Estimating the Radiated Emissions from Cables Attached to a Switching Power Supply in a MIL-STD 461 Test

Guang-Hua Li^{#1}, Wei Qian^{#2}, Andriy Radchenko^{#3}, Gary Hess^{*4}, Robert Hoecke^{*5}, Pete Jalbert^{*6}, Thomas Van Doren^{#7}, David Pommerenke^{#8}, Daryl Beetner^{#9}

[#]EMC Laboratory, Missouri University of Science and Technology
4000 Enterprise Dr. Rolla, MO, USA

¹g1bm4, ²wq3z9, ³ar8r3, ⁷vandoren, ⁸davidjp, ⁹daryl@mst.edu

^{*}Hamilton Sundstrand, USA

⁴gary.hess, ⁵robert.hoecke, ⁶peter.jalbert@hs.utc.com

Abstract—Common-mode currents on cables attached to a switching power supply generate radiated emissions which may interfere with near-by components. A relatively simple equivalent circuit model is developed to predict the radiated emissions measured in a MIL-STD-461 or RTCA/DO-160 test. The intent of this model is to provide an estimate of emissions that allows the designer to better understand the mechanisms behind emissions issues and to rapidly predict the impact of changes to the system, like adding filtering, changing components, or modifying cable connections. The model represents cables connected to the power supply as transmission lines, represents coupling from the cables to the antenna using lumped capacitors, and represents the balun in the antenna using a transformer. The simulated results match the measured results well. This simple SPICE model allows EMI issues to be investigated early in the design of switched mode power supplies.

Keywords—Radiated emissions, EMI modelling, MIL-STD 461D, biconical antenna, switched mode power supplies.

I. INTRODUCTION

A switched mode power supply rapidly switches relatively large voltages and currents, creating large values of di/dt and dv/dt [1]. These switched currents and voltages can drive antenna structures within the power supply circuit or attached cables to create radiating electromagnetic fields that can interfere with nearby equipment. Because of the large values of di/dt and dv/dt , switched mode power supplies are a common source of radiated emissions.

One method used to determine the radiated emissions from a switched mode power supply is the MIL-STD 461D/462D radiated emissions tests [2]. In this test, the DC power supply wires are brought outside the cable shielding, which may allow the common-mode switching currents to generate significant radiated emissions. A similar setup is used in the RTCA/DO-160 test. Common-mode filtering of the DC power supply lines can reduce the radiated emissions [3] [4], but it is difficult to know before the test what level of filtering is sufficient to reduce emissions to an acceptable level.

Several methods have been proposed to help the designer predict the emissions early in the design process. One method is to use a time domain field-circuit co-simulation technique [5]. This method extracts the circuit parameters and then simulates the system geometry with a 3D full-wave modelling tool. Another method analyzes the spectrum of the waveform within the power supply, and then uses dipole/loop antenna models to estimate the radiated emissions at standard measurement positions [1]. This method assumes the antenna is in the far field and structures are electrically small. These conditions are not always satisfied in the MIL-STD 461 test, especially at 10s of MHz and with the receiving antenna only 1m away from the device under test.

While these methods focus on the emissions directly from the printed circuit board and components, the primary emissions below a few hundred MHz are generated from the attached cables [6]. In the MIL-STD 461 test, engineers are generally not as interested in the radiated emissions from the power supply itself but rather in the radiation from the cables attached to the power supply. The radiated emissions from the cables can be obtained from a measurement of the common-mode current along the cables and a multiple-dipole model [7]. The disadvantage of using a measurement, rather than an estimate, of the common-mode current is that the measurement can only be obtained after the power supply has been manufactured. A technique is needed to estimate radiated emissions at the early design stages, so design engineers can develop filtering and other approaches to mitigate emissions before a prototype is manufactured.

In the following paper, an equivalent circuit model is developed to estimate the voltage at a biconical antenna output during a MIL-STD 461 or RTCA/DO-160 radiated emissions test of a switched mode power supply. The model is intentionally simple, so that the engineer can develop the model easily even for relatively complex setups, so that results may be generated quickly using SPICE simulation tools, and so the model can help build an intuitive understanding of the mechanisms that cause emissions. The estimated results will

guide the development of switched mode power supplies and other equipment early in the design process. The model is developed for the vertical polarization of the antenna, since the measured emissions are typically worse in that polarization, as will be demonstrated in this paper.

The model is described in detail in the following sections. Sections II and III describe the measurement setup and a full-wave simulation model developed to validate the simple equivalent circuit model. Section IV describes the development of the simple equivalent circuit model. The calculated results from the simple circuit model are compared with the measured results in Section V.

