Influence of System Layout on CM EMI Noise of SiC Electric Vehicle Powertrains

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Abstract—This paper investigates the influences of system layout on common mode (CM) EMI noise of an electric vehicle (EV) powertrain with a traction inverter using silicon carbide (SiC) MOSFETs. First, a system level conducted EMI model for the whole SiC EV powertrain is presented, which includes a battery pack, DC cables, a SiC inverter, AC cables, and a PMSM. Then, the impacts of system layout, such as the AC cable length, the AC cable type, and the DC cable type (shielded cable and unshielded cable) on CM EMI noise are analyzed through time domain simulations of the system level conducted EMI model. Next, a conducted EMI emission test-bed for a SiC EV powertrain is built. Finally, experiments on the test-bed are carried out to verify the influences of system layout on CM EMI noise in the SiC EV powertrain.

Index Terms— Cable, common mode (CM) electromagnetic interference (EMI), electric vehicle (EV) powertrain, silicon carbide (SiC) MOSFET, system layout.

I. INTRODUCTION

DUE to outstanding performance of wide-band-gap (WBG) devices such as higher switching speed and smaller loss, it can reduce the size of the powertrain and increase the mileage of electric vehicles (EVs) [1]–[4]. Therefore, development of inverters with WBG devices for EVs becomes a hot topic recently. Although inverters with silicon carbide (SiC) MOSFETs have been used in Tesla car and other products [5], [6], electromagnetic interference (EMI) issues of SiC MOSFETs' high switching frequency and high dv/dt are still concern.

In an EV powertrain, the inverter operates under PWM control, the inverter AC terminal potentials vary between the positive and negative rails of the DC bus, leading to high frequency step-like common-mode (CM) voltage source waveforms with a high value of dv/dt . The CM voltage source not only drives leakage current into the ground system (vehicle frame) due to parasitic capacitance in the powertrain (i.e. battery, inverter, cables, and traction motor) [7]–[9], which may induce EMI noise to various electronic devices and equipment in the car [10]. System layout determines many parasitic

parameters, impacts CM EMI noise propagation paths, and influences system CM EMI noise.

The modelling and suppression of conducted emission of SiC EV powertrains have been investigated by predecessors. Their works can be classified into three categories. First category of papers studied the noise source characteristics of SiC inverters. The EMI noise source of SiC inverters has three features in comparison to that of IGBT inverters. First, SiC inverters generate higher EMI noise for they work at a higher switching frequency [11], [12]. Second, the high dv/dt of SiC inverters, up to ten times higher than that of IGBT inverters, causes high EMI noise in powertrains [13], [14]. Lastly, serious switching ringing in the SiC MOSFET turn-off process causes extra EMI noise in powertrains [12], [15].

The second category of papers investigated EMI noise transmission paths. Noise transmission paths include cables, motors, etc. Permanent magnet synchronous motor (PMSM) EMI model is derived by either measurement [16], [17] or analytical model according to electric machine theory [18], [19]. The measurement based model is practical and useful for motor drive EMI simulation, but the physical meaning of the circuit is not clear. The analytical model has a clear physical meaning, and circuit parameters are estimated by numerical formulae or by electromagnetic field analysis. For an EV powertrain with a certain PMSM, the setup of cables impacts the EMI noise propagation paths and system conducted emission [20]–[25]. The effects of long cable on motor overvoltage and conducted emission problem have been studied in adjustable speed drive [20], [21]. In [22], the equivalent circuit model of the return paths of CM EMI noise currents in EV powertrain is proposed. The CM current return paths include braided shield of three-phase cables and the metallic vehicle body. In [23], an analytical approach to obtain the shield and ground currents as a function of the inner conductor current is presented to quantify the current distribution between the shield and the ground. In [24], the impact of connecting and disconnecting the shield terminals of the DC power bus on the line impedance stabilization network (LISN) voltage and the CM current is presented. In [25], the effects of separately shielded cables and cables with a total shield for three phases on the emission in EV powertrains are studied in time and frequency domain. The separately shielded cables achieve worse results.

The third category of papers tried to suppress EMI noise in the system. Filtering technique, cancelling technique, and balance

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Fig. 1. A diagram of conducted emission test setup of an EV powertrain.

technique for conducted EMI noise reduction have been reported in the literature. Filtering technique refers to the use of passive filters which are inserted to the converter system to block or bypass EMI noise [7], [26]. Cancelling technique usually refers to the use of active EMI filters which generate a current/voltage to cancel with EMI noise [27], [28]. Balance technique refers to the creation of a Wheatstone impedance bridge by adding several passive components to the system [29], [30].

