The Effects of PWM with High dv/dt on Partial Discharge and Lifetime of Medium- Frequency Transformer for Medium-Voltage (MV) Solid State Transformer Applications

Rachit Agarwal, Member, IEEE, Hui Li, Fellow, IEEE, Zhehui Guo, Student Member, IEEE, Peter Cheetham, Member, IEEE

Abstract — The medium-frequency (MF) transformer in a phase-shift modulated dc solid state transformer (SST) is prone to partial discharge (PD) that impacts the system reliability and lifetime. Tightly packed medium frequency transformer windings carrying pulse width modulation (PWM) voltages create favorable conditions for PD inception due to proximity between adjacent winding conductors and electric field enhancement because of spiral geometry. A peak potential condition is created between the adjacent posterior conductors of the primary and secondary windings as a result of phase-shifted modulation. This along with fast alternating electric fields incepts PD at lower than expected operating voltages. Early inception of PD lead to premature transformer failure leading to unanticipated DC SST down-time. The effects of PWM voltages containing high dv/dt switching transients on PD and lifetime characteristics of MF transformer in a dc SST is not yet understood, which is investigated in this paper. A non-intrusive PD detection strategy for MF PWM ac voltage is presented using high speed optical sensors. PD characterization is performed on Kapton polyimide insulated copper foil windings for a foil-type MF transformer. Winding samples are stress tested with steady state PWM voltages upto 2 kV and frequencies upto 50 kHz with high dv/dt upto 60 V/ns generated by a half-bridge inverter using 3.3 kV SiC devices while maintaining the transformer’s geometric profile. Accelerated dielectric lifetime characterization is also performed and novel lifetime prediction models are derived based on the acquired results containing both frequency and dv/dt dependent variables.

Index Terms — Medium-Frequency Transformer, Solid State Transformer, Partial Discharge, Transformer Lifetime, PWM, SiC, Medium-Voltage

I. INTRODUCTION

Leveraging the high voltage and high-speed capability of emerging wide band gap semiconductor devices, medium-voltage (MV) solid state transformer (SST) is gaining widespread applications in MVDC distribution, renewable energy collection, and fast charging stations. Medium-frequency (MF) transformer is crucial in a MV SST converter architecture to achieve galvanic isolation, high power density and high efficiency.

One primary design challenge of MF transformer is to implement desired insulation at MV PWM excitation without compromising on power density and efficiency. Onset of partial discharge (PD) is an indication of insulation issues in ac systems. Every discharge event reduces the insulation lifetime by degrading the insulation material leading to premature insulation failure.

Researches in [1], [2] have designed MF frequency transformers for inductor tank based MV dc SST with PWM frequency from 3 kHz to 20 kHz. The insulation material of the windings is presented but the insulation performance remains untested. Zhao et al. in [3] have designed a 500 kHz transformer with PTFE polymer based insulation that has been characterized up to 30 kV with short impulse voltage testing. Guo et al. have developed a 200 kW, 15 kHz Dual Active Bridge (DAB) SST medium-frequency transformer in [4] with partial discharge characterization up to 7.5 kV peak. The PD test is performed at 60 Hz sine ac voltage bearing different properties compared to PWM voltage. It is reported in [5] that partial discharge is heavily influenced by the voltage shape and PWM voltage with switching transients show stronger PD activity compared to sine and triangle voltages. The partial discharges research for motor windings under actual PWM excitation at greater than 60 Hz frequency has been reported in [6]–[9]. However, the research of PWM effects on PD of MF transformer within SST has not been reported. The PD characteristics in SST transformer is different from that of motor winding because of difference in PWM voltage, winding geometry and electric field distribution between motor and transformer. SST transformer windings are subjected to greater potential difference and faster alternating electric fields between the primary and secondary side of the transformer as a consequence of phase-shift modulation and high switching frequency of SST.

