refers to the reactive component of the current in the dielectric, $\varepsilon''$ is the imaginary part of the complex permittivity, which is related to the active component of the current in the medium. It also represents the dielectric loss in the insulation. $\varepsilon''$ can be expressed by the Debye equation as [20]:

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

(1)

where $\varepsilon_\infty$ is the dielectric constant at the optical frequency; $\tau$ is the relaxation time of the dielectric; $\gamma$ is the conductivity of the dielectric; $\Delta \varepsilon = \varepsilon_\infty - \varepsilon_s$, and $\varepsilon_s$ is the static dielectric constant.

Figure 1 shows the measurement result of $\varepsilon''$ of epoxy resin insulation (Bisphenol A-type) under different temperatures and frequencies. The measurement was carried out by the dielectric spectra method using Novocontrol equipment. The measured frequency ranges from 0.1 Hz to $10^6$ Hz, and the temperature ranges from 20°C to 160°C. The dielectric permittivity was first tested at low temperatures in the frequency range. Then, the temperature increased to a high value, and the measurement was repeated. After that, the temperature increased again with an interval of 20°C. The sample thickness is approximately 0.2 mm with a diameter of 30 mm. $\varepsilon''$ increases with temperature and frequency. When the temperature is higher than the glass transition temperature ($T_g$) of the epoxy resin insulation, $\varepsilon''$ tends to increase significantly. Hence, the frequency and temperature depend on the dielectric loss. By fitting the curve of $\varepsilon''$ with the temperature at 10 kHz in Figure 1, the equation of $\varepsilon''$ with temperature can be obtained, which is used in the dielectric loss calculation of epoxy resin insulation (2), as shown at the bottom of the next page.

According to previous works [2], [11], the expression of dielectric loss can be expressed considering linear and isothermal dielectrics:

$$P = \sum_{n=1}^{\infty} P_n = C_0 \sum_{n=1}^{\infty} \varepsilon''(n\omega) V_{n,RMS}^2$$

(3)
where \( C_0 \) is the vacuum capacitance (calculated using \( \varepsilon_0 \)) and \( V_{n,RMS} \) is the effective value of the corresponding harmonic voltage.

In general, it is not valid to calculate the dielectric loss using the superposition principle due to the nonlinear relationship between the dielectric loss and the voltage (or electric field). However, according to the previous work [11], the dielectric loss of harmonic content \( U_n \) can be calculated separately. The dielectric loss can be regarded as the addition of the loss contributions of all harmonics for a linear dielectric material. The method was used for dielectric heating calculations for arbitrary waveforms and fundamental frequency in any insulation system [11]. Although this method can be used for estimating the dielectric heating by the square-like voltage (involving harmonic power factor) in epoxy resin insulation, it is still difficult to use directly due to the complicated harmonic analysis. Hence, this paper studies the superposition effects of dielectric loss calculation in the epoxy resin under square-like voltage from another viewpoint. The additional dielectric losses can be considered in the following part.

**B. CALCULATION METHOD OF DIELECTRIC LOSS UNDER HIGH-FREQUENCY SQUARE WAVE VOLTAGE**

The voltage waveform considered in this paper is a bipolar high-frequency square wave with a constant duty cycle of 0.5. However, the real voltage in the HFT winding is not ideal, as shown in Figure 2 [21]. This indicates that the voltage has different harmonic contents. In addition, large spike voltages occur at the rising edge and falling edge. In general, this spike voltage is reduced by filtering and modulating methods under normal conditions. The peak value of the spike voltage is no more than 2 times higher than that of the peak of square wave voltage. However, the peak value of the spike voltage is much higher in some failure conditions. In another case, a high \( dV/dt \) characteristic behaves as a key issue in the working voltage. These characteristics are difficult to solve by only considering Equation (3).

If we enlarge the waveform, a clear waveform can be analyzed, as shown in Figure 3. The high spike voltage coupled with the square waveform can affect the \( dV/dt \) of the real voltage. As described in reference [2], to simulate the PWM voltage, the step response function of a low-pass filter was used to express the PWM voltage. A similar method is used here to approach the square wave voltage, as shown in Figure 3. In this simulation model, \( t_r \) is proposed to fit \( dV/dt \). A short \( t_r \) means a rapid increase in the square and spike voltages. A stable value of the step function can well fit the amplitude of the square wave voltage. For the spike pulse voltage, a narrow step function is used for a similar simulation, as shown in Figure 3 (the enlarged image). Harmonic voltages are also included in the waveform, which is calculated by Equation (3).