As mentioned above, although the noise characteristics of a SiC inverter have been studied, the modelling of noise transmission paths, and the EMI noise suppression of motor drive system have been published in the literature. A study on the impacts of system layout, such as AC cable length, AC and DC cable type (shielded cables and unshielded cables) on CM EMI noise of SiC EV powertrains is needed through both theoretical analysis and experimental results. This paper investigates the influences of system layout on CM EMI noise of a SiC EV powertrain. First, a system-level conducted EMI model for the whole powertrain is presented. Based on this model, the impacts of AC cable length, AC and DC cable type on CM EMI noise are discussed. Finally, experiments on a conducted EMI test-bed are carried out to verify the influences of the system layout on CM EMI noise in a SiC EV powertrain.

II. SYSTEM-LEVEL CONDUCTED EMI MODEL

Fig. 1 shows a diagram of the conducted emission test setup of an EV powertrain, which includes a battery pack, LISNs, DC cables, a SiC inverter, AC cables, and a PMSM. The battery pack chassis, LISN chassis, inverter chassis, and frame of the PMSM are connected to the ground plane for safety consideration.

In CM noise analysis, lower switches are replaced by voltage sources v_{AN} , v_{BN} , and v_{CN} . The positive DC terminal P and the negative DC terminal N are considered as short-circuited because the inverter DC voltage is almost fixed by using a bulk capacitor C_d . As a result, each of the upper switches is in parallel with the lower switch. Assuming that parameters of the positive DC line are the same as the negative line, CM currents in the positive and the negative DC lines are the same. Hence, LISNs terminals of node P_1 and node N_1 can be short-circuited. In the AC side, the PWM modulation for a three-phase inverter is symmetric, namely v_{AN} , v_{BN} and v_{CN} are shifted 120° between each other. In this case, node A , node B , and node C can be short-circuited in CM analysis because CM components of v_{AN} , v_{BN} and v_{CN} are the same, which is derived in detail in the

Fig. 2. A simplified CM EMI model of an EV powertrain.

Appendix-A. Assuming that parameters of phase A , phase B , and phase C are the same, CM currents in the three phases are the same. As a result, PMSM terminals of node A_1 , node B_1 , and node C_1 can be short-circuited. In addition, DC cables and AC cables are modeled as π -type lumped circuits, L_d and C_{dg} are the equivalent inductance and capacitance of DC cables, L_a and C_{ag} are the equivalent inductance and capacitance of AC cables. The CM model of the system is simplified and shown in Fig. 2. Z_{LISNs} is the impedance of the LISNs, which can be calculated through the circuit of LISN in Fig. 1. Z_{PM} is the CM impedance of the PMSM, which is obtained by measurement. It should be noticed that the distributed parameter effect is ignored in the simplified CM EMI model. According to the transmission line theory, this lumped circuit model for cables is suitable when the cable length l is electrically short at the excitation frequency, generally $l < \lambda/10$. In the prototype, it can be derived that the lumped circuit model can be used in the frequency lower than 10 MHz for DC cable is 1.8 m and AC cable is 1.6 m in the prototype.

The CM noise source v_{CM0} in Fig. 2 is defined as follows [32]:

$$v_{CM0} = \frac{v_{AN} + v_{BN} + v_{CN}}{3} \quad (1)$$

According to the circuit theory, CM LISN voltage v_{LISN} is expressed as follows:

$$V_{LISN} = -A_d \frac{Z_{dg}}{Z_{dg} + Z_{ag}} V_{CM0} \quad (2)$$

where V_{LISN} and V_{CM0} are the Laplace transformation of v_{LISN} and v_{CM0} , respectively. The AC impedance Z_{ag} , the DC impedance Z_{dg} , and the voltage ratio A_d from V_{LISN} to V_{dg} are expressed as follows:

$$\begin{cases} Z_{ag} = \frac{1}{s \left(3C_d + \frac{C_{ag}}{2} \right)} // \left(sL_a + Z_{PM} // \frac{1}{s \frac{C_{ag}}{2}} \right) \\ Z_{dg} = \frac{1}{s \left(3C_d + \frac{C_{dg}}{2} \right)} // \left(sL_d + Z_{LISNs} // \frac{1}{s \frac{C_{dg}}{2}} \right) \\ A_d = \frac{V_{LISN}}{V_{dg}} = \frac{Z_{LISNs} // \frac{1}{s \frac{C_{dg}}{2}}}{sL_d + Z_{LISNs} // \frac{1}{s \frac{C_{dg}}{2}}} \end{cases} \quad (3)$$