MF transformer is important for DC SST’s reliability since winding insulation failure can lead to short circuit fault between the high voltage and low voltage side. Survey of literature suggests that degradation of dielectric material is affected by PD activity and the life expectancy is substantially reduced in the presence of PD [10]. Singh et al. in [11] have experimentally evaluated the lifetime of HVDC converter’s line frequency transformer insulation under different ac voltage waveform patterns. The results show that insulation lifetime depends drastically on waveform pattern reducing the lifetime to less than 1 year for square voltage pattern whereas the lifetime is greater than 40 years for sinusoidal voltage. They have performed accelerated breakdown tests on oil in paper insulation material but have not characterized the material for partial discharges. Insulation lifetime is heavily dependent on ac frequency primarily due to the repetitive nature of partial discharge events following the rise and fall of alternating voltage. However the PD effects on transformer lifetime has not been studied in [11]. [12] shows that lifetime of polyimide
Kapton film insulation is significantly reduced when ac frequency is increased to 400 Hz from 60 Hz. The failure mechanism and method for failure assessment has not been reported for MF PWM transformers. This paper has studied the effect of PWM with high dv/dt switching transients on partial discharge and lifetime Characteristics of a MF Transformer for MV Solid State Transformer especially when SiC devices are applied. The tightly packed medium frequency transformer windings carrying high frequency PWM voltages with high dv/dt are more prone to partial discharges, which may lead to premature transformer failure leading to DC SST down-time. Hence, characterization of partial discharges and lifetime of transformer winding insulation at precise geometry and PWM voltage excitation is important. This paper presents a non-intrusive PD characterization strategy for foil-type MF transformer under high frequency PWM waveform using high speed optical sensors. Kapton (polyimide) insulated foil windings are stressed with steady state PWM voltages up to 2 kV and frequencies up to 50 kHz with high dv/dt up to 60 V/ns while maintaining the transformer’s geometric profile. The Inter-winding partial discharge inception and extinction characteristics for foil-type MF transformer is obtained, which provides an insight of transformer lifetime. Additionally, an extended transformer lifetime model considering PWM frequency and switching dv/dt is developed from accelerated winding breakdown tests. The model derives a mathematical relationship of switching frequency and switching speed influence on SST transformer’s lifetime.

This paper is organized as follows. Section II presents the dc SST Topology along with foil-type MF transformer construction. Inter-winding peak potential state unique to phase-shift modulated dc SST is analyzed and electric field finite element analysis (FEA) simulation results indicating 5x electric field enhancement between the primary and secondary winding is discussed in detail. In Section III, the transformer PD characterization methodology is addressed in detail with SiC based variable frequency and dv/dt voltage generator. Based on optical detection method, the PD inception voltage (PDIV) and PD extinction voltage (PDEV) are characterized for wide spectrum of PWM frequency between 10 Hz to 50 kHz. Post PD characterization, the foil windings are stress tested at 2 kV PWM until breakdown for frequencies between 10 kHz to 50 kHz and dv/dt of 30 V/ns and 60 V/ns. The findings are presented in Section IV. Based on the breakdown results, lifetime models are developed with varying frequency for a fixed dv/dt. Effect of dv/dt is quantitatively represented in the mathematical models. Finally, extended transformer lifetime model considering switching frequency and dv/dt is also discussed in Section IV.

II. SST CONFIGURATION AND TRANSFORMER INSULATION DISCUSSION

The dc grid technology is a promising solution to integrate a large amount of renewable energies and energy storage systems. At the transmission level, the high-voltage direct current (HVDC) is an emerging technology to integrate large renewable power plants. At the distribution level, medium-voltage dc (MVDC) grids are promising for the efficient connection of distributed renewable generation and storage systems. The dc SST that interconnects MVDC distribution grids and HVDC transmission grids therefore provides a key role in such dc grids. Fig. 1 shows a dc transformer to connect MVDC distribution grids and HVDC transmission grids using phase-shifted modulation method. The power transfer is controlled by adjusting the phase shift angle between the primary and secondary voltages of a MF transformer. The primary and secondary voltages of MF transformer is also shown in Figure 1.

A peak potential state is created between the primary and secondary side transformer windings during the duration of phase shift. In the modulation shown in Figure 1, \( \phi = 45^\circ \) is considered for simplicity. For this application, the MF transformer is designed for a unity turns ratio. Hence, the peak inter-winding potential \( V_{\text{IWP}} \) reaches 2x the dc link voltage \( V_{dc} \) for the duration of phase-shift in the positive half cycle between 0 and \( T_\phi \), mathematically represented by Eq. (1).