Complicated voltage waveforms, such as PWM voltage, square voltage, and impulse voltage with rising time, falling time, and overshoot, bring some difficulty in estimating the dielectric loss. It is necessary to propose a simple and effective method to evaluate the total dielectric loss considering the Fourier transform by involving the spike or impulse voltages. Dielectric insulation, such as stress grading tape (SGT) and conductive armor tape (CAT) insulation, presents dielectric parameters that are normally dependent on frequency, electric field, and temperature [22]. According to Parseval’s theorem, electric heating can be divided into two thermal sources, indicating the power of lower and higher harmonic

\[
\varepsilon'' = \begin{cases} 
0.04547 - 9.78 \times 10^{-4}T + 6.87 \times 10^{-6}T^2 & (20^\circ C < T < 120^\circ) \\
-0.00159 + 6.95 \times 10^{-7}e^{T/11} & (120^\circ C < T) 
\end{cases} 
\] (2)
orders [22]. This result indicated that the superposition rule was used to find the total temperatures corresponding to those frequencies [22]. The simulated results are consistent with the experiments.

In this work, the dielectric loss involving the harmonics and spike voltages under square waves can be calculated by considering the improved superposition principle. In this case, the influence of the square wave and spike voltage can be simulated separately.

Here we describe the calculation method in detail. The step response function of a first-order low-pass filter is described by the transfer function.

\[ G(f) = \frac{1}{1 + j\frac{f}{f_c}} \quad \text{with} \quad f_c = \frac{\ln \left( \frac{0.9}{0.1} \right)}{2\pi t_r} \quad (4) \]

where \( f_c \) is its cutoff frequency. The associated rise time \( t_r \) of the square wave corresponds to the time required for the voltage to transition from 10% to 90% of its peak-peak voltage \( V_{pp} = 2V_{sq} \). \( V_{sq} \) is the amplitude of the square wave voltage. \( f_s \) is the frequency of the square wave voltage. For the case considered here, \( t_r = 500 \) ns and thus \( f_c = 700 \) kHz. Moreover, since \( t_r \cdot f_s < 1 \% \), the slew rate is given by \( \frac{dV}{dt} \approx 0.8 \frac{V_{pp}}{t_r} \).

According to the Fourier transform, the effective value of the harmonic component of the real square wave voltage can be calculated as follows:

\[ V_{n,RMS} = \left( \frac{2\sqrt{2}}{n\pi} V_{sq} \right) |G(f_s n)| \]
\[ = \left( \frac{2\sqrt{2}}{n\pi} V_{sq} \right) \sqrt{\frac{1}{1 + \left( \frac{f_s}{f_c} n \right)^2}} \quad (5) \]

where \( n \) is an odd number. The dielectric loss can be expressed by:

\[ P = \left( \epsilon'' C_0 V_{sq}^2 \right) \frac{P'}{P} \quad (6) \]
\[ P' = \frac{8f_k}{\pi} \ln \left( \frac{f_c}{f_s} \right) r \quad (7) \]

where \( P' \) is the normalized loss, and \( r \) is the correction coefficient, which introduces the integral deviation concerning the Fourier component superposition. Here \( r = 1.16 \). Appendix A describes the information regarding \( r \).

