Predicting Radiated Emissions from an Electrical Drive System

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***Abstract* — A measurement-based SPICE model is proposed to predict radiated emissions from an electrical drive system over a frequency range from 20-300 MHz. The model combines a model for the radiated emissions from the cabling and housings with a model for coupling inside the electrical motor. The electromagnetic properties of the cabling and housings were captured with measured S-parameters. The coupling mechanisms inside the electrical machine were represented using a circuit-element based model. The intent is to provide insight into how coupling mechanisms and placement of structures in the motor affect radiated emissions from the drive system, and to give the designer an opportunity to evaluate the impact of changes to the motor design. The model was able to predict radiated emissions within several decibels of the measurement over the frequency range of interest, to provide insight into strategies for fixing emissions issues, and to provide estimates for the reduction in emissions that could be expected from each fix.**

Keywords— Circuit Model; CISPR 25; Coupling; Electrical Motor; Harness; System-level Emissions

I. Introduction

To meet the output power demands of drive systems while keeping their thermal losses to acceptable levels, PWM drive signals must have fast edge rates. These sharp edges give rise to broader high-order harmonics that travel through phase cables and couple common-mode currents to sensor harness cables in the electrical machine and radiate unintentional radio frequency energy, leading to electromagnetic emissions problems. The goal of the following work is to create a circuit-model representation of the coupling in the electric machine, particularly the coupling between the phase cables/windings and sensor feedback wires to combine it with an S-parameter measurements of electromagnetic properties of the cabling and housing in order to predict radiated emissions from the drive system. This approach will help engineers gain insights into potential radiating mechanism and how design changes will impact emissions in early design testing. Other authors [1-2] have approached similar problem using 3D full- wave modelling, however, full-wave models often require substantial computational resources and typically do not give immediate insight into the fixes of EMC problems. Because of inherent limitations in the available shielding and filtering options in a drive system, the best way of solving radiated emissions problems is to understand how high-frequency energy from the driving signal is coupled as common mode currents to the harness, and then mitigate that coupling path. The setup and drive system are described in section II of the paper. An overview of the common-mode coupling measurement is given in section III. Section IV describes how the measurement-based model is constructed. Section V introduces the methodology used to characterize coupling between the electrical machine phase inputs and feedback harness using circuit-element based modelling.

II. Drive System And Radiated Emissions Measurement Setup

As shown in Fig. 1, the drive system studied here consists of an inverter, three-phase AC motor, shielded 'phase' cables used to deliver 3-phase high-power drive signals to the motor, and a low voltage sensor harness used to feed operational parameters back to the inverter such as speed and direction of rotation. For this study, radiated emissions were measured using a VNA, rather than operating the system and measuring radiated energy using a spectrum analyzer. VNA port 1 was used to inject a stimulus to the drive output of the inverter while port 2 of the VNA was connected to an antenna measuring the radiated energy. These measurements were taken at multiple locations in the drive system. By taking the antenna factor into account and characterizing the received signal over multiple ports, it is possible to reconstruct total radiated energy.

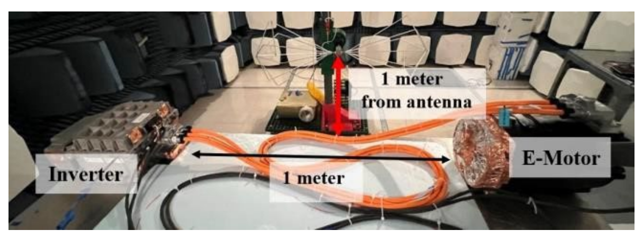

Fig. 1. Electrical drive system in a CISPR 25 type setup in a semi-anechoic chamber.

III. Constructing Measurement Based Model

A. Characterization of the Motor

Characterizing the impedance of each input to the motor and the coupling between them requires placing measurement ports on the motor. Similar measurement ports are needed to characterize the radiated emissions generated by signals at each location. Fig. 2 shows a special PCB adapter designed to allow common-mode connection of SMA ports to each wire pair in the sensor harness. Every cable in the harness is differential, but the pairs are shorted as they leave the electrical motor and connect to the adapter PCB to measure the common-mode only. Fig. 2 also shows an adapter that allows connection of SMA ports directly to the phase inputs of the electrical machine. Each adapter was built so that there was minimal disruption of the cable layout and that measurement could be taken either looking into the motor or looking into the connected cables (without motor loads attached). Fig. 3 portrays a simplified equivalent circuit of the coupling measurement.