TABLE I
EQUIVALENT INDUCTANCE AND CAPACITANCE OF DC AND AC CABLES

Item	Symbol	Shielded cable		Unshielded cable	
		Expression	Value	Expression	Value
DC cable	L_d	$l_d \frac{L_c - L_s}{2}$	51.8 nH	$l_d \frac{L_c + L_m}{2}$	848.3 nH
	C_{dg}	$2l_d C_{cs}$	1.5 nF	$2l_d C_{cg}$	60.7 pF
AC cable	L_a	$l_d \frac{L_c - L_s}{3}$	30.7 nH	$l_d \frac{L_c + 2L_m}{3}$	727.2 nH
	C_{ag}	$3l_d C_{cs}$	2.0 nF	$3l_d C_{cg}$	80.9 pF

The per unit length (p.u.l) parameters of DC and AC cables are provided in detail in the Appendix-B. The equivalent inductances and capacitances of DC and AC cables are listed in Table I, which are derived in detail in the Appendix-C. L_c is the p.u.l self-inductances of the cable core. L_s is the p.u.l self-inductances of the shield for shielded cables. L_m is the p.u.l mutual inductance between cores of one cable and another one. C_{cs} is the p.u.l capacitance between the core and the shield for shielded cables. C_{cg} is the p.u.l capacitance between the core and the ground plane for unshielded cables. l_d and l_a are the lengths of DC and AC cables, respectively. According to formulas in Table I and expression of L_c , L_s , L_m , C_{cs} , and C_{cg} in the Appendix-B, it can be seen that the equivalent inductance of shielded cables is much smaller than that of unshielded cables, whereas the equivalent capacitance of shielded cables is much larger than that of unshielded cables. This is more intuitive when we compare the values in Table I.

For the reason that v_{CM0} in (1) is mainly determined by the characteristics of the SiC MOSFET, the gate drive circuit, and the parasitic parameters of the commutation loop [33], and has little relationship with DC and AC cable type. Hence, the amplitude of V_{LISN}/V_{CM0} can be used to compare LISN voltages of systems with different types of cables. Fig. 3(a) shows the amplitude of V_{LISN}/V_{CM0} of a system with shielded DC and AC cables and a system with shielded DC cables and unshielded AC cables. Fig. 3(b) shows the amplitude of V_{LISN}/V_{CM0} of a system with unshielded DC cables and shielded AC cables and a system with unshielded DC and AC cables. It can be seen that no matter shielded DC cables or unshielded DC cables are used, CM LISN voltage of the system with unshielded AC cables has low harmonics. Fig. 3(c) shows the amplitude of V_{LISN}/V_{CM0} of a system with shielded DC and AC cables and a system with unshielded DC cables and shielded AC cables. Fig. 3(d) shows the amplitude of V_{LISN}/V_{CM0} of a system with shielded DC cables and unshielded AC cables and a system with unshielded DC and AC cables. It can be seen that if shielded AC cables are used, CM LISN voltage of the system with unshielded DC cables has low harmonics. If unshielded AC cables are used, CM LISN voltage of the system with unshielded DC cables has low harmonics in one frequency range, but has high harmonics in another frequency range. Based on the analysis above, unshielded DC cables are used while shielded AC cables are used.

Theoretical analysis based on the simplified CM EMI model

Fig. 3. The amplitude of V_{LISN}/V_{CM0} vs. cable type (a) a system with shielded DC and AC cables vs. a system with shielded DC cables and unshielded AC cables, (b) a system with unshielded DC cables and shielded AC cables vs. a system with unshielded DC and AC cables, (c) a system with shielded DC and AC cables vs. a system with unshielded DC cables and shielded AC cables, and (d) a system with shielded DC cables and unshielded AC cables vs. a system with unshielded DC and AC cables.

Fig. 4. A SiC inverter structure [31].

TABLE II
PARAMETERS OF THE INVERTER [31]

Component	Item	Symbol	Quantity
Laminated DC busbar	Self-inductance	L_{bd}	27.8 nH
	Mutual inductance	M_{bd}	19.8 nH
	Resistance (@ 100 MHz)	R_{bd}	45.0 mΩ
	Capacitance of DC+ to the heatsink	C_{bp}	6.2 pF
AC busbar	Capacitance of DC- to the heatsink	C_{bn}	25.3 pF
	Self-inductance	L_{ba}	11.9 nH
SiC MOS	Capacitance of drain to the heatsink	C_d	119.5 pF
DC capacitor (4 in parallel)	Capacitance	C_0	39.7 μF
	ESL	L_0	6.8 nH
	ESR	R_0	5.8 mΩ

Fig. 5. An inverter EMI model [31].

shows that systems with different types of DC and AC cables have big differences in CM LISN voltages. However, it is difficult to predict the spectrum of CM LISN voltage accurately since parasitic parameters of the SiC inverter and distribution parameter effect of cables are ignored. Here, an accurate system-level EMI model based on parameter extraction is introduced for discussing influences of system layout, such as cable length and cable type on CM LISN voltage.