![Figure 1: SST architecture with two level PWM voltage](image-url)
ideally, \( T_\phi \) and \( T_s/2 \), both primary voltage \( V_{pri} \) and secondary voltage \( V_{sec} \) are at the same potential due to transformer turns ratio \( n = 1 \), making \( V_{IWT} \) hold zero potential difference. At \( T_s/2 \), the negative half cycle begins, again increasing \( V_{IWT} \) to \( 2 \cdot V_{dc} \) between \( T_s/2 \) and \( (T_s/2 + T_\phi) \). Hence, the winding-to-winding voltage constitutes of unipolar square wave bearing twice the switching frequency of transformer PWM voltage, width equal to the operating phase-shift angle and two times amplitude of switching transients. The fast alternating electric field between the tightly packed transformer windings significantly increases the stress on the primary edges of the windings and creates favorable conditions for partial discharge inception as well as to accelerated insulation ageing due to PD activity. PD can happen either between microvoids with the winding or between the posterior insulation surfaces of primary and secondary side windings. Therefore, the interwinding insulation is challenging for phase-shifted operation based dc SSI due to the peak potential state. The intra-winding insulation between two adjacent layers; and the winding-to-core insulation is also prone to PD inception while the potential difference in both cases are smaller than inter-winding potential difference, hence the focus of this work is on inter-winding insulation.

A MF transformer with nanocrystalline core and copper foil windings is designed for a dc SST with phase-shifted operation to achieve high power density and low loss [13]–[15]. The transformer is structured in a UU shape with separate winding structure as shown in Fig. 2. The windings are insulated with Kapton (polyimide) insulation because the mechanical properties of Kapton allows it to bend freely compared to other insulation materials. This allows better control over foil winding construction, combined with thin insulation thickness improves the coupling of transformer.

Separate winding structure may suffer from higher leakage inductance due to lower magnetic coupling as compared to concentric or interleaved winding structures [4], the separate structure however, exhibits the best inter-winding insulation due to natural separation between the primary and secondary sides, often aided by a small air gap. On the other hand, in interleaved winding structure, the gap between the primary and secondary and secondary winding foil layers on top of each other to enhance the magnetic coupling. Interleaving creates the peak potential state throughout the winding length due to continuous close proximity of primary and secondary conductors wound together with no air-gap to support the dielectric strength. Consequently, the entire winding bulk is vulnerable to PD in interleaved structure, whereas only the anterior edge facing the other winding is prone to PD in separate winding structure. Hence, separate winding structure is adopted for this work.

For transformer winding structure, PD inception depends on the electric field and dielectric strength between primary and secondary conductors. Electric field intensity is associated with the geometry and proximity of conductors carrying mismatched electric potential. The inter-winding electric field severity is analyzed using 2-D axisymmetric FEA simulation on a simplified winding structure which consist of 1 layer of kapton insulation with adhesive silicone backing over 2 mil thick copper foil. The thickness of silicone and kapton is 1 mil each. The relative permittivity of kapton is 3.4 and that of silicone adhesive as 2.8. In this simulation, the primary side copper winding potential is set to 2 kV and the secondary side is set to 0 V to be consistent with experimental condition for PD evaluation. 0.2 mm gap distance in air represents a densely packed transformer with maximum fill factor. The zoom-in simulation results in Fig. 3 show 4x-5x electric field enhancement along the entire lateral edge of the primary and secondary windings. This can lead to PD inception at lower than anticipated DC link voltages leading to unexpected transformer insulation failure. The simulation also demonstrates the edge effect predominantly enhancing the electric field at the filleted edge of the winding. Such sharp edges are a common occurrence formed during the bending and shaping process of copper metal. In addition, ~2x field enhancement between copper, adhesive and kapton creating favorable PD condition within the micro cavities between the material layers.

It is important to note that fast alternating electrical field is created by the fast switching PWM voltage of the MF transformer along with the electric field enhancement leading to significant PD activity between the micro cavities as well as between the windings. In addition, the dielectric losses and unexpected local temperature rise can be expected owing to medium frequency PWM pulses. The fast dv/dt, fast switching...
frequency along with switching transients can drastically reduce the lifetime of insulation in SST; the weakest point being the MF transformer inter-winding insulation because it is usually designed to withstand the peak PWM voltage occurring in SST. Therefore, it is crucial to evaluate the PWM effects on PD between the inter-winding insulation for MF transformer. In the next section, the inter-winding PD is experimentally characterized under fast PWM voltages.