B. Characterization of the Drive System

To create a SPICE model that predicts radiated emissions from the entire drive system, it is also necessary to characterize the input impedance looking into the harnesses connected to the motor, measure the transfer characteristics from the inverter to the motor (i.e. S_{11} and S_{21} of phase cables), and characterize currents on individual wire or wire pairs to the radiated fields. To capture the radiated emissions from individual wires or wire pairs in the harness, these wires were driven with port 1 of a VNA while measuring the received voltage at a nearby antenna using VNA port 2. A high-level diagram of the procedure is shown in Fig. 4. The harness adapter PCB connected to the motor can be configured to drive individual differential wire pairs in the harness to radiate, without driving energy into the motor. A similar measurement is performed on the phase cables. Even though, the phase cables are shielded, they still have a chance to radiate substantially at some frequencies. The total set of measurements is summarized in Table I. After characterizing the system, all measurements are combined into two different S-parameter blocks as shown in Fig. 5. The left block defines the characteristics of the drive system. For instance, the H1 and Antenna Horizontal ports reflect measurement of radiated emission from the H1 cable to the horizontally polarized radiated electric field. The right block represents measurements looking into the electrical motor. Measurements looking into each sensor pair (H1-H6) and each phase cable are represented.

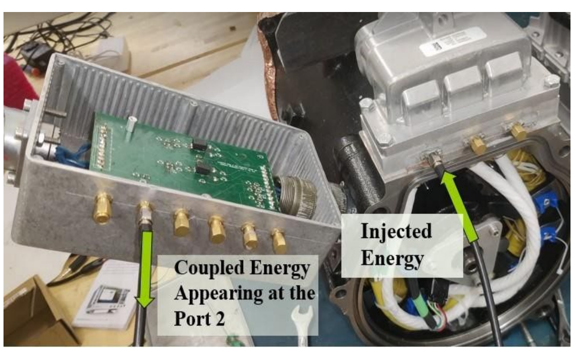

Fig. 2. Setup and adapters used to measure common-mode coupling and input impedances.

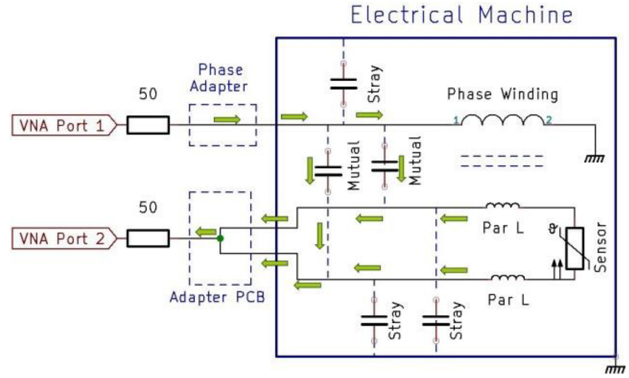

Fig. 3. Simplified equivalent circuit of coupling measurement between phase input and sensor harness. Green arrows indicate the direction of the common mode current.

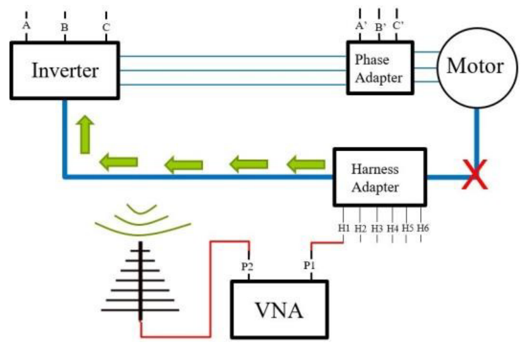

Fig. 4. High-level diagram of the measurements required to define black box and circuit-based models of the motor drive system. Here, harness H1 is driven with port 1 of the VNA and radiated emissions are measured at port 2.

TABLE I. MEASUREMENTS TO CONSTRUCT PREDICTIVE MODEL

Measurement	VNA Port 1	VNA Port 2
Radiated emissions from sensor pair	Sensor pair (individually)	Nearby antenna
Radiated emissions from phase cables	Inverter output	Nearby antenna
Phase cable characteristics ($S_{11,}$ S_{21})	Inverter output	Electrical machine phase input
Coupling inside electrical machine	Electrical machine phase input or sensor pair	Electrical machine phase input or sensor pair
Coupling inside inverter	Inverter output	Inverter output or sensor pair (at motor)

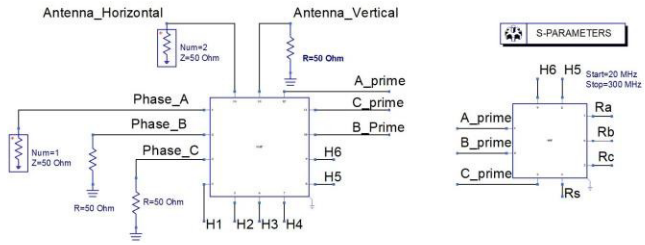

Fig. 5. Measured S-parameter blocks representing the coupling and emissions from the system (left) and the characteristics of the motor (right).