The total dielectric loss based on the simulation in Figure 3 can be expressed as:

\[ P = \frac{8f_k}{\pi} \ln \left( \frac{f_c}{f_s} \right) r \left( \epsilon'' C_0 V_{sq}^2 \right) \quad (8) \]

Equation (8) is only available for the dielectric loss calculation in uniform and isothermal dielectrics under a uniform electric field. In general, the electric field distribution in the HFT insulation is nonuniform. Therefore, the element electric field should be considered. According to the electric field distribution in an HFT insulation structure, Equation (8) can be rewritten as follows:

\[ P = \frac{8f_k}{\pi} \ln \left( \frac{f_c}{f_s} \right) r E_0 \epsilon'' E_{sq}^2 \quad (9) \]

where \( E_{sq} \) is the element electric field in the HFT insulation. It can be noted that the dielectric material is not uniform due to the slight variation of the dielectric parameter \( \epsilon'' \) in Figure 1. However, it changes little with the temperature (<120 °C). If we consider the approximate treatment, the dielectric is still regarded as a uniform medium. Otherwise, we indeed consider the variation of the dielectric response parameter \( \epsilon'' \) (Figure 1) in the following FEM simulation.

C. DIELECTRIC LOSS CALCULATION OF THE SIMULATED SPIKE VOLTAGES

To calculate the additional dielectric loss caused by the spike voltages, a similar method of narrow step function simulation is used, as shown in Figure 4. The spike voltage is regarded as a narrow square waveform, which is equivalent to the enlarged spike voltage in Figure 3. \( T_s \) is the voltage period of the square wave. \( T_0 \) is the defined pulse width of the spike voltage. \( k \) is the scale parameter. \( kT_0 \) is the duration of the simulated spike voltage. \( m \) is the amplitude ratio between the spike voltages and the square wave.

The simulated function \( f(t) \) is expressed by:

\[ f(t) = 2\sqrt{2} m V_{sq} \sum_{n=1}^{\infty} \sin(2\pi n f_s t + \phi_n) \frac{\sin(2\pi n f_s t)}{n\pi} \]
\[ \times \sqrt{1 - \cos \left( \frac{2\pi n kT_0}{T_s} \right)} \sqrt{\frac{1}{1 + \left( \frac{1}{T_0/c_n} \right)^2}} \quad (10) \]

where \( \phi_n = \pi/2 - \pi n kT_0/T_s \).
The effective value of each harmonic component is described below:

\[ V_{n,RMS} = \frac{2m}{n\pi} \sqrt{1 - \cos \left( \frac{2n\pi kT_0}{T} \right)} V_{sq} \left[ \frac{1}{1 + \left( \frac{m}{T_0T} \right)^2} \right]^{0.5} \]  

(11)

According to Equation (11) and Equation (3), the additional dielectric loss of the spike voltage can be given by:

\[ P_a \approx \frac{8m^2f_c}{\pi} \left[ \ln \left( T_0f_c/T \right) r - q(k) \right] \left( \varepsilon'' C_0 V_{sq}^2 \right) \]  

(12)

where \( q(k) \) is the coefficient related to \( k \). The specific values of \( q(k) \) are discussed in Appendix B.

The applied voltage is regarded as the superposition of the square wave voltage and the transient spike voltage. Hence, the Fourier components are superposed in the linear dielectric. Due to the same rising time of the square and spike voltages, the spectra of the spike and square voltages are likely to overlap. The additional dielectric losses cannot be ignored.

\[ P_{ST} = C_0 \sum_{n=1}^{\infty} \varepsilon''(nT_cT_0) (2\pi fn) \cdot 2Re \left( V_{S,n,RMS} \cdot V_{T,n,RMS}^* \right) \]  

(13)

\[ P'_{ST} = P''_{ST} + 2 \left( \frac{\pi}{2m} \right) \]  

where \( V_{S,n,RMS} \) is the effective value of the \( n \)th harmonic in the square wave voltage. \( V_{T,n,RMS}^* \) is the complex conjugate of the effective value of the \( n \)th harmonic in the spike voltage.

In combination with Equations (5), (11), and (13), \( P'_{ST} \) can be expressed as:

\[ P'_{ST} \approx \frac{16\sqrt{2}mf_c}{\pi}d(k) \]  

(14)

where \( d(k) \) is the coefficient depending on the \( k \). The specific values of \( d(k) \) are calculated in Appendix B.