III. TRANSFORMER PD CHARACTERIZATION WITH VARIABLE SWITCHING FREQUENCY AND HIGH DV/DT

PD detection methods can be classified into electrically coupled methods and non-intrusive methods. Electrically coupled methods include the traditional coupling capacitor method where the PD activity is obtained by measuring the PD displacement current off a coupled capacitor to the specimen under test. While this method is standardized in the IEC 60270 [16] for 50/60 Hz ac PD measurement, it is unsuitable for higher frequency PWM PD measurements. Another method is ground current measurement using high frequency current transformer (HFCT) [17], while this method exhibit good performance irrespective of voltage waveform shape, it suffers from severe interference due to switching inrush currents. For PWM waveform, the inrush current overlaps the PD signal making it hard to identify. On the other hand, the non-intrusive methods include optical detection using Photo Multiplier Tube (PMT) [8], electromagnetic detection using ultra high frequency (UHF) antenna [18] as well as acoustic & electrochemical detection using ultrasound and ozone sensors. Acoustic and electrochemical detection method is based on secondary-response detection and are too slow for precise PD detection. Electromagnetic detection satisfies the detection speed requirement but the high-speed switching EMI interferes with the PD signal requiring extensive post processing to separate PD from noise. In many cases, especially at partial discharge inception voltage (PDIV) and partial discharge extinction voltage (PDEV), PD signals contains lower amplitude than EMI noise, that remains undetectable post signal processing.

The optical detection method using photo multiplier tube is fully isolated from electrical disturbances. Since light is a compulsory byproduct of PD and is the fastest form of energy, PMT based PD detection satisfies the detection speed and sensitivity requirements for MF power electronic applications. Additionally, no post-processing of data is required which makes it easy and compact. The PD characterization system for foil-type MF transformer is developed and shown in Fig. 4 where it consists of three main parts: (1) MF PWM Generator, which is the source of PWM voltage between the primary and secondary windings; (2) Transformer winding test setup, that is built to hold windings under test maintaining the transformer’s geometry; and (3) Optical PD measuring instrument, that detects the optical photons discharged during PD event and converts it into electrical signal for acquisition. Each subcomponent is described in detail as follows:

1) MF PWM Generator:

The PWM generator is shown in Fig.4 (b) which is a half-bridge inverter using discrete 3.3 kV SiC MOSFETs from GeneSiC. The maximum dc-link voltage is selected as 2 kV. Optically isolated gate drivers with desat protection drive the MOSFETs to switching frequencies up to 50 kHz, generating unipolar PWM output. The PWM frequency is varied between 10 Hz to 50 kHz. The dv/dt is limited by the parasitic capacitance associated with the winding sample and the parasitic inductance of the external current limiting resistance inserted between the PWM generator and the winding test sample. Peak dv/dt of 60 V/ns is achieved by the circuit. A second test case is attained by dropping the dv/dt to 30 V/ns by modifying the gate resistance.

2) Transformer Winding Test Setup:

The detailed design parameters of this foil-type MF transformer were presented in [14]. A winding test setup is custom built in the lab with fiberglass G-10 insulating material. Since intra-winding turn to turn insulation is not the focus of this work, the custom test setup shown in Fig. 4(c) holds one layer of primary and one layer of secondary winding on each side while maintaining the geometry of real transformer. The winding sample is constructed with a 2 mil thick copper foil [19] shaped and layered with 3M 1093 Kapton insulation consisting of around 1 mil thick adhesive silicone backing and 1 mil of
polyimide kapton insulation. The insulation is rated to high temperature class of 180°C and high dielectric strength of 7.5 kV.

