

Investigation of Motor Winding Overvoltages in Integrated WBG-Based Motor Drive Systems

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Abstract— Cable-connected motor winding insulation is prone to failures owing to reflected wave (RFW) overvoltages (OV). RFW is caused by the impedance mismatch between source and load and impacted by the impedance interactions of the motor drive system and pulse width and risetime of the excitation source. According to the literature, the OV across the motor winding is less detrimental in an integrated motor drive due to the absence of cable. However, in this paper, two scenarios are shown which can cause detrimental voltage stress across the winding in an integrated wide band gap (WBG)-based drive system. First, WBG-based motor drive generates short risetime and short pulse width that excites the higher frequency resonance network of the integrated motor winding. So, it brings higher OV amplitude across the motor winding. Second, voltage stress across motor winding is shown to worsen when the antiresonance of the winding (least impedance) coincides with OV resonance frequency across it, termed as antiresonance phenomenon (ARP). Due to the absence of cable, the ARP is bound to happen in an integrated drive system. Experimental results are given to validate the claims.

Keywords—Integrated drive system, WBG_ based drive, overvoltage stress, reflected wave.

I. INTRODUCTION

The transient voltages caused by traveling waves through the cable between the inverter and the motor can cause higher motor side overvoltages (OV) known as reflected wave phenomenon (RWP) [1], lowering the insulation reliability [2]. Motor winding insulation failure is reported to be one of the main causes of motor failures [3] which gains more importance to this study. On the other hand, integrated motor drives gain popularity where space is a primary concern [4]. Even though much research has been done in characterization and quantification of RWP [1] and [5], it is yet to be analyzed with the integrated motor drive systems and effects of WBG excitations on that.

On one hand, emerging application of wide band gap (WBG) devices in motor drive systems despite the reduced switching losses, improved waveform quality and reduced package size [6], brings shorter pulse width and shorter risetime to the system [7]. Also, the new generation design of high-

power density motor drive with low winding impedance is growing [8]. Such a motor winding and cable impedance create a complex combination of resonances/ antiresonances. See Fig. 1 as the schematic for a motor drive system. WBG power electronics induces higher dV/dt and di/dt into the system resonances, increasing voltage stress at high frequencies across the motor winding insulation [9] and [10].

On the other hand, it is known that the long cables always cause critical OVs across the load due to a higher OV magnitude, and the motor drives with shorter cables are immune from that [11]. However, knowledge only on the OVs' magnitude does not guarantee the reliability of the motor windings. Antiresonance phenomenon (ARP), overlapping of antiresonance of motor winding differential mode (DM) impedance with OV frequency across it is detrimental as it exacerbates the stress on windings. The factor of the ratio of overvoltage magnitude to impedance across it ($|\text{overvoltage}/\text{impedance}|$), should be analyzed as shows the system prone to failure due to the high voltage stress [9] and [12].

The rest of the paper is as follows. First, two scenarios 1) WBG excitations and 2) occurrence of the ARP that can be detrimental regarding voltage stress across motor winding insulation in an integrated drive system are introduced. Then, practical test results are given. Finally, the conclusion and future work is presented.

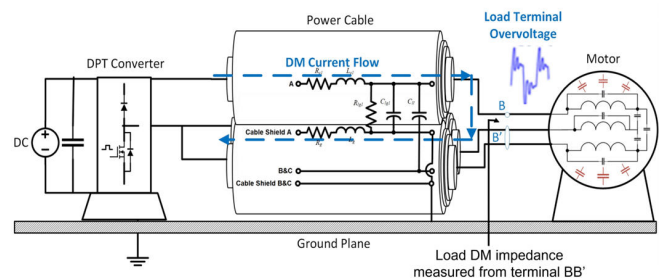


Fig. 1. Cable connected motor drive system DPT schematic.

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II. OVERVOLTAGES ACROSS MOTOR WINDING IN AN INTEGRATED DRIVE SYSTEM

It is mentioned in previous works that the OV due to the long cable between the motor and the inverter can be eliminated with an integrated drive system [11]. However, it is not always the case and there are scenarios which can be detrimental for winding insulation health even in an integrated motor drive system. A lack of clear understanding of the OVs could cause insulation degradation for the motor winding. Two of the scenarios which may cause detrimental voltage stress are discussed in the following.