A. Inverter Model

Fig. 4 shows an inverter structure [31], which is made up of 3-phase SiC MOSFET inverter bridges and DC capacitors with low equivalent series inductance and resistance (ESL, ESR). The parasitic parameters of the laminated DC busbar, the AC busbar, and the SiC MOSFETs are extracted by ANSYS Q3D, whereas the parameters of DC capacitors are measured by an E4990A impedance analyzer from Keysight. These parameters are listed in Table II [31]. Fig. 5 shows the inverter EMI model [31]. The drain-source voltages of the SiC MOSFETs are modeled as trapezoidal voltage sources [13].

The rise time and fall time of the trapezoidal voltage sources in

Fig. 6. A diagram of the gate drive circuit for a SiC inverter bridge.

TABLE III
PARAMETERS OF THE GATE DRIVE CIRCUIT

Item	Symbol	Quantity
Driving voltage	V_c / V_e	+18/-5 V
External gate resistance	R_G	2.5 Ω
SiC MOS internal gate resistance	R_g	1.1 Ω
Gate driver output resistance	R_d	0.4 Ω

Fig. 7. Experimental drain-source voltages of a SiC MOSFET when DC voltage is 320 V and drain current is 60 A (a) turn-off, and (b) turn-on.

Fig. 4 and 5 are obtained through measurements on a classical double-pulse-test platform. A SiC MOSFET C2M0025120D from Wolfspeed is selected for experiments. A diagram of the gate drive circuit for a SiC inverter bridge is shown in Fig. 6. The gate drive circuit contains the digital optocouplers and the gate drivers (IXDI614YI). The driving voltage and the gate resistance are listed in Table III. Waveforms of the SiC MOSFET drain-source voltage v_{ds}(t) are obtained when DC voltage is 320 V and drain current is 60 A. Fig. 7(a) and (b) show test results of v_{ds}(t) in the turn-off and turn-on process, respectively. The rise time of v_{ds}(t) is 10.1 ns, and the fall time of v_{ds}(t) is 15.4 ns.

B. Cable Model

Fig. 8 shows a setup of shielded cables and unshielded cables for DC and AC connections according to CISPR 25, 2016 [34]. The p.u.l parasitic parameters of shielded cables and unshielded cables are extracted by ANSYS Q3D and listed in Table IV.

The frequency range of conducted emission of EV powertrain by voltage method is 150 kHz–108 MHz [34]. The minimum

Fig. 8. A setup of the DC cables and AC cables (a) shielded DC cables, (b) unshielded DC cables, (c) shielded AC cables, and (d) unshielded AC cables.

TABLE IV
PARASITIC PARAMETERS OF THE CABLES

Type	Item	Symbol	Quantity
Shielded	Self-inductance of a core	L_c	583.3 nH/m
	Self-inductance of a shield	L_s	531.5 nH/m
	Mutual inductance of a core and its shield	L_{cs}	531.4 nH/m
	Mutual inductance of cores/shields of one cable and another cable	L_m	385.9 nH/m
	Capacitance of a core and its shield	C_{cs}	482.8 pF/m
	Capacitance of shields of one cable and another cable	C_{ss}	47.8 pF/m
	Capacitance of shield and the ground	C_{sg}	19.1 pF/m
	Resistance of a core (100 MHz)	R_c	0.26 Ω /m
	Resistance of a shield (100 MHz)	R_{cs}	0.11 Ω /m
	Resistance of the ground (100 MHz)	R_g	0.024 Ω /m
Un-shielded	Self-inductance of a core	L'_c	610.0 nH/m
	Mutual inductance of cores	L'_m	388.6 nH/m
	Capacitance between cores	C'_{cc}	31.9 pF/m
	Capacitance of a core and the ground	C'_{cg}	18.3 pF/m
	Resistance of a core (100 MHz)	R'_c	0.16 Ω /m
	Resistance of the ground (100 MHz)	R'_g	0.024 Ω /m

electromagnetic wavelength is:

$$\lambda_{\min} = \frac{v}{f_{\max}} = \frac{1}{\sqrt{\mu\epsilon} \cdot f_{\max}} \approx 1.9\text{m} \quad (4)$$

where v is the velocity of propagation of the waves on the lines, $\mu = \mu_0$, $\epsilon = \epsilon_0\epsilon_r$, are the permeability and the permittivity of the surrounding medium, respectively ($\epsilon_r = 2.2$ for the insulation).

The DC cables and AC cables are divided into small segments. The length of each segment l is electrically short at the excitation frequency, generally $l < \lambda_{\min}/10$ (0.19 m). Hence the segments can be represented as lumped circuits. Finally, the length of each segment is set to $l = 0.1$ m.