3) Optical PD Measurement:

PD are always accompanied by light radiation throughout the entire PD event from primary ionization to extinction. Photo Multiplier Tube (PMT) can detect faint optical signals and the large active lens area makes it ideal to catch the scattered light from the source [20]. Hence, PMT provides high sensitivity and fast response time that is required to optically detect partial discharges. In addition, optical PD detection is a non-invasive technique requiring no physical voltage and current measurements from the circuit. This makes it naturally immune to the switching artifacts produced by the fast switching power electronics circuit. Hence, PD detection is possible by visualizing the raw data with no post-processing required. Utmost care should be taken to ensure that the test area is light-free with no external sources of light that can add noise to the measurement. The optical PD measurements are validated by comparing them with the PD measurements obtained by Heafly coupling capacitor based PD detector at 60 Hz. Consistent results are obtained by both methods validating the authenticity of PMT based optical PD detection.

The experimental testbed is shown in Fig. 4(d). The test is performed inside the Faraday cage facility to isolate the test circuit from switching noise and other background noises produced by the PWM source. Faraday cage is equipped with dedicated climate control equipment that maintains consistent ambient conditions of 22°C and 28% relative humidity. The grounded Faraday cage is built with solid steel on all six faces of the room, which also provides an optical noise-free environment for accurate PD detection. PMT is placed vertically facing the adjacent edges of the primary and secondary side winding samples and PWM voltage excitation is given to the primary winding. The distance between PMT lens and winding sample is kept at approximately 6 inches. The voltage across the winding is measured with a high speed differential voltage probe. The voltage measurement is plotted against the output of the PMT to identify PD along the voltage waveform. The voltage $V_{TR}$ is plotted against the ground current $I_{BD}$ during accelerated life tests. The data is visualized on an oscilloscope with 1 GHz bandwidth placed outside the Faraday cage. Common mode chokes are placed in between the long measurement leads to filter the radiated EMI noise generated by the fast switching SiC MOSFETs of the PWM generator at the rising and falling edges of the PWM voltage. The secondary side winding specimen is grounded in order to create a unipolar peak potential state identical to phase-shift modulated DC SST.

PD characterization experiments were performed on foil winding specimens under varying PWM frequency. The test scenarios are listed in Table 1. For each test case, the frequency is kept constant and the voltage of the PWM generator is increased progressively until light photons are detected by the PMT. The voltage across the winding specimen and the PMT output voltage is recorded in a mixed signal oscilloscope for real-time visualization. Presence of light (discharge) is indicated by the PMT by its characteristic negative voltage pulses. PMT measurements exhibit the periodic nature of discharge that is aligned with the rising and falling edge of the

| Test Case | PWM Frequency | dv/dt |
|-----------|---------------|-------|
| 1         | 10 Hz         |       |
| 2         | 100 Hz        |       |
| 3         | 1 kHz         |       |
| 4         | 10 kHz        | 30 V/ns|
| 5         | 20 kHz        |       |
| 6         | 30 kHz        |       |
| 7         | 40 kHz        |       |
| 8         | 50 kHz        |       |
| 9         | 10 Hz         |       |
| 10        | 100 Hz        |       |
| 11        | 1 kHz         |       |
| 12        | 10 kHz        |       |
| 13        | 20 kHz        |       |
| 14        | 30 kHz        |       |
| 15        | 40 kHz        |       |
| 16        | 50 kHz        |       |

TABLE I

Test Cases Used for PD Characterization

Figure 5. Partial Discharge Inception Voltage (PDIV) measurement results with $dv/dt = 30$ V/ns at: (a) 10 kHz PWM frequency; (b) 50 kHz PWM frequency

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PWM voltage pulse, thus proving that the measured light is partial discharge. The MF PWM generator voltage at which partial discharge incepts is recorded as partial discharge inception voltage.

Partial discharge inception voltage (PDIV) measurements at 10 kHz PWM and 50 kHz PWM with dv/dt of 30 V/ns is shown in Fig. 5 (a)-(b) respectively. The pulsed output of PMT aligns with the rising and falling edges of the voltage waveform indicating presence of PD activity at the first quadrant and third quadrant of the ac wave. PD pattern in the first and third quadrant of the ac waveform is a typical characteristic in ac waveforms due to space charge accumulation. The specimen is held at a voltage marginally greater than PDIV for short duration then the PWM generator voltage is progressively decreased until no PD is detected by the PMT. The voltage at which PD extinguishes is recorded as partial discharge extinction voltage. This implies that once PDIV is reached, PD activity will continue until the DC SST system voltage is reduced to reach PDEV. It should be noted that for each test case, fresh winding specimens are tested until three congruent results are obtained. Premature PD activity was observed in bad samples containing air pocket defects hence, they were eliminated from the study.