Therefore, the total dielectric loss can be expressed as:

\[ P_{total} = P + P_a + P_{ST} \]

\[ = \left[ r + m^2 \left( r - \frac{q(k)}{\ln(f_c/k)} \right) + \frac{2\sqrt{2}md(k)}{\ln(f_c/k)} \right] \]

\[ \times \frac{8f_c}{\pi} \ln \left( \frac{f_c}{k} \right) \left( \varepsilon'' C_0 V_{sq}^2 \right) \]  

(15)

The ratio between the total dielectric loss and the square wave dielectric loss is described by:

\[ \eta = \frac{P_{total}}{P} = 1 + m^2 \left[ \left( r - \frac{q(k)}{\ln(f_c/k)} \right) + \frac{2\sqrt{2}md(k)}{\ln(f_c/k)} \right] \]  

(16)

According to the above equation, the total dielectric loss depends on \( m \) and \( k \). Here, we select \( m = 0.5, 1, 1.5, 2, 2.5 \) and \( k = 1, 2, 3, 4, 5 \) to calculate the ratio \( \eta \). The \( \varepsilon'' \) has a substantial increase at higher frequencies (> 1 MHz). In this case, there are still some contributing components (> 1 MHz) in the Fourier conversion. However, the fundamental frequency is 10 kHz. Even though the 1MHz is considered, the increase in \( \varepsilon'' \) at high frequency has little effect on the dielectric loss calculation. We also quantified this effect by comparison with the numerical calculation of the Fourier sum. The dielectric loss under the first 200 harmonics was calculated. When \( n > 100 \) (i.e., harmonic frequency >1 MHz, a larger \( \varepsilon'' \) was used), the difference between the results obtained and the results when \( \varepsilon'' \) is the fixed value is only 2.5%. This is mainly caused by the lower harmonic voltage amplitude at a high frequency (1 MHz).

Figure 5 shows the calculated results. The total dielectric loss increases with the increase in \( m \) and \( k \). When \( m = 2.5 \) and \( k = 5 \), \( \eta \) can reach 6.8. In this case, the total dielectric loss is 6.72 times higher than that of the ideal square wave voltage. Therefore, the spike voltages with a high \( dV/dt \) contribute greatly to the total dielectric loss. Hence, the analysis and discussion of the influence of the spike voltages on the electric field and thermal stress are of great importance to the HFT performance used in high-power density PET systems.

To verify the proposed method, the dielectric losses were calculated (the first 70 main harmonics are superimposed) directly by Equation (3) under square waves with and without spike voltages \((m = 2.5, k = 5)\). It was found that the result of Equation (3) is 3.86 W, and that of Equation (8) is 3.67 W without spike voltages. The error is approximately 4.9%. The dielectric loss calculated by Equation (3) with spike voltages is 25.62 W, and it is 24.95 W by Equation (15). The error is approximately 2.6%. Therefore, the proposed method is effective in estimating the dielectric loss under a square wave with spike voltages.

It should be noted that the proposed method is useful to calculate the dielectric loss with high efficiency. It is beneficial for HFT design and application. If Equation (3) containing harmonics and spike voltages is directly used, it spends much time dealing with the Fourier decomposition and the superposition. Furthermore, the proposed method is available.
for the thermal field calculation of insulation structures in HFTs, which is discussed in the following section. However, Equation (3) is difficult to use for FEM simulation.

III. ELECTRIC FIELD AND THERMAL STRESS SIMULATION OF HFT INSULATION STRUCTURE

A. FEM SIMULATION MODEL

An HFT structure in a dual active bridge DC-DC converter used in a PET system is selected for the electric-thermal field simulation. The detailed parameters of the HFT are described in Table 1. The electromagnetic field can be given by:

$$\nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) + \sigma \frac{\partial \vec{A}}{\partial t} + \sigma \nabla \phi = 0$$  \hspace{1cm} (17)

where $\vec{A}$ is the vector magnetic potential; $\phi$ is the scalar potential; $\mu$ is the permeability, and $\sigma$ is the conductivity.

The governing equation of thermal field is described by:

$$\lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q = C_p \rho \frac{\partial T}{\partial t}$$  \hspace{1cm} (18)

where $\lambda_x$, $\lambda_y$ and $\lambda_z$ are the thermal conductivities of the transformer components in different directions; $C_p$ is the heat capacity at atmospheric pressure; $\rho$ is the component density; $t$ is the time; $T$ is the temperature of the transformer, and $q$ is the heating power density.