Fig. 9. DC cable EMI model (a) shielded DC cables, (b) unshielded DC cables.

Fig. 10. An EMI model of the PMSM [31].

Fig. 9(a) and (b) show EMI models of shielded DC cables and unshielded DC cables, respectively. Similarly, EMI models of shielded and unshielded AC cables can be obtained.

C. PMSM Model

Fig. 10 shows a lumped-circuit model of a PMSM [31].

D. System-Level Conducted EMI Model

The system-level conducted EMI model is assembled from the models of components, including LISNs, DC cables, a SiC inverter, AC cables, and a PMSM. The couplings between components are ignored.

III. INFLUENCE OF SYSTEM LAYOUT ON CM EMI NOISE

The influences of system layout, including AC cable length, AC cable type, and DC cable type on CM EMI noise are investigated according to the system-level EMI model. The parameters of the inverter operating point are listed in Table V.

TABLE V
CONDUCTED EMI NOISE TEST CONDITIONS

Item	Symbol	Quantity
DC voltage	V_{dc}	320 V
Fundamental AC line voltage	V_{AB}	182 V rms
Fundamental phase current	I_A	40 A rms
Fundamental frequency	f_o	200 Hz
Switching frequency	f_s	10 kHz

Fig. 11. Simulation amplitude spectral envelopes of V_{LISN} of systems with 1.6 m and 4.8 m shielded AC cables.

The inverter operates under continuous SVPWM.

To investigate the influences of AC cable length on CM EMI noise of the SiC EV powertrain, circuit simulations in time domain for systems with 1.6 m and 4.8 m shielded AC cables are carried out, respectively. A bunch of 1.8 m shielded DC cables is used in the system. For discussing the impacts of AC cable type on system CM EMI noise, systems with 1.6 m shielded AC cables and 1.6 m unshielded AC cables are simulated, respectively. A bunch of 1.8 m shielded DC cables is used in the system. To discuss the influences of DC cable type on system CM EMI noise, systems with 1.8 m shielded DC cables and 1.8 m unshielded DC cables are simulated, respectively. A bunch of 1.6 m shielded AC cables is used in the system. In addition, when shielded AC cables are used, two terminals of the shielding layers are connected to the inverter chassis and the PMSM frame, respectively. Similar, when shielded DC cables are used, two terminals of the shielding layers are connected to the inverter chassis and the LISN chassis, respectively. The CM LISN voltage V_{LISN} is the arithmetic average of the voltages on the 50 Ω resistors installed on the LISNs. The spectral of V_{LISN} are calculated through the Fourier series.

A. AC Cable Length

Fig. 11 shows the simulation amplitude spectral envelopes of V_{LISN} of powertrains with 1.6 m and 4.8 m shielded AC cables. The amplitude spectral envelopes of V_{LISN} of a powertrain with short shielded AC cables is lower in low frequency range and

Fig. 12. Simulation amplitude spectral envelopes of V_{LISN} vs. AC cable type (a) a systems with 1.8 m shielded DC cables and 1.6 m shielded AC cables vs. a systems with 1.8 m shielded DC cables and 1.6 m unshielded AC cables, and (b) a systems with 1.8 m unshielded DC cables and 1.6 m unshielded AC cables vs. a systems with 1.8 m unshielded DC cables and 1.6 m unshielded AC cables.

is higher in high frequency range than that of a powertrain with long shielded AC cables. When the 4.8 m shielded AC cables are replaced by the 1.6 m shielded AC cables, the amplitude peak of V_{LISN} spectra reduces about 10 dBV.

B. Shielded AC Cable and Unshielded AC Cable

Fig. 12(a) shows the simulation amplitude spectral envelopes of V_{LISN} for systems with shielded AC cables and unshielded AC cables when shielded DC cables are used in both of the systems. The amplitude spectral envelopes of V_{LISN} are almost equal in the frequency range of 150 kHz–4 MHz and 9–108 MHz between the two systems. However, the system with shielded DC cables and unshielded AC cables has much lower CM noise (with a maximum value of 30 dBV) in the frequency range of 4–9 MHz. Fig. 12(b) shows the simulation results for systems with shielded AC cables and unshielded AC cables when unshielded DC cables are used. The amplitude spectral envelope of V_{LISN} of the system with unshielded DC and AC cables is lower (with a maximum value of 12 dBV) in the frequency range of 2–9 MHz. It can be seen that no matter shielded DC cables or unshielded DC cables are used, the amplitude spectral envelopes of V_{LISN} of the system with

Fig. 13. Simulation amplitude spectral envelopes of V_{LISN} vs. DC cable type (a) a systems with 1.8 m shielded DC cables and 1.6 m shielded AC cables vs. a systems with 1.8 m unshielded DC cables and 1.6 m shielded AC cables, and (b) a systems with 1.8 m shielded DC cables and 1.6 m unshielded AC cables vs. a systems with 1.8 m unshielded DC cables and 1.6 m unshielded AC cables.

unshielded AC cables is low.