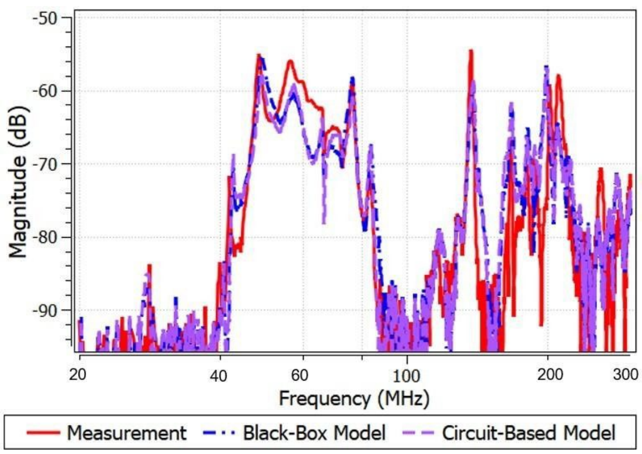

Fig. 6. Comparison of radiated emissions when driving phase-A of inverter as found in measurement, as predicted using an S-parameter model of the motor, and as predicted using a circuit-based model of the motor.

While not the final goal, the two measurement-based S-parameter blocks were used together to predict radiated emissions as shown in Fig. 6 when driving the phase-A cable from the inverter and measuring in the horizontal polarization. The model was able to reconstruct system-level radiated emissions within a few decibels of the measured values for each antenna polarization and when driving each phase, demonstrating the accuracy of the characterization process.

IV. Circuit-Based Model of Coupling inside the Electrical Machine

While a model using measured S-parameter blocks is able to accurately predict radiated emissions, a circuit-based model of the motor, where circuit elements correspond to real structures, is preferred. Such a model provides a clear link between structures in the motor and the relevant electrical parasitics, provides the user with an intuitive understanding of how the characteristics of the motor drive radiated emissions, and thus provides the engineer with a solid framework to intelligently design the motor with respect to EMC. Creating an accurate model from 20-300 MHz is challenging in part because the phase and sensor harness cables inside the motor are electrically large over part of this frequency range. To model the structures with lumped elements, wires must be segmented into electrical short parts and cascaded. The method of developing the circuit-based model was as follows:

1. Measure complete set of S parameters looking into ports for the motor and sensor harness, for all differential pairs in the sensor harness and for each phase cable, as described in Section III.
2. For each port (phase inputs and sensors wires), create a circuit model to fit measured input impedance by relating each segment of circuit to corresponding geometry (Fig. 7) and estimating and tuning circuit parameters to match measured S_{11} (magnitude and phase – Fig. 8). Coupling between circuits is ignored at this time.
3. After creating circuits representing common-mode input impedances from step 2, pick two “ports” (phase inputs or sensor wires), identify structure where coupling may occur, and create circuit elements in the model corresponding to this coupling (Fig. 9). Begin with engineering estimates and then tune coupling parameters (only) to best fit measured S_{21} (Fig. 10).
4. After identifying the main elements that determine self-impedance and coupling, tune all parameters together to best match the measured values of S_{11} and S_{21}. Construct entire circuit and further tune values (modestly) if required.

Fig. 9 shows the circuit model found for the phase input to the motor and one of the sensor pairs going into the motor. Fig. 8 shows a comparison between measured and predicted input impedance looking into the phase input found using this circuit model. Fig. 10 shows the measured and predicted values of S_{21} between the phase input and the given sensor pair. This procedure was repeated for all three phase inputs and the two most problematic sensor pairs in the harness. The two most problematic sensor pairs showed an 11 dB higher coupling from the phase inputs compared to other sensor wires.

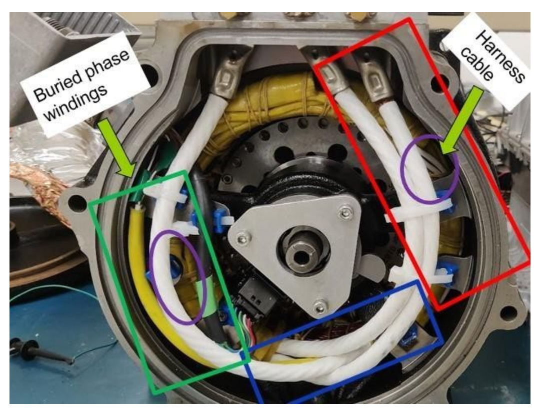

Fig. 7. Structures associated with circuit elements representing phase C and one of the sensor harness cables. Corresponding circuit segments are shown in Fig. 9.