First, a 3D model of the HFT is constructed. After that, the electrical and thermal parameters of the HFT materials, such as the magnetic core, the insulating material, and the windings are selected, as shown in Table 2.

The total dielectric loss of the epoxy resin insulation can be calculated by the above-proposed method. The losses of magnetic core and windings are calculated under high-frequency square voltages. Figure 6 shows the B-H curve of magnetic material (Zn-Mn ferrite). It is used for the dynamic loss calculation.

The core loss is calculated by the Waveform-Coefficient Steinmetz Equation (WcSE) with flux waveform coefficient $F_{eq}$ [23].

$$P_v = F_{eq} K_{d_{m}} \beta f^\alpha$$  \hspace{1cm} (20)
where $K$, $\alpha$, and $\beta$ are the Steinmetz coefficients and $B_{m}$ is the maximum value of the magnetic flux density. WcSE introduces waveform coefficient to calculate core loss.

The waveform coefficient $F_{\text{eq}}$ of the magnetic flux is described as:

$$F_{\text{eq}} = \frac{\frac{T}{2} \int_{0}^{T/2} |B(t)| \, dt}{\frac{T}{2} \int_{0}^{T/2} B_{\text{peak}} \sin(\omega t) \, dt} \tag{21}$$

where $B_{\text{peak}}$ is the peak value of the flux density under nonsinusoidal excitation.

Due to the severe skin and proximity effects of the current in the windings at high frequency, the winding loss calculation should be modified by considering the skin depth. It is necessary to use the AC resistance coefficient $F_{r}$ of the windings. Similarly, the current in the windings of the HFT also contains high-frequency harmonics under nonsinusoidal excitation. Hence, based on the Fourier transform and superposition effect, the total winding loss can be expressed below:

$$P_{\text{winding}} = \sum_{n=1}^{N} F_{r,n} R_{dc} I_{\text{rms},n}^2 \tag{22}$$

where $F_{r,n}$ is the $n$th harmonic AC resistance coefficient, and $I_{\text{rms},n}$ is the $n$th harmonic RMS current.

**B. DIELECTRIC LOSS DISTRIBUTION**

The electric field distribution of the HFT insulation structure is calculated by FEM (not shown here). A high electric field distortion occurs between the primary and secondary windings. The maximum field occurs between the windings. Compared with the ideal square wave voltage, the addition of spike voltage enhances the maximum electric field. It can be enhanced from 7 kV/mm to 25 kV/mm by a high spike voltage ($m = 2.5, k = 5$). The spike voltage can significantly increase the electric field in the winding insulation.

According to the calculated electric field and the dielectric loss calculation, Figure 7 shows the dielectric loss distribution in epoxy resin insulation of the HFT structure. The dielectric loss is mainly concentrated at the end of the winding positions (in the insulation), which is consistent with the electric field distribution. The dielectric loss depends on the multi-frequency electric fields. When the rated power of the HFT is 10 kW, the total dielectric loss is approximately 3.67 W without the spike voltages. A similar distribution of dielectric loss is obtained with the spike voltage, as shown in Figure 7b. The dielectric loss increases with the spike voltages. It can increase to 24.95 W, which is three times higher than that without spike voltages. As a consequence, a high thermal field occurs due to the spike voltages.

**C. INFLUENCE OF SPIKE VOLTAGE PARAMETERS ON THE HOT-SPOT TEMPERATURE**

The total calculated dielectric loss is used as the heat source of epoxy resin insulation to calculate the temperature distribution of the HFT structure. The insulation structure has a stable temperature (24–225°C) without spike voltages. The hot-spot temperature is approximately 24.9°C inside the insulation. Figure 8 shows the results of hot-spot temperature in the HFT insulation with the spike voltages ($m = 0.5, 1, 1.5, 2, 2.5$ and $k = 1, 2, 3, 4, 5$). The hot-spot temperature in the transformer increases with the increase in $m$ and $k$. The highest hot-spot temperature is approximately 55.2°C, which can be increased by 35.2°C with the spike voltages. Therefore, it is necessary to use the proposed model and method to calculate the temperature in the HFT insulation to improve the thermal analysis in HFT applications.