C. Shielded DC Cable and Unshielded DC Cable

Fig. 13(a) shows the simulation amplitude spectral envelopes of V_{LISN} for systems with shielded DC cables and unshielded DC cables when shielded AC cables are used in both of the systems. The amplitude spectral envelopes of V_{LISN} are almost equal in the frequency range of 150 kHz–3 MHz and 20–108 MHz between the two systems. However, the system with unshielded DC cables and shielded AC cables has lower CM noise (with a maximum value of 12 dBV) in the frequency range of 3–8 MHz and 10–20 MHz. Fig. 13(b) shows the simulation amplitude spectral envelopes of V_{LISN} for systems with shielded DC cables and unshielded DC cables when unshielded AC cables are used in both of the systems. The amplitude spectral envelope of V_{LISN} of the system with unshielded DC and AC cables is lower (with a maximum value of 15 dBV) in the frequency range of 1.5–5 MHz and 10–20 MHz, but is higher (with a maximum value of 10 dBV) in the frequency range of 5–8 MHz. It can be seen that using unshielded DC cables when shielded AC cables are used can reduced the amplitude spectral envelope of V_{LISN} in the full frequency range.

Fig. 14. A conducted emission test platform for an EV powertrain.

Fig. 15. Experimental and simulation amplitude spectral envelopes of V_{LISN} .

IV. EXPERIMENT VERIFICATION

Fig. 14 shows a conducted emission test platform for an EV powertrain, which was built based on the IEC international standard CISPR 25, 2016 [34]. The DC source (Chroma 17040) simulates a battery pack and supplies DC voltage. A 12 V, 100 Ah lead-acid battery is used as a low voltage auxiliary power supply of the inverter. The LISN chassis, inverter chassis, and frame of the PMSM are connected to the ground plane. All of the tests are carried out at the same inverter operation point, which has been listed in Table V. The inverter operates under continuous SVPWM. The LISN voltages are measured by an oscilloscope, the spectral of V_{LISN} is calculated through the Fourier series.

To verify the system-level EMI model, experiments were carried out on the conducted EMI test platform of a SiC EV powertrain. Fig. 15 shows the experimental and simulation amplitude spectral envelopes of V_{LISN} . The experimental amplitude spectral envelope of V_{LISN} matches the simulation amplitude spectral envelope well in the frequency range of 150 kHz–40 MHz. However, the experimental results are about 6 dBV higher than the simulation results in the frequency range of 40–108 MHz. There are two possible reasons for the error between the simulation and experimental results in high frequency range. First, in the presented model, switching ringing of drain-source voltages is ignored in the simulation model, which enhances the high frequency EMI noise [12], [15]. As a result, the simulation amplitude spectral envelope of V_{LISN} is undervalued in high frequency range. Second, at

Fig. 16. Experimental amplitude spectral envelopes of V_{LISN} of systems with 1.6 m and 4.8 m shielded AC cables.

frequencies higher than 30 MHz, the experimental amplitude spectral envelope of V_{LISN} is lower than -60 dBV (1 mV), which is sensitive to measurement accuracy.

With respect to the influence of AC cable length, Fig. 16 shows the experimental amplitude spectral envelopes of V_{LISN} of powertrains with 1.6 m shielded AC cables and 4.8 m shielded AC cables. The amplitude spectral envelopes of V_{LISN} of a system with 1.6 m shielded AC cables is lower in low frequency range (including the amplitude peak frequency) and is higher in high frequency range than that of the system with 4.8 m shielded cables. Replacing the 4.8 m shielded AC cable by the 1.6 m shielded AC cables, the amplitude spectral envelope of V_{LISN} reduces about 10 dBV in the frequency range of 150–900 kHz, and increases about 4–10 dBV in the frequency range of 4–9 MHz.

With respect to the impact of AC cable type, experimental amplitude spectral envelopes of V_{LISN} for systems with shielded AC cables and unshielded AC cables are compared. The experimental results are shown in Fig. 17(a) when shielded DC cables are used in both of the systems. In this case, the amplitude spectral envelope of V_{LISN} of the system with unshielded AC cables is almost the same as that of the system with shielded AC cables in the frequency range of 150 kHz–4 MHz and 9–108 MHz. However, it reduces significantly (the maximum reduction is 27 dBV) in the frequency range of 4–9 MHz. In Fig. 17(b), both of the systems use unshielded DC cables. In this case, the amplitude spectral envelope of V_{LISN} of the system with unshielded AC cables is much lower (the maximum difference is 15 dBV) than that of the system with shielded AC cables. Hence, the system with unshielded AC cables has low CM LISN voltage no matter shielded DC cables or unshielded DC cables are used.

