EMC Modeling of AC Motor Drive

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Student Paper Abstract

Senior Design Teams from Rose-Hulman Institute of Technology and the Missouri University of Science and Technology are developing the electromagnetic compatibility (EMC) of an AC motor control system. EMC modeling and design require attention because FCC and foreign governments set limits on electromagnetic emissions. Additionally, EMC modeling and design can potentially lower the cost associated with electromagnetic interference mitigation and improve product performance. Modeling the coupling paths in a device before production can provide insight into the electromagnetic behavior of the device. It is important that engineers appreciate how geometries affect the electromagnetic behavior of the device as they develop schematics and consider layout options. The circuit geometry will have associated parasitic elements (inductances and capacitances) that can provide common-mode current paths and thus contribute to significant radiated emissions. Using computer simulation and laboratory measurements, circuit models can be augmented so that non-intended paths which result from the presence of these parasitic elements are included in the system models. When engineers have access to the complete circuit, including the parasitic elements, they can identify the major emission sources and work to reduce their effect early in the design process.

Two subtasks have dominated the EMC modeling process, modeling the IGBT package and modeling the motor and cables. The IGBT package is responsible for the majority of emissions due to large, fast-switching currents. This rich spectral content is coupled onto the cable and motor where it is effectively radiated. Modeling the IGBT package has required extracting parasitic capacitances and inductances from the geometry in the package. These geometries have been modeled in CST, a numerical electromagnetic solver, in order to determine their parasitic contributions. Laboratory measurements have been conducted with an impedance analyzer and network analyzer to then validate these simulations and refine models when necessary. The package schematic can then be updated with parasitic values to determine common-mode current coupling paths.

The motor can be modeled by a high frequency circuit using an impedance analyzer to take common mode and differential mode measurements. The cable's length and frequencies of operation dictate they be modeled as transmission lines. Their characteristic impedance is measured with a TDR so a transmission line model can be developed. The effect of ferrites on cable impedance and emissions is also being investigated by taking measurements with and without the ferrites and observing the effect of the ferrite's impedance on the emissions and cable impedance.

Key Words

Student Paper, Electrical Engineering, Electrical and Computer Engineering

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Introduction

Electromagnetic compatibility (EMC) modeling and design require attention because governments set limits on electromagnetic emissions. Additionally, this work can potentially lower the cost associated with electromagnetic interference (EMI) mitigation and improve product performance. Modeling the coupling paths in a device before production can provide insight into the electromagnetic behavior of the device. It is important that engineers appreciate how geometries affect the electromagnetic behavior of the device as they develop schematics and consider layout options. The circuit geometry will have associated parasitic elements (inductances and capacitances) that can provide common-mode current paths and thus contribute to significant radiated emissions. Using computer simulation and laboratory measurements, circuit models can be augmented so that non-intended paths which result from the presence of these parasitic elements are included in the system models. When engineers have access to the complete circuit, including the parasitic elements, they can identify the major emission sources and work to reduce their effect early in the design process.

Senior Design Teams from Rose-Hulman Institute of Technology and the Missouri University of Science and Technology are developing the electromagnetic compatibility (EMC) characteristics of an AC motor control system. This motor controller is designed to operate low horsepower motors used in applications from belt control to industrial mixers. The device requires three phase 480V as a power source and rectifies this input. The controller then converts this DC power into three phase power once again at the necessary motor requirements through use of an insulated gate bi-polar transistor (IGBT) package and a microcontroller. In the case discussed herein, the EMI source for the motor control module is switching currents. These are expected to be largely due to IGBT[2] and switch mode power supplies (SMPS), but could also include contributions from other sources. These large, switching currents lead to strong time-varying electromagnetic fields. The EM energy from these sources is coupled to the power cables due to the presence of common-mode current paths created from parasitics. The coupling paths source EM energy to a receiver, which is sometimes thought of as an antenna and modeled as an effective impedance. In our case, the EMI antenna is the cables from the drive to the motor.

From previous experience, the IGBTs will be the presumed source of EMI energy due to the large, fast-switching currents and proximity to a large metallic heat sink. Therefore, our work has focused on modeling the IGBT package and characterizing the motor and cable impedance.