II. MEASUREMENT SETUP

Before developing the simplified equivalent circuit model, the MIL-STD-461 test setup was explored through measurements and full-wave simulation. In the MIL-STD-461 test, the switched mode power supply is connected to test cables for evaluating radiated emissions. Part of the test cable is brought outside of the cable shield to connect to a Line Impedance Stabilization Network (LISN). To develop a model of the radiated emissions, a simple setup was created as shown in Fig. 1 that mimics the MIL-STD-461 test. The signal from the Vector Network Analyzer (VNA) represents the noise output of the switched mode power supply. Port 1 of the VNA drives a coaxial cable over a metal table. The coaxial cable is 1.01 m long and represents the shielded wires that are part of the MIL-STD-461 test. This coaxial cable will be called the “shielded cable” throughout the text. A 1.07 m long solid bare wire is attached to the inner conductor of the coaxial cable and is terminated at the far end by a short or an open. This cable represents the power wire separated from the shielded cable bundle in the MIL-STD-461 test. In the actual MIL-STD-461 test, the wire would be terminated with roughly 50-ohms by a LISN, but using an open or a shorted termination allowed the model to be tested at its limits. The shield of the coaxial cable was shorted at both ends to a large metal table, as in the MIL-STD-461 test. The table was 1.2 m wide and 2.4 m long. The cables under test were held 5 cm above the metal table by a styrofoam insulator. The metal table was 0.9 m above the chamber floor. The axis of the cable under test was located 10 cm away from and parallel to the edge of the metal table. The mid-point of the receiving biconical antenna [8] was 0.9 m from the edge of the metal table and 1 m above the chamber floor. The antenna was connected through a balun to port 2 of the VNA. Radiated emissions were measured inside a 3 m semi-anechoic chamber to avoid ambient interference.

The transmission coefficient $|S_{21}|$ between the cables under test and the biconical antenna was used to characterize the radiated emissions from the cables. The radiated emissions were measured for both the vertical and horizontal polarizations of the antenna from 10 MHz to 400 MHz.

III. FULL-WAVE NUMERICAL MODEL

A full-wave numerical model of the measurement setup was created before developing the simplified circuit model to provide better understanding of the coupling mechanisms

between the cable under test and the antenna. The full-wave model was constructed in EMCoS EMC Studio [9] and simulated with Method of Moments solver TriD. Fig. 2. shows the general view of the simulation model. The antenna model includes the 4:1 (200:50 Ω) balun model as a non-radiating network model, defined by scattering parameters [10].

The infinite perfect electric conducting (PEC) ground plane shown in Fig. 2 represents the floor of the semi-anechoic chamber. The cable under test was placed on the metal table as in the experimental setup. The material for the metal table and the antenna is aluminium.

A. Validation of full-wave model

A variety of measured results and simulated results using the full-wave numerical modelling tool were compared to validate the full wave model as shown in Fig. 3. Results were generated for vertical and horizontal polarizations of the antenna and for both open and shorted terminations of the cable under test. The measured and simulated values match within 2 dB over most of the frequency range.

The worst emissions (highest values of $|S_{21}|$) occur when the bare wire is terminated with a short and the antenna is in the vertical polarization. The value of $|S_{21}|$ when the wire is shorted is about 10 dB higher when the antenna is in the vertical polarization than when it is in the horizontal polarization.

(a) Measurement setup in a 3 m semi-anechoic chamber

(b) Diagram of the bare wire with load impedance Z_L , attached to a shielded cable driven by a voltage source V_s with source impedance Z_s of VNA.

(c) Diagram showing antenna and cable position.

Fig. 1. Setup for measuring the radiated emissions from a cable mimicking the MIL-STD 461 test.

Fig. 2. Full-wave numerical model of the measurement setup.

(a) $|S_{21}|$ for vertical and horizontal polarizations of the antenna with the bare wire shorted to metal table.

(b) $|S_{21}|$ for vertical and horizontal polarizations of the antenna with the bare wire terminated in an open circuit.

Fig. 3. Comparison of measured $|S_{21}|$ results with the results generated by the full-wave numerical model.

The resonance frequencies are related to the lengths of the two transmission lines formed by common-mode currents on the shielded cable above the metal table and by currents on the bare wire above the metal table. The common mode currents on the shielded cable are driven largely through mutual

inductive coupling from the circuit including the bare wire. For a transmission line shorted at both ends, the lowest frequency resonance occurs when the line length equals $\lambda/2$. The bare wire is terminated with 50 ohms where it connects to the coaxial cable in the MIL-STD-461 tests. Because this impedance is well below the characteristic impedance of the transmission line, it looks much like a short. When the bare wire is shorted to the metal table, the resonance frequencies of the 1.07 m shielded cable and 1.01 m bare wire are therefore 142 MHz and 130 MHz, respectively. For a transmission line open on one end and shorted on the other, the lowest frequency resonance occurs when the line length is $\lambda/4$. When the bare wire is terminated with an open, the resonance frequency of the shielded cable remains unchanged at 142 MHz, but the resonance frequency of the bare wire is reduced to 65 MHz.