With respect to the influence of DC cable type, Fig. 18 shows the experimental amplitude spectral envelopes of V_{LISN} for systems with shielded DC cables and unshielded DC cables. Shielded AC cables are used in both of the system. The system with unshielded DC cables has low CM LISN voltage. The amplitude spectral envelope of V_{LISN} of the system with unshielded DC cables is 4–10 dBV lower in the frequency

Fig. 17. Experimental amplitude spectral envelopes of V_{LISN} vs. AC cable type (a) a system with 1.6 m shielded DC cables and 1.8 m shielded AC cables vs. a system with 1.8 m shielded DC cables and 1.6 m unshielded AC cables, and (b) a system with 1.8 m unshielded DC cables and 1.6 m shielded AC cables vs. a system with 1.8 m unshielded DC cables and 1.6 m unshielded AC cables.

Fig. 18. Experimental amplitude spectral envelopes of V_{LISN} for a system with 1.8 m shielded DC cables and 1.6 m shielded AC cables and a system with 1.8 m unshielded DC cables and 1.6 m shielded AC cables.

range of 3–8 MHz and 10–20 MHz than that of the system with shielded DC cables.

V. CONCLUSION

In this paper, the influences of system layout, such as AC cable length, AC cable type, and DC cable type on CM EMI

noise of a SiC EV powertrain were investigated. With respect to AC cable length, spectra of CM LISN voltage with short AC cables has low amplitude peak. In the prototype, the amplitude peak of V_{LISN} of a system with 1.6 m shielded AC cables reduces about 10 dBV than that of a system with 4.8 m shielded AC cables. With respect to AC cable type, a system with unshielded AC cables has lower CM noise on LISN voltage no matter shielded DC cables or unshielded DC cables are used. In the prototype, when shielded DC cables are used, the maximum reduction of V_{LISN} amplitude spectral envelope is 27 dBV in the frequency range of 4–9 MHz in the system with unshielded AC cables. When unshielded DC cables are used, the maximum reduction of V_{LISN} amplitude spectral envelope is 12 dBV in the frequency range of 2–10 MHz in the system with unshielded AC cables. With respect to DC cable type, a system with unshielded DC cables has lower CM noise on LISN voltage when shielded AC cables are used. In the prototype, the maximum reduction of V_{LISN} amplitude spectral envelope is 10 dBV in the frequency range of 3–8 MHz and 10–20 MHz in the system with unshielded DC cables.

APPENDIX

A. CM Noise Source

In the AC side, since the PWM modulation for a three-phase inverter is symmetric, v_{AN} , v_{BN} and v_{CN} are shifted 120° between each other. Therefore, $V_{\text{BN}}(n)$ and $V_{\text{CN}}(n)$ can be expressed as follows:

$$\begin{cases} V_{\text{BN}}(n) = V_{\text{AN}}(n)e^{-jn\frac{2\pi}{3}}, \\ V_{\text{CN}}(n) = V_{\text{AN}}(n)e^{-jn\frac{4\pi}{3}} \end{cases} \quad (5)$$

Substituting (5) into (1) yields:

$$V_{\text{CM0}}(n) = \frac{1 + e^{-jn\frac{2\pi}{3}} + e^{-jn\frac{4\pi}{3}}}{3} V_{\text{AN}}(n) \quad (6)$$

For zero sequences, $n = 3m$, $m = 1, 2, \dots$, (6) can be simplified:

$$V_{\text{CM0}}(n) = V_{\text{AN}}(n) = V_{\text{BN}}(n) = V_{\text{CN}}(n) \quad (7)$$

For positive sequences, $n = 3m + 1$, $m = 1, 2, \dots$, (6) can be simplified:

$$V_{\text{CM0}}(n) = 0 \quad (8)$$

For negative sequences, $n = 3m + 2$, $m = 1, 2, \dots$, (6) can be simplified:

$$V_{\text{CM0}}(n) = 0 \quad (9)$$

It can be seen that the zero sequences generate CM noise, whereas the positive sequences and the negative sequences do not generate CM noise. In addition, CM components (zero sequences) of v_{AN} , v_{BN} and v_{CN} are the same according to (7). As a result, inverter AC terminals of node A, node B, and node C can be short connected in CM noise analysis.

B. Cable Parameters

1) Shielded Cables

The p.u.l self-inductance of a cable core and the p.u.l self-inductance of a cable shield [23] are expressed as follows:

$$\begin{cases} L_c = \frac{\mu_0}{2\pi} \ln\left(\frac{2h}{r_c}\right), \\ L_s = \frac{\mu_0}{2\pi} \ln\left(\frac{2h}{r_s}\right) \end{cases} \quad (10)$$

where μ_0 is the vacuum permeability, h is the height of the cable above the ground plane, r_c is the radius of the cable core of the shielded and unshielded cables, r_s is the radius of the cable shield.