IGBT Modeling

In modeling the IGBT package (see Fig. 1), the main priority was to build a geometry-specific reproduction of the parasitic capacitances and inductances of the IGBT module and append these parasitics to the circuit schematic.

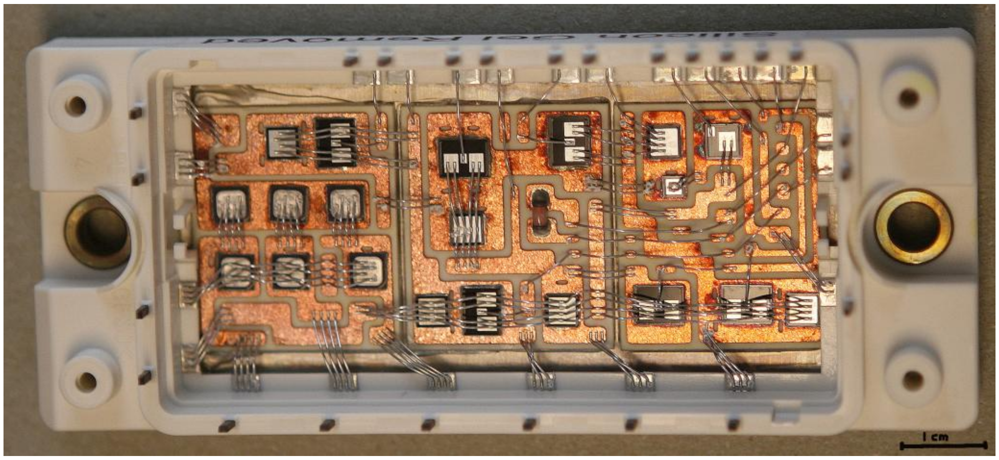

Fig. 1 – Scaled Image of IGBT

The geometry of the package presents two dominant parasitic capacitances: copper area fills to area fills and area fills to heat sink (see Fig. 2).

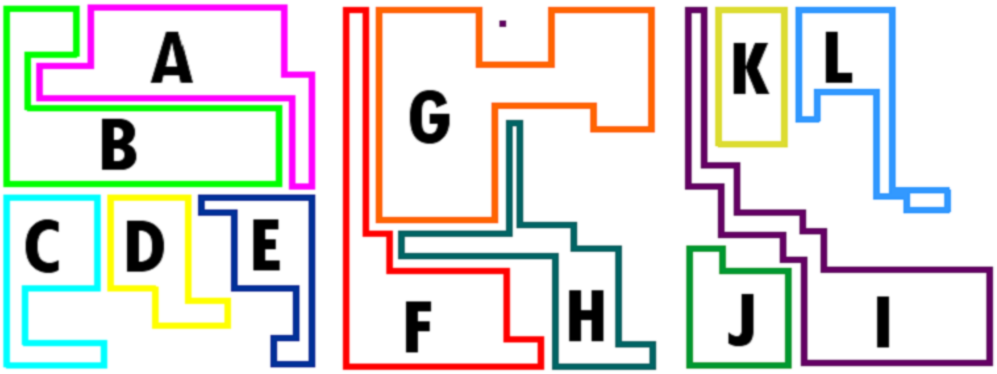

Fig. 2 – Labeled Area Fills

First, we modeled these capacitances using CST, a numeric electromagnetic field simulator. To effectively model these areas, measurements were taken of the IGBT geometry using a micrometer and caliper. In addition, the dielectric constant of the alumina substrate was measured. Models of each of these area fills were then constructed in CST and their capacitances obtained from an impedance graph. The largest area fill to area fill capacitance was less than 10% of the smallest area fill to heat sink capacitances. Therefore, we concluded that the area fill to heat sink capacitances *would dominate the capacitive coupling paths. These parasitic values were then taken and included in the original circuit schematic[3] as shown in Fig. 3.*