A. Overvoltages in System with WBG Excitation

The higher frequency and shorter risetime of WBG devices can excite the resonance network of the system more, so higher amplitude of the OV can happen across the motor winding. To show the risetime and pulse width impact in a WBG-based motor drive system, a trapezoidal shape voltage source shown in Fig. 2(a) is modeled as switching devices are the main noise sources in power electronic devices [13]. Fig. 2(b) shows the harmonic spectrum of a trapezoidal waveform. So, the harmonic spectrum in Fig. 2(b) starts with 0 dB/decade up to the first breakpoint $f_1=1/\pi\tau$. The value drops with the slope of -20 dB/decade up to $f_2=1/\pi\tau_r$. Beyond this point, the magnitude drops by the slope of -40 dB/decade. Fig. 3 describes how fast the short rise time (τ_r) and shorter pulse width (τ) in HF excitations increase the bandwidth of the noise sources using WBG. The black waveform in Fig. 3 shows a motor impedance response with higher frequency resonances which happens in an integrated motor due to the less inductance value compared to the red waveform. Although, the resonance network of a motor with the impedance response such as red waveform can be excited by Si drive system, it can't excite an integrated motor drive resonance network. However, GaN excitation can still excite the resonance network in an integrated motor.

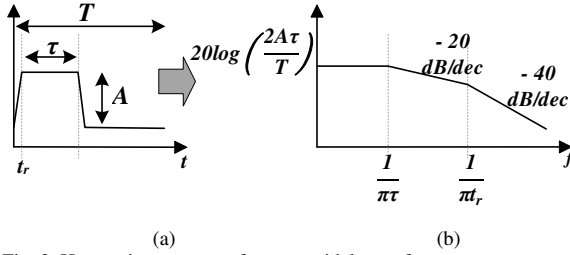


Fig. 2. Harmonic spectrum of a trapezoidal waveform

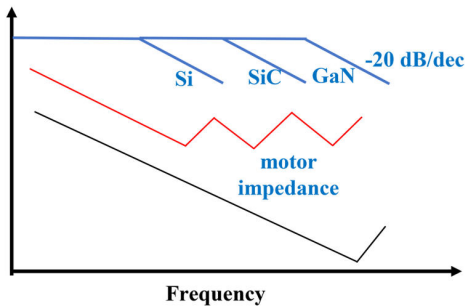


Fig. 3. AR excitation by different WBG

B. ARP in an Integrated Motor Drive

It is essential to highlight the importance of the ARP as critical voltage stress study. The occurrence of ARP could change with variations in the design and layout configuration of the system in a segregated motor drive system (using cable connecting the converter to the load) [9] and [12]. However, it should be highlighted that integrated drive system is always bound to occurrence of ARP. This is due to the absence of cable in such kind of a system in which the OV resonance frequency across the load terminal is the same as the load antiresonance frequency.

To better explain the ARP occurrence, Fig. 4 shows a sample of a FFT of the OV versus DM impedance waveform in a WBG-based drive system. As indicated in Fig. 4, the OV across load has three resonances of which the third resonance coincides with the load DM impedance AR; ARP happens. The first and second resonances are away from the load impedance AR with a good margin [12].

III. EXPERIMENTAL RESULTS

A test setup established to validate the OV stress critical scenarios in an integrated motor drive system and comparison with the segregated one. Fig. 5(a) shows the test setup for segregated motor drive. The test setup for the integrated drive system is given in Fig. 5(b). Experimental setups are comprised of WBG split phase DC/AC converter [14] used as double pulse test (DPT) board, motor coil as load and cable connecting the converter to the load in the segregated drive system. In this paper to present the guideline of the study, coils are used as the sample of motor winding to represent a low impedance motor winding with HF impedance interactions in a WBG-based motor drive system. The DM impedance measurements across the load are gained using Bode 100 Network Analyzer and the coils are set up in the same testbed as DPT as in Fig. 5. The load terminal voltage is measured with Tektronix THDP0200 200 MHz differential probes. Similarly, 1 GHz oscilloscopes MSO56 by Tektronix were utilized to have precise and accurate measurements.

A. Overvoltages in System with WBG Excitation

DPT is performed on integrated drive configuration. The FFT of the voltage across the coil is shown for integrated system with short and longer risetime in Fig. 6(a). As it is-