The mutual inductance between the shield and the inner conductor of any cable is taken to be equal to the self-inductance of the cable shield L_s [23].

The mutual inductance between the cores of one cable and another cable, the mutual inductance between the shields of one cable and another cable, and the mutual inductance between the core of one cable and the shield of another cable are the same, which is expressed [23] as follows:

$$L_m = \frac{\mu_0}{4\pi} \ln\left(1 + \frac{4h^2}{s^2}\right) \quad (11)$$

where s is the distance between the centers of the cores of both cables.

The p.u.l capacitance between the core and the shield of any cable is expressed [35] as follows:

$$C_{\text{cs}} = \frac{2\pi\epsilon_r}{\ln\left(\frac{r_s}{r_c}\right)} \quad (12)$$

where ϵ_r is the dielectric constant of the cable insulation layer.

2) Unshielded Cables

The p.u.l self-inductance of an unshielded cable core is equal to the expression of L_c in (10).

The p.u.l mutual inductance between cores of one unshielded cable and another one is equal to the expression of L_m in (11).

The p.u.l capacitance between the unshielded cable core and the ground plane is expressed [35] as follows:

$$C_{\text{cg}} \approx \frac{2\pi\epsilon_0}{\ln\left(\frac{2h}{r_c}\right)} \quad (13)$$

Fig. 19. Shielded DC cable model (a) lumped circuit model, and (b) an equivalent circuit.

C. Parameters of Cable's Lumped Circuit

1) Shielded DC Cables

For shielded DC cables, cores of the two cables are shorted at both the inverter side and the LISN side according to the analysis in Section II. In addition, shields of the two cables are short-circuited to the ground plane at both the inverter side and the LISN side. According to the multiconductor transmission line theory, the lumped circuit model of shielded DC cables is shown in Fig. 19(a). Fig. 19(b) shows an equivalent circuit of the shielded DC cables.

Obviously, the equivalent capacitance is expressed as follows:

$$C_{dg(s)} = 2l_d C_{cs} \quad (14)$$

The voltage of cable core and cable shield are expressed as follows:

$$\begin{cases} V_c = sl_d L_c I_c + sl_d L_s I_s + sl_d L_m I_c + sl_d L_m I_s \\ V_s = sl_d L_s I_s + sl_d L_s I_c + sl_d L_m I_c + sl_d L_m I_s \end{cases} \quad (15)$$

For the reason that cable shields are shorted by the ground plane, we have $V_s = 0$. Substituting it into V_s expression in (15)

Fig. 20. Unshielded DC cable model (a) lumped circuit model, and (b) an equivalent circuit.

yields:

$$I_s = -I_c \quad (16)$$

Substituting (16) into V_c expression in (15) yields:

$$V_c = s \cdot l_d \frac{L_c - L_s}{2} \cdot 2I_c \quad (17)$$

So, the equivalent inductance of shielded DC cables is expressed as follows:

$$L_{d(s)} = l_d \frac{L_c - L_s}{2} \quad (18)$$

2) Unshielded DC Cables

Fig. 20(a) shows the lumped circuit model of unshielded DC cables. Fig. 20(b) shows an equivalent circuit of unshielded DC cables.

The equivalent capacitance is expressed as follows:

$$C_{dg(u)} = 2l_d C_{cg} \quad (19)$$

The voltage of cable core is expressed as follows:

$$\begin{aligned} V_c' &= sl_d L_c I_c' + sl_d L_m I_m' \\ &= s \cdot l_d \frac{L_c + L_m}{2} \cdot 2I_c' \end{aligned} \quad (20)$$

So, the equivalent inductance of shielded DC cables is:

$$L_{d(u)} = l_d \frac{L_c + L_m}{2} \quad (21)$$

3) Shielded AC Cables and Unshielded AC Cables

Similar to the derivation of equivalent inductance and capacitance for shielded DC cables and unshielded DC cables, the equivalent capacitances of shielded AC cables and unshielded AC cables are expressed as follows:

$$\begin{cases} C_{ag(s)} = 3I_a C_{cs}, \\ C_{ag(u)} = 3I_a C_{cg} \end{cases} \quad (22)$$

The equivalent inductances of shielded AC cables and unshielded AC cables are expressed as follows:

$$\begin{cases} L_{a(s)} = I_a \frac{L_c - L_s}{3}, \\ L_{a(u)} = I_a \frac{L_c + 2L_m}{3} \end{cases} \quad (23)$$

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