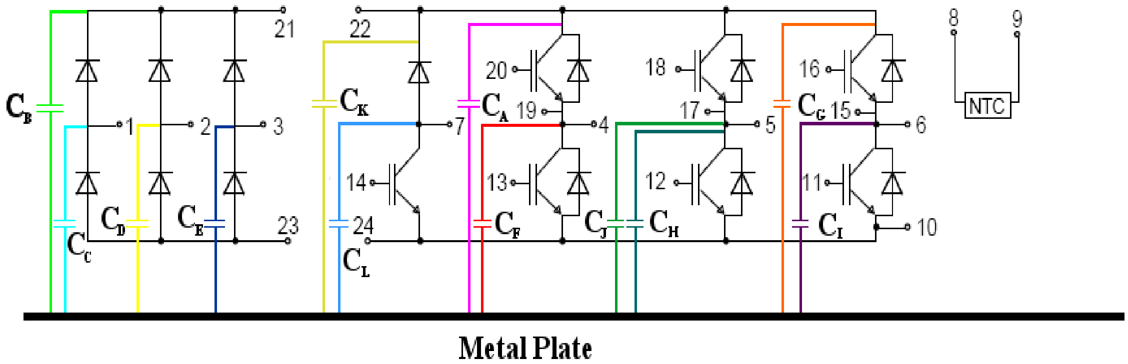

Fig. 3 – Updated IGBT Schematic

The simulated values for these capacitances are also shown in Table 1.

Table 1 – Area to Area Fill Simulated Capacitances

Region	**Capacitance (pF)**	**Region**	**Capacitance (pF)**
A	34.5	G	57.3
B	38.8	H	25.6
C	19.1	I	45.1
D	15.4	J	17.3
E	16.0	K	15.1
F	35.9	L	19.3

To validate these models, we took laboratory measurements of the three largest area fill to heat sink capacitances (B, G, and I) using an impedance analyzer as seen in Table 2.

Table 2 – Area Fill to Heat Sink Capacitances

Region	**Measured (pF)**	**Simulated (pF)**	**% Difference**
B	37.7	38.8	2.9
G	53.3	57.3	7.2
I	39.4	45.1	13.7

Two of these capacitances agreed to within 8%. The largest region I agreed to 14%. Region I has a long, narrow appendage which allows outside fields to interact with it. However, we were still satisfied with the agreement of our measurements. Knowing that our models suited our actual parasitics, we could then accept the CST calculated capacitances.

The next step in modeling the IGBT package was to determine the self inductances of each of the three phase legs (Phase Leg 1 is shown as an example in Figs. 4 and 5). Each phase leg corresponds to one of the three phases in the three phase power.