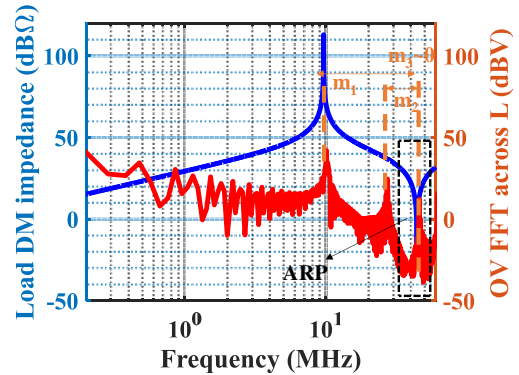


Fig. 4. Introduction on ARP occurrence

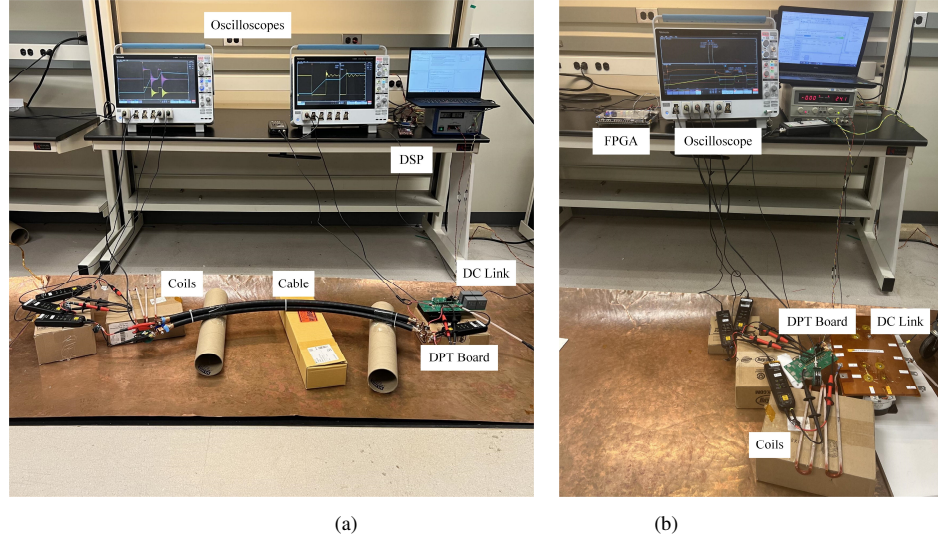


Fig. 5. Experimental setup, DPT test using (a) 1-m cable (b) integrated coil and converter.

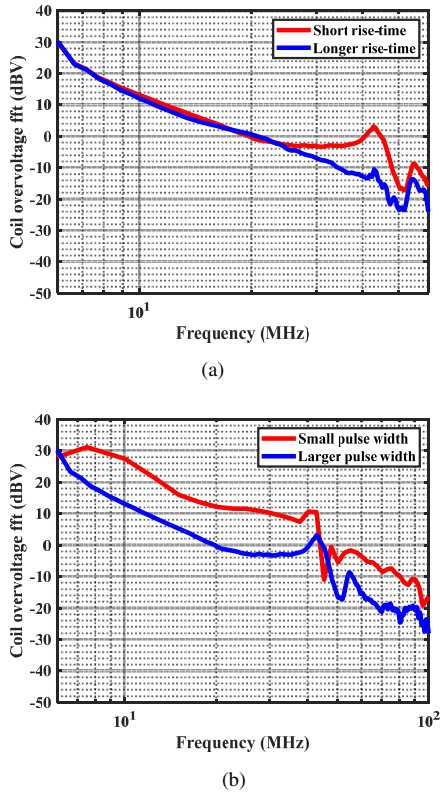


Fig. 6. WBG excitation of an integrated motor drive (a) short vs. longer t_r , (b) short vs. larger τ

-shown the OV resonance amplitude is higher in the case with shorter risetime. The test is repeated for the short and longer pulse width excitation under 100 V DC bus voltage. The amplitude of the OV resonances is higher for shorter pulse width excitation in a WBG-based drive system as shown in Fig. 6(b). The risetime and pulse width values in each of the cases and the

WBG excitation source impacted HF bandwidth ($\frac{1}{\pi t_r}$ and $\frac{1}{\pi \tau}$) is given in table 1.

The $1/\pi t_r$ and $1/\pi \tau$ frequencies shift to the right respectively for shorter risetime and shorter pulse width as demonstrated in Fig 3. This results in higher amplitude of the resonances, which validates the amplitude of the OV resonances given in Fig. 6.

B. ARP in an Integrated Motor Drive

In Fig. 7 and 8 (a), the OV across the motor coil terminal under DPT test is shown for segregated drive system and the integrated one, respectively. The test is kept same for both cases under 100 V DC source and the same DPT pulse width and risetime ($\tau = 1 \mu s$ and $t_r = 8 ns$). It can be seen from Fig. 7 and 8 (a) that the OV amplitude across coil is higher in the segregated system compared to the integrated one. However, in the following, the study of the ARP in both systems shows that the coil is under voltage stress in integrated drive as well. The superimposition of the OV resonances with the coil DM impedance is given in frequency domain in Fig. 7 and 8 (b). Although there is a higher amplitude OV resonance across the motor coil in segregated system (Fig. 7 (b)), the ARP does not happen in this case. As can be seen from Fig. 7 (b), the OV frequencies are away from the load DM impedance AR using 1m cable. As it is shown in Fig. 8 (b), although the amplitude of the OV resonance is less in the integrated system compared to the segregated one, coincides with the coil DM AR-