The correlation of PD characteristics with switching frequency is derived by increasing the switching frequency of test waveforms. It should be noted that the tests were performed at 8 different PWM frequencies and 2 dv/dt cases as listed in Table 1. All the tests were performed in climate controlled lab area with ambient temperature averaging to 25°C and at normal atmospheric pressure. More than three fresh samples were identically fabricated and tested for each case. The first test case is PWM frequency of 10 Hz. The dc-link voltage of the MF generator was progressively increased in increments of 25 V and the specimen is held at each voltage for a few seconds before the progressive increase. The voltage is increased until PD is detected by the PMT and the voltage is recorded as PDIV. The red curve in Fig. 6 represents PDIV test results. The PDIV for sub kilo-hertz PWM frequencies is found higher than kilo-hertz frequencies. At 10 kHz and above frequencies, the PDIV is 25% lower than PDIV at 100 Hz. Moreover, beyond 10 kHz, PDIV shows negligible dependence on PWM frequency. On one side, the shape of voltage waveform influences the distribution of voltage with the winding sample. On the other, the fast switching potential difference with switching transients influence the discharge physics at microscopic levels within the same conductor as well as between two adjacent conductors. Hence marginal dependence of PDIV on switching frequency is observed when comparing the results of sub kilo-hertz low PWM frequencies with tens of kilo-hertz frequency. This can be explained by Cole-Cole model [21] that describes the inverse relationship of dielectric permittivity with frequency. However, state of the art DC SST’s MF transformer withstands PWM frequencies between 10 kHz to 50 kHz, where PDIV shows no dependence on PWM frequency.

Partial discharge extinction voltage (PDEV) can be up to 35% below PDIV[22], hence, the MF transformer should be designed in such way that its absolute peak operating voltage is always below PDEV so that the discharges that are incepted during a temporary over voltage are definitely quenched at the restored operating voltage. To measure PDEV, the test sample is held at a voltage higher than PDIV, a value greater than 25% over PDEV is used in this case and then the dc-link voltage is progressively decreased at 5 to 10 V intervals until the pulsed output of PMT disappears and V_{PMT} = 0 against V_{TR}. It should be noted that when V_{TR} reaches close to PDEV, the strength of the discharge decreases considerably which is exhibited by the lower amplitude and width of the PD pulses measured by the PMT. The PD activity also becomes aperiodic. PDEV is the voltage at which PD is completely extinguished. Therefore, PDEV is recorded at the dc-link voltage where no PD is detected by the PMT for more than a minute. The blue curve in Fig. 6 represents PDEV test results. Identical ratio between PDIV and PDEV values is obtained for all test cases. It is noted that the PDIV and PDEV in Fig. 6 are measured without considering the voltage ringing effect. This is due to the fact that voltage ringing can be limited by design.

Two dv/dt cases of 30 V/ns and 60 V/ns have been tested for PDIV and PDEV at PWM frequencies between 10 Hz to 50 kHz for both dv/dt. No variation in measured quantities were observed during the test that exhibits that PD characteristics are independent of tested dv/dt in PWM waveform. An explanation to this behavior is linked with the PWM waveform shape where voltage commutation is naturally fast due to steep voltage rising and falling edges. Although the change of dv/dt from 30 V/ns to 60 V/ns is significant from the semiconductor standpoint despite that, it was not enough to generate a difference in PD characteristics.

It is crucial to understand the PD characteristics of MF transformer windings because each PD event degrades the insulation material. In doing so, it considerably reduces the lifetime of the MF transformer. Since PD event is a function of switching frequency, the lifetime of the transformer is inversely proportional to the switching frequency. Next section highlights the lifetime characteristics of MF transformer.

IV. LIFETIME MODEL DEVELOPMENT

Each partial discharge event degrades the insulation and reduces the lifetime. The winding specimen was subjected to repetitive partial discharge which degraded insulation material, creating an electric arc flashover through a pinhole defect on the surface of the insulation.