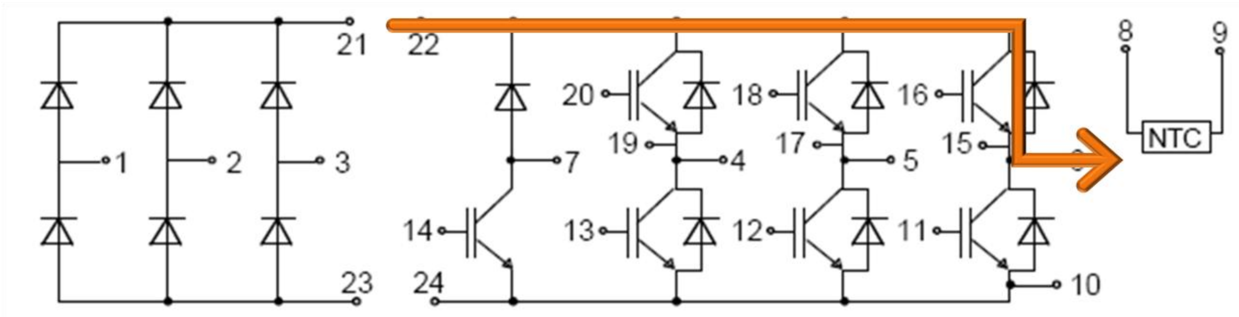

Fig. 4 – Schematic Path of Phase Leg 1

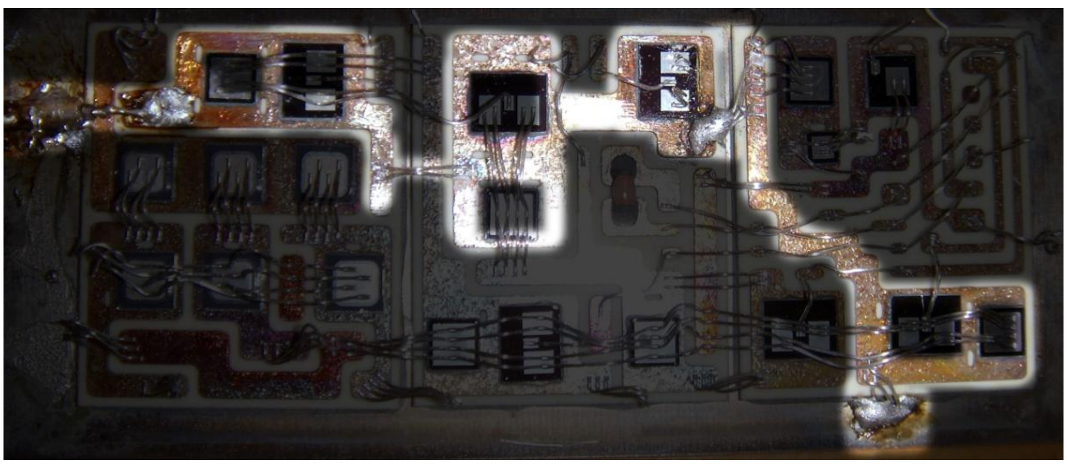

Fig. 5 – Image of Path of Phase Leg 1

These phase legs were developed as three individual loops with returns through the grounded heat sink. Models of each phase leg including bond wires according to the area geometries were constructed in CST. In a similar manner to the capacitance calculation, each inductance was extracted from an impedance curve (values are shown in Table 3). Next, these simulations were once again validated with laboratory measurements. All three phase legs agreed to within 6% of the simulated value. Similarly, we know that our inductance models accurately reflect the actual inductances.

Table 3 – Phase Leg Inductances

Phase Leg	**Measured (nH)**	**Simulated (nH)**	**% Difference**
1	13.3	13.1	1.3
2	12.1	12.8	5.6
3	9.1	8.7	4.5

Currently, we are attempting to extract the partial inductances of each area fill and bond wire. We are simulating each area fill and bond wire as its own small loop and extract each pieces' inductance. We are also using high frequency impedance measurements and simulations to match poles. Using our capacitance values, we can adjust inductance values to match up with the poles in our impedance curve. Based on our results for each phase leg, we know that the sum of the partial inductances in each phase leg should be equal to the total inductance of each phase leg. Once a suitable model has been developed, the schematic can then be modified to include these parasitic inductances.

Motor and Cable

The main goal of the motor and cables modeling was to characterize an impedance, formulate and test methods for suppressing EMI that emerges from a motor and cables setup being drive by an AC motor drive. To achieve this goal, we constructed a test setup as a means to develop a model. Using the model, we can simulate suppression methods, and verify them with the setup.

A drawing of the test setup is shown in Fig. 6. The test setup has an aluminum grounding plane as a base. The motor is wired as in its high voltage configuration and the wires rest on foam to separate them from the grounding plane by 10cm as specified by CISPR standards[1]. At the opposite end of the grounding plane, approximately 8.5 feet away from the motor, is an 'L' shaped aluminum adapter plate fastened to the grounding plane with copper tape. An N-type bulk head connector is mounted to the plate and the wires are soldered to one end of the adapter; copper tape is used to reinforce the connection to the grounding plane. The opposite end of the N-type bulk head connector is our test point.