IV. EQUIVALENT CIRCUIT MODEL

While a full-wave model is capable of predicting the emissions in a MIL-STD-461 test, a full wave model can be difficult and time consuming to construct, may not always be easy to modify, and may not provide the user with intuition as to why a certain configuration causes a problem or how to fix the problem. To meet this need, an equivalent circuit model was created to roughly estimate the radiated emissions. The model focuses on emissions when the antenna is vertically polarized, since these emissions are typically worst. Models for the horizontal polarization will be presented in future papers.

Capacitive coupling from the cable to the antenna is expected to be the dominant coupling mechanism. Near field mechanisms will dominate far field radiation because the biconical antenna is in the near field of the system under test over most of the 10-400 MHz test band. When the biconical antenna is in the near field of a radiating source, it is more sensitive to the electric field than to the magnetic field. The capacitive coupling can be represented by lumped capacitors between the cables and the antenna. The good match between the measured result and the circuit modelled result supports this assumption.

A. Capacitive Coupling Based Equivalent Circuit Model for the Biconical Antenna in Vertical Orientation

Capacitive coupling between the antenna, cables, and table occurs primarily as a result of the five capacitors shown in Fig. 4. C_{SAT} is the capacitance from the shielded cable to the top half of the antenna. C_{WAT} is the capacitance from the bare wire to the top half of the antenna. C_{GAT} is the capacitance from the metal table to the top half of the antenna. C_{GAB} is from the metal table to the bottom half of the antenna. C_{ATB} is the capacitance from the top half of the antenna to the bottom half. The values of these capacitances were extracted from the 3D numerical model using MAS/MoM Static3D solver of EMC Studio [11]. The weak coupling from the shielded cable and the bare wire to the bottom half of the antenna was neglected, since the bottom half of the antenna sits below the metal table and coupling would be small.

Fig. 4. Five capacitors responsible for capacitive coupling to the antenna.

Fig. 5. Transmission line model of the shielded cable and the bare wire.

In this simple model, the capacitors C_{SAT} and C_{WAT} are connected, respectively to the center of the shielded cable and to the center of the bare wire. The voltages at these positions can be determined by treating the cable and wire as transmission lines, as shown in Fig. 5. The noise source driving the cable under test is represented by V_S and Z_S , which is an equivalent source from VNA using Thevenin's theorem. These elements represent port 1 of the VNA in the S21 measurements. The outer conductor of the shielded cable and the metal table form transmission line 1 with an air filled medium. It should be emphasized that this transmission line is formed by current flowing on the outside of the shield above the metal table, not by currents flowing on the inside of the shielded cable. The bare wire and the metal table form transmission line 2.

The characteristic impedance of these transmission lines can be determined from the equation [12]

$$Z_o = \frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \cosh^{-1}\left(\frac{h}{r_w}\right) \quad (\Omega) \quad (1)$$

where r_w is the radius of a wire at height h above an infinite return plane. The characteristic impedance of the transmission lines is thus approximately $Z_{01} = 179.5 \Omega$ for the shielded cable and $Z_{02} = 234.5 \Omega$ for the bare wire. Their length can be expressed as an equivalent time delay. Since each transmission line is surrounded mostly by air, the phase velocity of each line is approximately equal to the speed of light in free space. The time delay can be calculated by

$$\text{time delay } t_d = \frac{\text{length}}{v_p} \bigg|_{v_p=c} \quad (2)$$

which gives $t_{d,1} = 3.352 \text{ ns}$ and $t_{d,2} = 3.556 \text{ ns}$.

Using the capacitors and transmission line models shown in Fig. 4 and 5, an equivalent circuit for the overall setup is shown in Fig. 6. The inductor L terminating the bare wire represents the equivalent inductance of the "short" from the bare wire to the metal table. The inductor M represents the mutual inductive coupling between the left-hand side loop

Fig. 6. Equivalent circuit model of measurement setup.

(transmission line 1) and the right-hand loop (transmission line 2) in Fig. 5, resulting from the "short" between the cable shield and the metal table. These inductance values, L and M , are estimated. Each transmission line is divided into two equal halves. The voltage at the center of the transmission lines is assumed to be capacitively coupled to the antenna.

B. Equivalent Circuit Model for Antenna 50 Ω :200 Ω Balun

A 50 Ω to 200 Ω impedance transforming balun is built into the biconical antenna to match the high impedance of the antenna to the 50 Ω measurement equipment. The balun also converts the differential output of the antenna (ports 2 and 3 in Fig. 7) to a single-ended output at the measurement equipment (port 1 in Fig. 7).