When the core loss and winding loss are considered, the temperature distribution of the HFT increases, as shown in Figure 9 (without spike voltages). The losses of the magnetic core and windings play major roles in HFT loss. The temperature presents a significant increase. The hot-spot
temperature is 108°C without spike voltages. As a consequence, insulation suffers from a much higher external temperature. The insulation performance can be affected by the external high temperature from the losses of the magnetic core and windings.

The hot-spot temperature \( T_{\text{max}} \) occurs in the middle of the secondary winding. Similarly, when considering the addition of the different spike voltages, \( m = 0.5, 1, 1.5, 2, 2.5 \), and \( k = 1, 2, 3, 4, 5 \), \( T_{\text{max}} \) are calculated, as shown in Figure 10. The hot-spot temperature increases with \( m \) and \( k \). A high spike voltage with a large pulse width can significantly increase the temperature. \( T_{\text{max}} \) can reach 135°C under \( m = 2.5 \) and \( k = 5 \).

D. DIELECTRIC LOSS AND THERMAL STRESS OF INSULATION UNDER FAILURE CONDITIONS

Failure conditions, such as overvoltage and large current (short circuit of the windings), can lead to an increase in the electric field and HFT loss. In this paper, similar simulations are carried out by considering the overvoltage and the large current (1–5 times higher than that of rated values). The electric field increases with increasing voltage, especially at the end of the primary winding. The maximum electric field can reach 53.9 kV/mm when the voltage is 5 times higher than that of the rated voltage (1 kV). In this case, the insulation suffers from high electric stress with mixed frequency, leading to the production of partial discharge. As a consequence, dielectric breakdown occurs.

Figure 11 shows the hot-spot temperature of the HFT under a large current. This indicates that the hot-spot temperature presents an obvious increase with the current. It can reach 280°C within one minute, which is much higher than the glass transition temperature \( T_g = 125°C \) of epoxy resin. In this case, insulation failure probably occurs within a short time due to a significant thermal runaway. In addition, the increase in current can significantly increase the losses of the magnetic core and windings, resulting in overheating in the HFT. However, the dielectric loss presents little change when the temperature is lower than \( T_g \). The dielectric loss depends on the electric field, not the current.

E. EFFECT OF AMBIENT TEMPERATURE ON THE HOT-SPOT TEMPERATURE OF HFT

According to Equation (3), the dielectric loss depends on the imaginary part of the dielectric constant \( \varepsilon'' \). When the temperature is lower than \( T_g \), \( \varepsilon'' \) shows a slight decrease in the temperature. However, at high temperatures (above \( T_g \)), \( \varepsilon'' \) increases significantly. To study the influence of ambient temperature on dielectric loss and transformer temperature, the dielectric loss and hot-spot temperature of the HFT through iteration under the condition of \( m = 2.5 \) and \( k = 5 \) were calculated. Table 3 shows the calculated dielectric loss, hot-spot temperature, and temperature rise in the HFT model under different conditions. At room temperature (20°C), the dielectric loss and hot-spot temperature are low even though spike voltages are involved. However, they present a significant increase at high external temperatures \( T_g = 125°C \). In this case, the dielectric loss and hot-spot temperature significantly increase. The temperature can reach
TABLE 3. Dielectric loss and transformer temperature rise at different ambient temperatures.

| Ambient temperature (°C) | Dielectric loss (W) | Transformer hot-spot temperature (°C) | Temperature rise (°C) |
|--------------------------|---------------------|--------------------------------------|----------------------|
| 20                       | 24.95               | 55.2                                 | 35.2                 |
| 125                      | 48.91               | 174                                  | 49                   |

174°C after considering the high contents of large spike voltages. The temperature rise is 49°C, which is 1.4 times higher than that at room temperature. Therefore, when the temperature is close to the $T_g$ of the insulating material, the HFT failure rate increases by thermal runaway.

F. DIELECTRIC LOSS UNDER HIGH BASIC IMPULSE INSULATION LEVEL

As mentioned above, the dielectric loss increases with increasing spike voltage and duration, maximum ratio m, and amplitude of the rated voltage. If the HFT is required to meet a higher basic impulse insulation level (BIL), the ratio m is probably high. The resulting high dielectric loss can cause serious dielectric heating, causing the degradation and aging of the insulation in HFT.