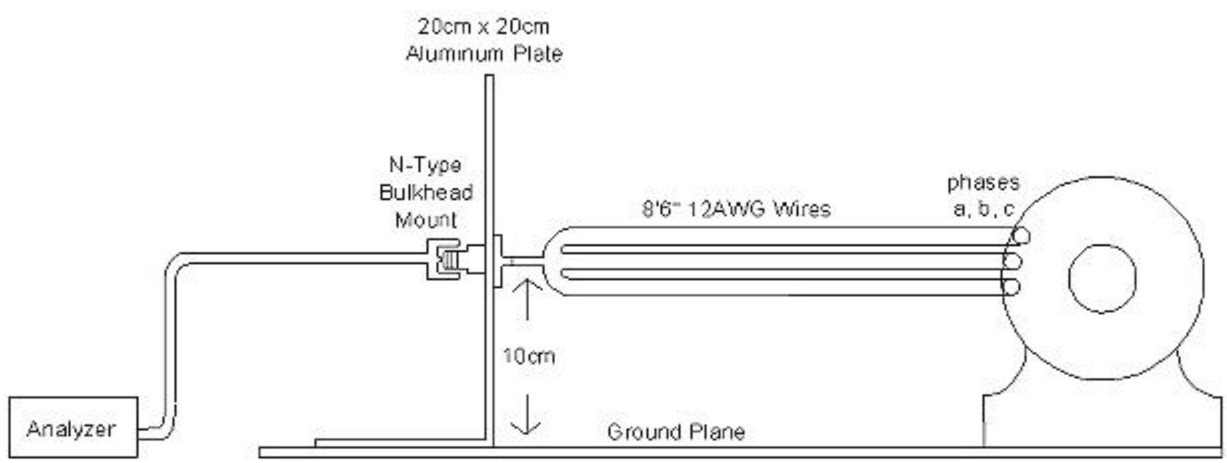

Fig. 6 – Motor and Cables Test Setup Drawing

Using an impedance analyzer, we were able to capture the setup's impedance in magnitude and phase as shown in Fig. 7. Using the red highlighted region in Fig. 7, we were able to calculate a low frequency capacitance of 2.60nF. Our initial plan was to model the motor as an ideal capacitor; this model is accurate until 30 kHz. We determined that this would not be sufficient and a more complex model would be needed. Our region of interest is in the tens of megahertz and the simple capacitor model is inadequate in that area.

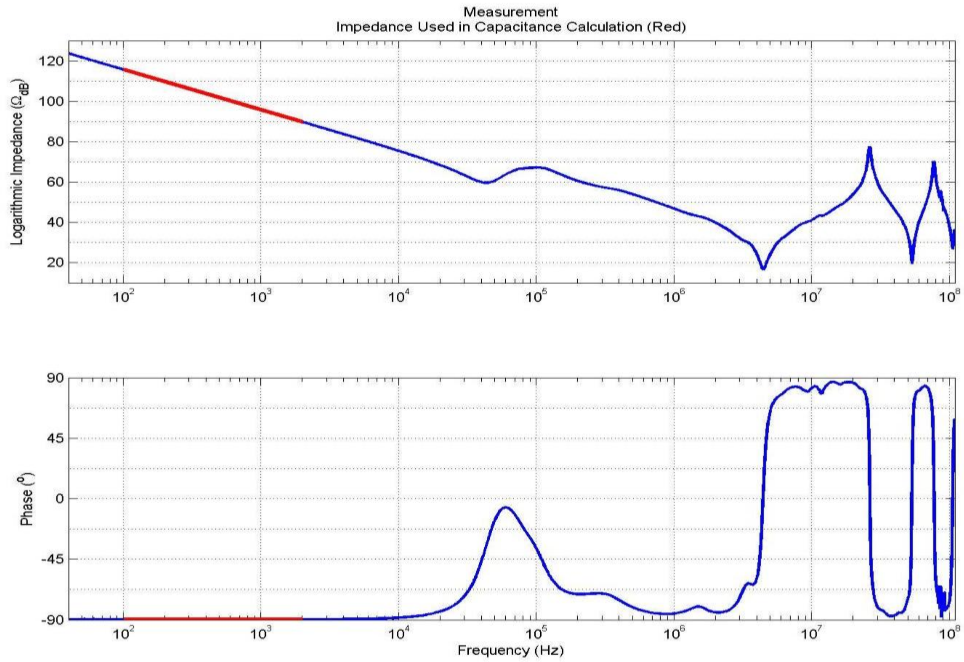

Fig. 7 –Impedance Spectrum as Seen from Adapter Plate using Impedance Analyzer

We followed the method developed by Schinkel et. al.[4] for constructing a high frequency motor model [1]. The test required measuring the impedance of the motor in both a common mode and differential mode setup. Using these measurements, we constructed the high frequency per phase circuit model as shown in Fig. 8. Using the common mode circuit model we overlaid the measured impedance and the simulated impedance as shown in Fig. 9. The per phase circuit can be refined to include the notch between 10MHz and 20MHz but has been deferred until we recreate and simulate the differential mode circuit model.