To study the lifetime characteristics of Kapton insulated foil winding, dielectric breakdown (life) tests were performed in the lab. Five switching frequencies between 10 kHz to 50 kHz are
selected with two dv/dt cases of 30 V/ns and 60 V/ns to maintain consistency with the partial discharge characteristics measurement. This dv/dt and frequency combination is adequate for SiC enabled DC SST. Test setup shown in Fig. 4(a) has already been discussed in previous section, hence it will not be discussed again in this section. For each data point, more than 3 samples are tested to identify and avoid stochasticity in hand made winding samples.

The winding sample is stress tested at square ac peak voltage 2 kV by maintaining the input voltage until dielectric breakdown occurs. The dielectric breakdown (BD) test is performed in presence of partial discharges since the test voltage is beyond PDIV as tested in previous section. The ac voltage is plotted on the oscilloscope by measuring \( V_{Tr} \). When dielectric breakdown occurs, the voltage insulation between the primary and secondary side no longer exists which can be observed by the sudden fall of measured voltage \( V_{tr} \). At this instant, a voltage difference is created at the current limiting resistance \( R_{ext} \) inserted between the half bridge and the windings. This resistance limits the short circuit current to \( V_{BD}/R_{ext} \) to a safe value for the semiconductor device. At the same time, de-sat protection activates and ceases the switching action to protect the circuit from an arc fault. Activation of de-sat protection observed with the rise in measured current \( I_{BD} \) is an indication of a dielectric breakdown of winding insulation. The test is repeated for each operating point with new samples until three homogenous breakdown times are achieved. Broken down winding samples are tested under a microscope to assess the damage and identify the pinhole breakdown spot that remains unnoticeable by naked eye. The magnitude of damage remains small due to negligible current flow in the test circuit. The breakdown energy will increase when the transformer winding is loaded with current.

The electrical measurements obtained at the breakdown instant for 10 kHz PWM frequency is shown in Fig. 7(a) and for 50 kHz PWM frequency in Fig. 7(b). It should be noted that breakdown occurs either during the rising edge of the voltage, shown in Fig. 7(b) or in between the peak voltage level, shown in Fig. 7(a). This behavior is due to the unipolar nature of the PWM potential difference applied at the MF transformer winding sample, which enhances the electric field between the primary and secondary winding during the I\(^{\text{st}}\) and II\(^{\text{nd}}\) quadrant of the ac waveform. During the III\(^{\text{rd}}\) and IV\(^{\text{th}}\) quadrant, the electric field decreases at the beginning of III\(^{\text{rd}}\) quadrant and increases only when the next ac cycle begins.

The breakdown times obtained for each test case is plotted in Fig. 8. From the plot, it is evident that dielectric breakdown is highly dependent on the ac frequency and follows an inversely proportional relationship with ac frequency. The breakdown time is significantly shorter for 50 kHz ac frequency as compared to 10 kHz ac. The test is repeated for two rise and fall dV/dT condition: 30 V/ns & 60 V/ns. MF transformer lifetime models are developed from the obtained test results which will be discussed in the next sections. The lifetime test results obtained for AC PWM frequency of 10 kHz to 50 kHz are utilized to derive a lifetime model for foil-type transformers that can extrapolate the lifetime of the winding specimen at a desired ac frequency by using one experimentally obtained lifetime test data as reference shown in Eq. (2) where \( L_{fa} \) is lifetime at PWM frequency \( n \); \( L_{ref} \) stands for the measured lifetime at a reference frequency; \( f_{ref} \) is the reference frequency at which \( L_{ref} \) is measured; \( f_i \) is the PWM frequency of interest to calculate lifetime and \( k \) is the experimentally derived constant that is dependent on dv/dt of PWM waveform. Similar lifetime model has been derived in [10] for motor windings. The derived model shows good confidence extrapolating the lifetime of foil winding at any desired frequencies by using one experimentally obtained lifetime at set operating conditions as reference.

\[
L_{fa} = L_{ref} \left( \frac{f_{ref}}{f_i} \right)^k \tag{2}
\]

Insulation life heavily depends on the PWM frequency and follows an inverse relationship. The alternating electric fields imparts stress on the insulation material. If the applied voltage is beyond PDIV, there will be inception and extinction of partial discharges in each ac cycle. Hence, the number of PD events in a unit time is proportional to the PWM frequency. This means that at higher PWM frequency, there will be more PD events in a unit time compared to a lower PWM frequency. As a consequence, at high frequency, the insulation material will suffer from higher degradation due to PD than at low PWM frequency. As a result of dielectric degradation due to PD, fastest breakdown is observed at 50 kHz during the test.