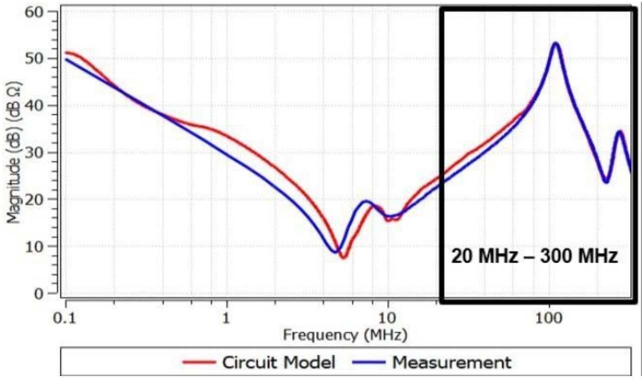

Fig. 8. Comparison between measured common-mode impedance (Z_{11}) looking into the phase input and the tuned circuit model.

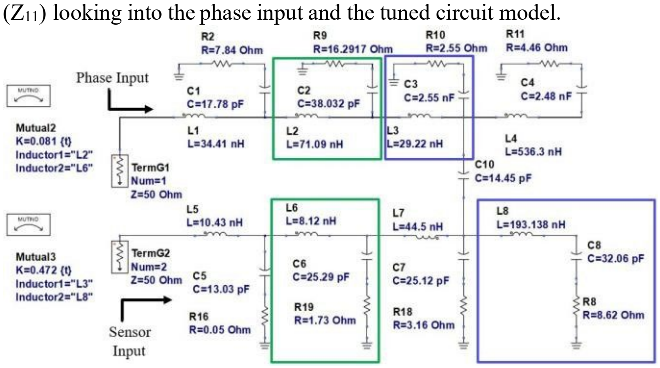

Fig. 9. Tuned circuit model characterizing common mode impedances of phase input and one of the problematic sensor pairs in the motor harness, as well as the mutual terms between them.

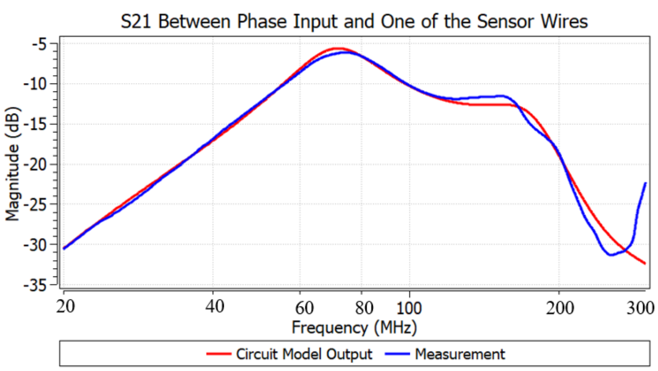

Fig. 10. Comparison of the measured and circuit-base modeled common-mode coupling between phase input and one of the two problematic sensor pairs in the motor.

Some of the segments represented in Fig. 9 include substantial resistance associated with the return plane. This resistance is due to magnetic loss associated with the steel enclosure of the electrical motor and is only significant at high frequencies. Some segments also show a high capacitance to the return plane. These high values typically take place within the motor windings and are similar to values measured by other researchers [3-4]. After obtaining a circuit representation of the electromagnetic characteristics of the motor, the measured S-parameter model of the motor in Fig. 5 can be replaced with the circuit representation. A comparison of the measured and predicted emissions when driving the phase A inverter port are shown in Fig. 6. The emissions predicted using the circuit-based model are nearly identical to those predicted when using the measured S-parameter model of the motor and closely match the actual measurement. With an exception around 45 and 65 MHz, predicted results are within 1-2 dB of the measurement. The results in Fig. 6 assume a uniform energy distribution across the entire frequency band, since the inverter port is driven with the VNA. The energy inthe inverter PWM signals, however, tends to decrease at 20 -40 dB/decade. As a result, the emissions at lower frequencies (particularly the 40-80 MHz band) will be much larger than at high frequencies. If the inverter PWM signal were available, it could be used to drive the model to predict the actual radiated emissions.

VI. Conclusion

A measurement-based model of a motor drive system was developed to predict the impact of changes to the motor design on radiated emissions. The model was able to predict radiated emissions within 10 dB or less from 20-300 MHz, nearly matching the measured emissions at most frequencies. Importantly, the use of a circuit-based representation of the electromagnetic characteristics of the motor gives the user the opportunity to understand the coupling mechanisms within the motor and how changes to the motor configuration may impact radiated emissions. This model gives the engineer a relatively intuitive tool with which to guide changes to the motor design with respect to EMC, without requiring the development of a highly sophisticated full-wave model. Full wave models require substantial time to develop and computational resources to simulate, and do not always provide significant insight into how design changes are driving emissions.

Acknowledgement

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