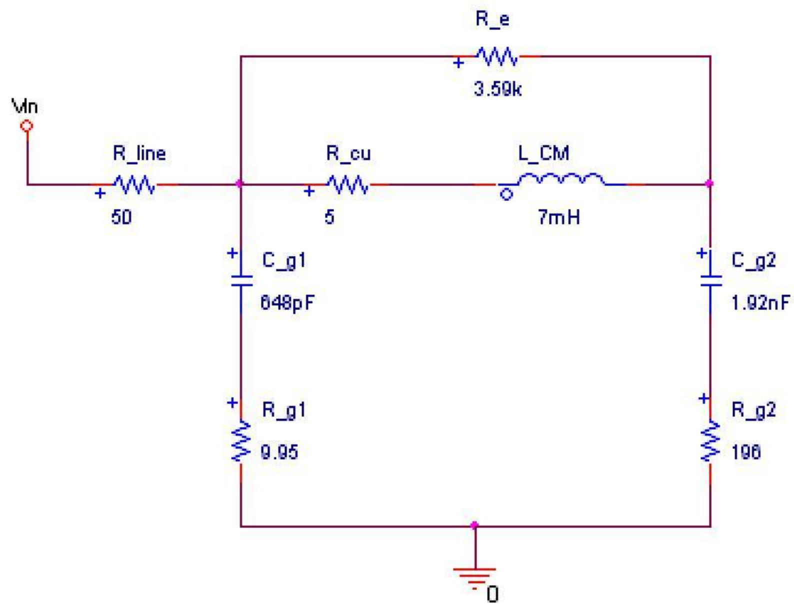

Fig. 8 – Circuit Model from Common Mode and Differential Mode Measurements

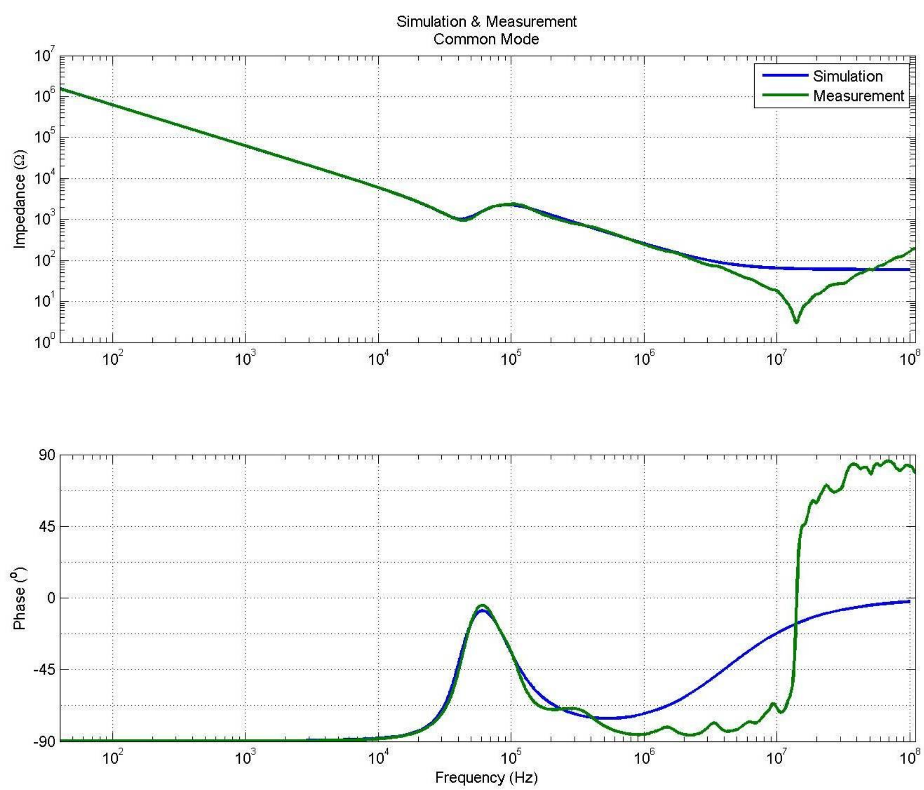

Fig. 9 – Common Mode Comparison: Simulation vs. Measurement

Part of obtaining the model of our system is modeling the cables as a transmission line. Using the Time-Domain Reflectometer (TDR) we were able to see reflected waves on motor and cable setup. Using this data, we approximated the characteristic impedance of the line to be 234Ω. The calculated characteristic impedance was 263Ω. This gives us a percent error of about 11%. This value is acceptable for us given the assumptions of a foam permittivity of 1 and a line to grounding plane distance much greater than the wire diameter. To verify our claim concerning the foam we used to the TDR as a means of calculating the permittivity. We calculated the time it took a wave to propagate down the line. Knowing the length of the line, we can calculated the velocity of propagation and therefore calculate the relative permittivity. The relative permittivity was found to be approximately 1.03.