An equivalent circuit model for the balun is shown in Fig. 8, when connected to a 50-ohm VNA. There is a DC connection between the three ports of the balun and the metal chassis. A center-tapped transformer is used to create the 4:1 impedance transformation. The coupling factor K of the transformer was set to 1. The inductance L_1 of the primary turn was estimated to be 30 nH. In addition to the transformer, the balun has a 0.63 m long, 50 Ω coaxial cable connected at port 1 and shorter transmission lines connected to ports 2 and 3. These transmission lines have both dielectric loss (loss tangent = 0.02, close to that of FR4) and conductive loss (resistivity equal to copper). The relative dielectric constant is 4.2. While the balun includes common-mode rejection circuitry, this circuitry was not included in the model.

The balun model was validated by making direct S-parameter measurements with a VNA. When measuring the S parameters, two semi-rigid coaxial cables were connected to ports 2 and 3. These two cables were approximated to have the same characteristics as the transmission line at port 1 except with a length of 2 cm. These transmission lines are not part of the balun, but only a part of the measurement setup used to validate the balun model.

Measured and simulated S-parameters for the balun are shown in Fig. 9. The magnitude of the simulated and measured S-parameters matches within less than 1 dB and shows the expected 180 degree shift in phase. The attenuation is 4 dB rather than the ideal 3 dB due mainly to the dielectric and conductor losses in the transmission lines.

(a) Block diagram of balun

(b) Picture of the three-terminal balun

Fig. 7. The balun built into the biconnical antenna.

Fig. 8. Equivalent circuit model of the balun connected to a VNA.

C. Equivalent Circuit Model for Overall MIL-STD-461 Measurement Setup with Vertical Polarization

In the actual measurement, ports 2 and 3 of the balun are connected directly to the top and bottom of the biconnical antenna. Including the balun in the equivalent circuit model in Fig. 6 yields the circuit model shown in Fig. 10. This model represents the MIL-STD-461 measurement setup for a vertical antenna polarization.

V. VALIDATION OF EQUIVALENT CIRCUIT

The equivalent circuit model in Fig. 10 was validated by comparing measured and simulated values of the transmission coefficient $|S_{21}|$ from the cable input to the antenna. Fig. 11 shows the comparison. At frequencies below 200 MHz, the equivalent circuit predicted values of S_{21} within 5 dB of the measured values. The resonant frequencies at 130 MHz and 142 MHz are accurately predicted by the equivalent circuit model. The differences in the measured and simulated peak values at these frequencies are within 2 dB. The second harmonic frequency at 260 MHz is also predicted well, but the predicted amplitude is lower than the measured amplitude. The reason for this underestimation is still under investigation.

(a) Magnitude

(b) Phase

Fig. 9. Comparison of measured and simulated S-parameters for the 50 Ω, 200 Ω balun.

VI. CONCLUSION

Methods are needed to estimate the measured emissions in a MIL-STD 461 test early in the design process. The estimate can be rough, so long as it reasonably determines the peak emissions. A simple equivalent circuit model was developed for this purpose. The model estimates the measured emissions from a shielded cable connected to a bare wire which is shorted to the metal table, when the antenna is in the vertical polarization. A model was only developed for the vertical polarization, since the emissions are typically worse for this polarization than for horizontal polarization. Because the cable is in the near-field of the antenna below a few hundred MHz and the antenna is primarily sensitive to electric fields, the coupling from the cable to the antenna could be represented accurately using only lumped capacitors between the antenna, cables, and the table. Transmission line models of the cable were required to capture resonant effects. While the test-setup is simple, it is a fair representation of the emissions from a single cable in the MIL-STD 461 test and can be easily extended to more complicated real-world setups.

Fig. 10. Equivalent circuit model for the measurement setup in Fig. 1(a) for a vertical antenna polarization and a 10-400 MHz frequency range

Fig. 11. Comparison of the measured and simulated values of S21 from the cable to the antenna, when the antenna is in the vertical position and the bare wire is shorted to the metal table.

Preliminary results show that the equivalent circuit model predicts the radiated emissions over much of the frequency band up to 400 MHz, including the first resonance. While better results are possible from a full-wave numerical model, results are good enough to provide estimate of emissions early in the design process and to show the potential impact of changes to the system. In addition, the simplicity of the equivalent circuit model allows one to understand the mechanisms that cause an emissions problem and how that problem might be fixed. Since the model is implemented in SPICE, it can quickly and easily be used with existing circuit models of system components.

Future study will explore methods to analytically estimate values of the coupling capacitors and will validate the ability of the model to predict emissions from a real system.

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