1) Hence, thermal management should be considered in the HFT design under the high BIL requirement to reduce the dielectric loss and improve the heat dissipation of the HFT. Some strategies should be carried out.

2) Increase the insulation distance, such as the distance between the core and the winding and between the windings. As a result, the electric field in the insulation decreases, leading to a reduction in the dielectric loss. However, it can increase the HFT size, increasing the cost of the HFT.

3) Reduce the working frequency of the HFT. The decrease in frequency reduces the total dielectric loss, but it restricts the application of the HFT under high frequency.

4) Reduce the harmonics and spike voltages. The harmonics and spike voltages can be reduced by improving the HFT structure, filtering, and reducing the parasitic parameters.

5) Using Z-winding (folding winding). This method can improve the electric field distortion and reduce the maximum electric field and the high local dielectric loss density.

6) An air and water cooling system should be considered in the winding insulation to improve heat dissipation.

IV. CONCLUSION

In this paper, a calculation of dielectric loss under high $dV/dt$ spike voltages coupled with square wave voltages was proposed. After that, the influence of spike voltages and failure conditions on the electric field and temperature distribution were discussed. Several conclusions are summarized below:

1) A step function that is equivalent to spike voltage superposition is proposed for quantitatively calculating the dielectric loss. Furthermore, a similar narrow step function was used for the simulation of the spike voltage at the rising/falling edge.

2) The dielectric loss under a square wave with spike voltages was higher than that of the square wave. It increased with the spike voltage and the duration.

3) The spike voltages enhanced the electric field and temperature in the insulation. The high external temperature (close to the $T_g$ of epoxy resin) significantly increased the HFT temperature when the additional loss caused by spike voltages is considered.

4) When the transformer temperature was higher than the $T_g$ of epoxy resin, $\varepsilon''$ increased greatly, resulting in a high dielectric loss. It increased the risk of insulation failure.

It can be concluded that the high $dV/dt$ square wave with spike voltages is of great importance to the loss and electric field of the insulation. It is necessary to study the additional dielectric loss by spike voltages, especially under the requirement of a high BIL. Future work should consider the effects of the leakage inductance and distributed capacitance of the HFT on the spike and harmonic voltages. The dielectric breakdown, conductivity, and thermal conduction of epoxy insulation under square waves with spikes should be studied. Improvement methods, such as nanocomposites and insulation optimization for HFT application, are needed.

APPENDIX A

CALCULATION METHOD OF DIELECTRIC LOSS UNDER HIGH-FREQUENCY SQUARE WAVE VOLTAGE

The calculation process of equation (8) is described below. According to equation (5) and equation (3), the $P'$ can be expressed by:

$$P' = \frac{16f_s}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n-1} \left( \frac{1}{1 + \left( \frac{f}{f_c} \right)^2 (2n-1)} \right)$$  (A-1)

The equivalent transformation of equation (A-1) can be obtained as follows:

$$P' = \frac{16f_s}{\pi} \sum_{n=1}^{\infty} \left( \frac{1}{2n-1} - \frac{\left( \frac{f}{f_c} \right)^2 (2n-1)}{1 + \left( \frac{f}{f_c} \right)^2 (2n-1)} \right)$$  (A-2)

Because $n$ is close to infinity, $P'$ can be approximated as:

$$P' \approx 16f_s \int_{1}^{+\infty} \left( \frac{1}{2x-1} - \frac{\left( \frac{f}{f_c} \right)^2 (2x-1)}{1 + \left( \frac{f}{f_c} \right)^2 (2x-1)} \right) dx$$  (A-3)

The result of $P'$ from equation (A-3) is calculated by:

$$P' \approx \frac{16f_s}{\pi} \lim_{x \to \infty} \ln \left( \frac{\sqrt{2x-1}}{\sqrt{1 + \left( \frac{f}{f_c} \right)^2 (2x-1)}} \right)$$
where $r$ is the correction coefficient. In this paper, $r$ can be calculated by the ratio of (A-3) to (A-4) within the first 10 harmonic losses. The estimated value $r = 1.16$ is used.