Next, we investigated the effects of ferrites on the impedance. By increasing the impedance over certain frequencies we can decrease emissions. The effects of the ferrites are shown in Fig. 10.

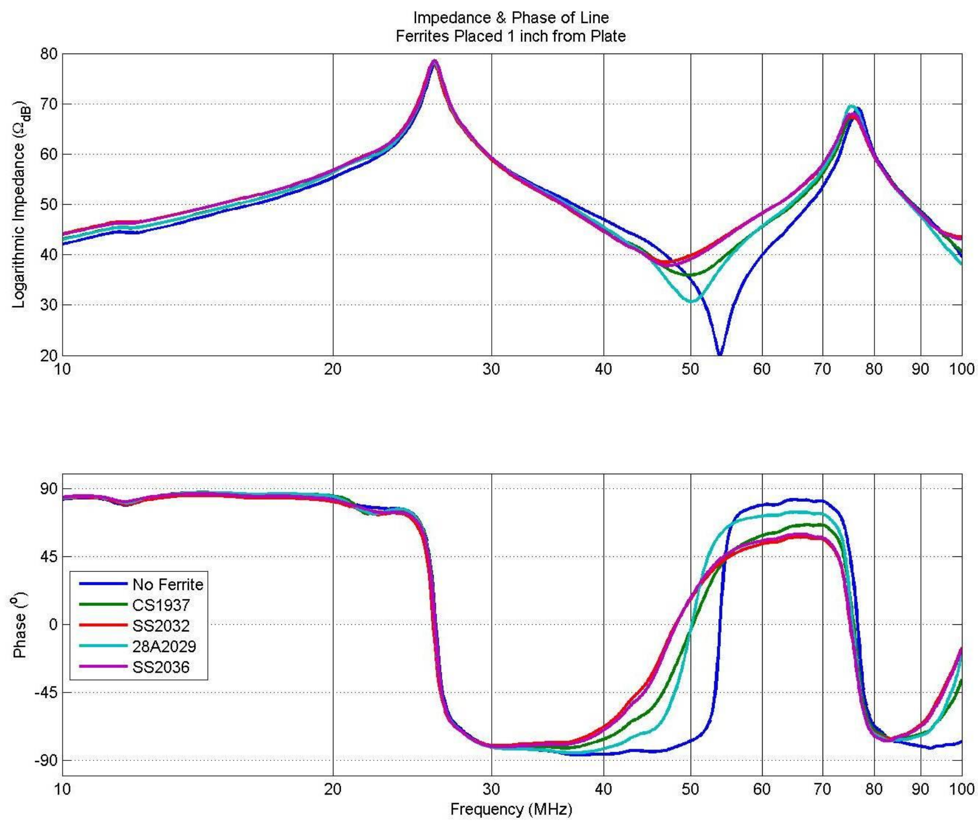

Fig. 10 – Impedance Analyzer: Effects of Ferrites 1 inch from Plate

The ferrites performed as expected by increasing the impedance in the region of interest. To ensure that emissions were being mitigated, we tested the effect of ferrites on emissions. Running the motor at its rated values, we used the spectrum analyzer in conjunction with a current probe to capture emissions. Emissions measurements were taken with various ferrites attached to the cables. To verify that the ferrites were operating as suspected we plotted the impedance of the motor and cables with the absolute emissions below. This data is given in Fig. 11. It is evident that where the impedance increases the emission decreases.