Table 1. Excitation source parameters of the practical DPT tests

Test	a		b	
	Longer t_r	Shorter t_r	Longer τ	Shorter τ
t_r (ns)	8	16	8	
τ (μs)	1		1	0.5
$\frac{1}{\pi t_r}$ (MHz)	40	20	40	
$\frac{1}{\pi \tau}$ (kHz)	0.6		0.6	1.2

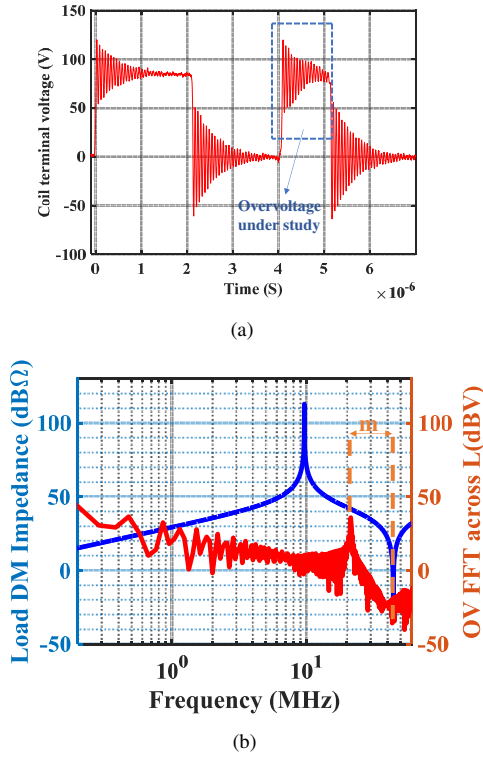


Fig. 7. (a) Coil terminal voltage (b) OV vs coil impedance in the segregated system.

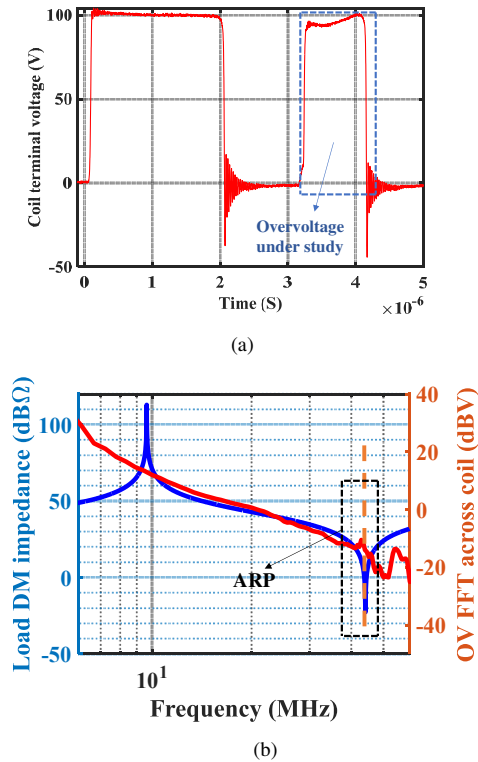


Fig. 8. (a) Coil terminal voltage (b) OV vs coil impedance in the integrated system.

impedance. Hence, the voltage stress (overvoltage/impedance), across the load could be detrimental in this case [11]. The overvoltage stress is calculated for the segregated and integrated system at 20 and 45 MHz which is $\frac{80V}{108\Omega} = 0.74$ and $\frac{18V}{0.067\Omega} = 265$, respectively. The values given in this paper are only to demonstrate the voltage stress that could be higher in integrated drive system and detail investigation based on insulation tolerance required to be studied.

In this section, the same excitation source is used for the segregated and integrated drive systems. However, due to the purpose of higher power density design of integrated systems, they are derived with higher frequency and risetime. So, other than occurrence of ARP in the integrated system, the voltage stress could be even worse due to WBG excitation. i.e., both scenarios together put the insulation health under critical situation.

IV. CONCLUSION

In this paper it is shown that the OV stress can still be detrimental for the motor winding insulation despite the higher frequency resonance network and no cable in an integrated motor drive. WBG excitation and ARP occurrence cause higher voltage stress across the motor winding indicated as the cause of that. This study shows the importance of filter/ insulation design to alleviate voltage stress. Also, improved reference of HF power stability data for standards should be developed taking into consideration the influences from WBG power devices on the filter sizing and other system components.

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