Square wave and PWM wave voltage contain infinite harmonics. According to the calculation in reference [2], the dielectric loss from fundamental wave to $f_n f_x$ harmonic is superimposed. Furthermore, the high orders of harmonics that are greater than $f_n f_x$ are ignored. Due to the low percentage of the dielectric loss above $f_n f_x$, we also ignored the influence of high order of harmonics (greater than $f_n f_x$) in this paper.

Firstly, the harmonic order is converted from $n$ into $x$. Then, the approximate value of dielectric loss $P'$ is used by involving its limitation when $x$ is positive infinity. Consequently, the calculation can be simplified and improved.

**APPENDIX B**

**CALCULATION METHOD OF DIELECTRIC LOSS UNDER SIMULATED SPIKE VOLTAGES**

The calculation process of equation (12) is described below. According to equation (11) and equation (3), the $P'_a$ can be expressed by:

$$P'_a = \frac{8m^2 f_s}{\pi} \sum_{n=1}^{\infty} \frac{1 - \cos \left( \frac{2\pi k T_0}{T_s} \right)}{n} \frac{1}{1 + \left( \frac{n}{T_0 f_c} \right)^2}$$  \hspace{1cm} (B-1)

$P'_a$ is expressed as the difference between two parts, namely:

$$P'_a = P'_a - P'_a$$  \hspace{1cm} (B-2)

where $P'_a$ can be expressed as:

$$P'_a = \frac{8m^2 f_s}{\pi} \sum_{n=1}^{\infty} \frac{1 - \cos \left( \frac{2\pi k T_0}{T_s} \right)}{n} \frac{1}{1 + \left( \frac{n}{T_0 f_c} \right)^2}$$  \hspace{1cm} (B-3)

The form of equation (B-3) is similar to that of equation (A-1). The same method can be used to calculate equation (B-3), and the results are as follows:

$$P'_a \approx \frac{8m^2 f_s}{\pi} \ln \left( \frac{f_c}{f_s} \right) r$$  \hspace{1cm} (B-4)

$P'_a$ can be approximated using MATLAB, i.e

$$P'_a \approx \frac{8m^2 f_s}{\pi} \frac{q(k)}{\ln \left( \frac{T_0 f_c}{1} \right)} (B-5)$$

where $q(k)$ is the coefficient related to $k$. When $k$ is 1, 2, 3, 4, and 5 respectively, $q(k)$ is 2.83, 0.29, 1.68, 1.39, 1.16. Therefore, $P'_a$ can be expressed as:

$$P'_a \approx \frac{8m^2 f_s}{\pi} \ln \left( \frac{T_0 f_c}{1} \right) r - q(k)$$  \hspace{1cm} (B-6)

Therefore, the additional dielectric loss of the spike voltage can be given by:

$$P_a \approx \frac{8m^2 f_s}{\pi} \frac{q(k)}{\ln \left( \frac{T_0 f_c}{1} \right)} (e^{c_0} V_{\text{square}})$$  \hspace{1cm} (B-7)

The $\ln(T_0 f_c)$ and $\ln(f_c/f_s)$ are the coefficients from the step response function of a low-pass filter, respectively. They have the same value. Considering the equations (5), (11), and (13), $P'_{\text{ST}}$ can be expressed as:

$$P'_{\text{ST}} \approx \frac{16\sqrt{2} m f_s}{\pi} \sum_{n=1}^{\infty} \frac{1 - \cos \left( \frac{\pi (2n-1) k T_0}{T_s} \right)}{2} \left( \frac{\cos \left( \frac{\pi (2n-1) k T_0}{T_s} \right)}{2} \right)^2$$  \hspace{1cm} (B-8)

The approximate value of $P'_{\text{ST}}$ can be calculated by MATLAB:

$$P'_{\text{ST}} \approx \frac{16\sqrt{2} m f_s}{\pi} d(k)$$  \hspace{1cm} (B-9)

where $d(k)$ is the coefficient depending on $k$. When $k$ is 1, 2, 3, 4, and 5 respectively, $d(k)$ is obtained as 0.603, 0.696, 0.707, 0.709, 0.710, respectively.

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