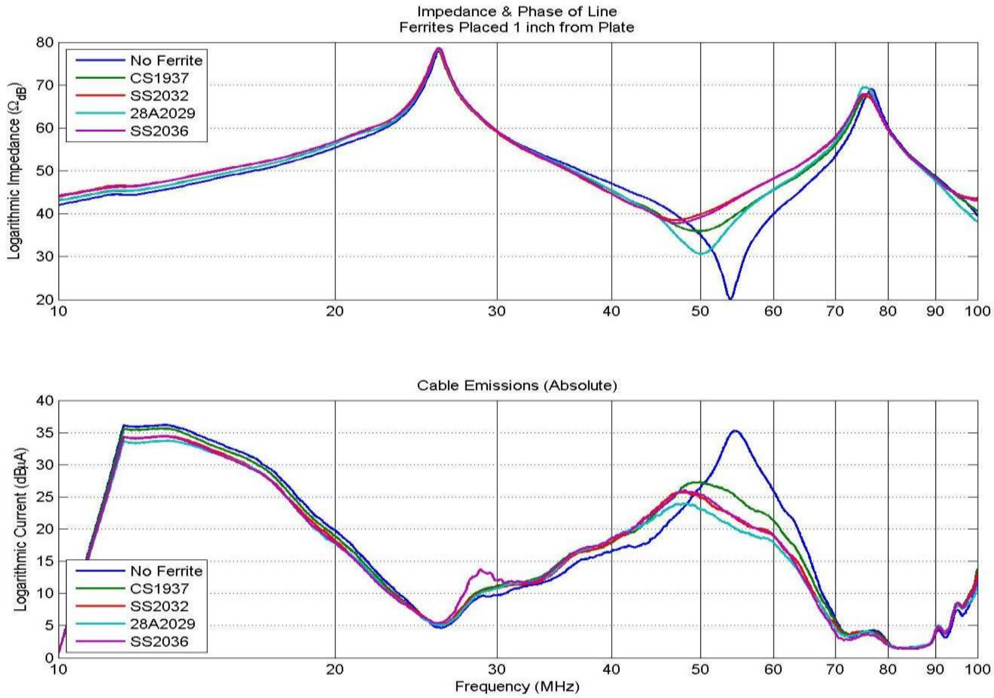

Fig. 11 – Ferrite Comparison: Impedance (top) & Absolute Emissions (bottom)

At this point we have a model for our motor that has been verified with one of two desired methods and we have the means to simulate a cable model. The effectiveness of ferrites has been tested and verified. To supplement this we need to simulate our models with ferrites and resolve any major discrepancies.

Conclusion

EMC modeling is essential for government compliance and robust design. Engineers can utilize models and augmented schematics to design device layout and geometry in order to minimize EMI. As an example, we have modeled an AC motor drive. An EMC model including parasitic capacitances and inductances for an IGBT package has been developed and validated with simulation and laboratory measurements. A high frequency model for the motor and a transmission line model for the cables has also been developed and verified.

Bibliography

1. IEC CISPR, *Electromagnetic Compatibility: Including Radio Interference*.

2. Mohan, Undeland, and Robbins, *Power Electronics: Converters, Applications and Design*, New York: Wiley, 1989.

3. Pak, T.T., “EMI Investigation of a Hybrid Electric Vehicle Traction Drive.” Masters Thesis, University of Missouri-Rolla, 2000.

4. Schinkel, M., Guttowski, S., and John, W., “Efficient HF Modeling and Model Parameterization of Induction Machines for Time and Frequency Domain Simulations,” *Applied Power Electronics Conference and Exposition, 2006. APEC ‘06. Twenty-First Annual IEEE*, pp. 6, Mar. 2006.

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