Additionally, the exponent of the frequency rational term \( k \) varies with dv/dt because breakdown is dependent on switching.
speed as well. The exponent of frequency rational term is obtained by curve fitting of experimentally obtained breakdown times. The calculated values are $k = 1.25$ for $dv/dt$ of 30 V/ns and $k = 1.4$ for $dv/dt$ of 60 V/ns. This establishes that the breakdown characteristics for the transformer winding is dependent on both switching frequency and switching speed. Faster switching speeds will negatively impact the MF transformer lifetime. Hence, an extended model is developed in the next section that considers the effect of PWM frequency and $dv/dt$.

Unlike PDIV, switching speed impacts the breakdown endurance of Kapton insulated foil winding. In Fig. 8 the magenta curve plots the results obtained at 30 V/ns switching speeds and the blue curve plots 60 V/ns switching speed. The test results for 30 V/ns show slightly better dielectric breakdown endurance than the faster 60 V/ns case. In the previous section, lifetime model is derived for varying PWM frequency at a fixed $dv/dt$. The experiment results conclude the dependency of insulation lifetime on switching speed which is factored into the model with the exponential constant of the switching frequency rational. Based on the experimental data, an extended lifetime model is derived as shown in Eq. (3). This model is an extension of Eq. (2) and accounts for change in PWM frequency as well as effect of $dv/dt$. The extended model is obtained by curve fitting of experimental breakdown data and this model is used to extrapolate the lifetime in $\forall$ 9 using 10 kHz as $f_{ref}$ and experimentally obtained lifetime at $dv/dt = 30$ V/ns as $L_{ref}$.

$$L_{f_n,dv/dT_n} = L_{ref} \left( \frac{f_{ref}}{f_n} \right)^{1.25} \left( \frac{dv/dT_{ref}}{dv/dT_n} \right) \frac{f_n}{dv/dT_n}$$  \hspace{1cm} (3)

The model is then used to extrapolate the lifetime at 20 kHz to 50 kHz for switching speed of 30 V/ns and 10 kHz to 50 kHz for 60 V/ns. The presented extrapolation boundary is between 10 kHz and 50 kHz because that is the range of experimental test data that is used for model validation. The model tolerance is within 17% of the experimental data where the highest deviation observed from the 30 kHz test data. For the other frequencies the model prediction lies within the experimental error boundaries, thus proving the effectiveness of the extended lifetime model for foil type medium frequency transformers. The effect of peak PWM voltage is not considered because of inability to obtain experimental results at greater than 2 kV dc link voltages. This is because the PWM source is built using 3.3 kV device.

V. CONCLUSION

Novel findings on partial discharge characteristics for a foil type transformer constructed with Kapton insulation over copper foil is presented in this paper. PD inception voltage and PD extinction voltage is characterized for PWM frequencies between 10 Hz to 50 kHz. PDIV and PDEV values are about 18% higher for PWM frequencies less than 1 kHz. PD characteristics are found to have negligible dependency on $dv/dt$ for the two $dv/dt$ test cases.

Dielectric breakdown experiments are also performed in the lab with varying switching frequency and switching speed and accelerated breakdown tests were performed in presence of partial discharge. Lifetime of Kapton insulated foil winding exhibits negative exponential relationship with switching frequency and $dv/dt$. Transformer lifetime models are derived for varying frequency from empirically obtained test results and a unified lifetime model considering the effect of frequency and switching speed is also developed. The derived models serve as baseline for MF transformer lifetime estimation, real-time health monitoring as well as accelerated lifetime testing for DC SSTs. The derived models provide valuable lifetime information that can support converter optimization to achieve best efficiency, power density and reliability. Future work will continue to improve the insulation design to obtain PD free operation at high $dv/dt$ MF PWM. The obtained lifetime model considers two electrical factors: frequency and $dv/dt$. Future work is also targeted to enhance the lifetime model by including the effect of voltage stress to identify the dominating factor in PD inception and winding breakdown. The effect of ambient conditions will also be studied along with winding to core insulation.

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