MEASUREMENT METHODS TO CHARACTERIZE CONDUCTED EMI SOURCES

Hocheol Kwak, Haixin Ke and Todd Hubing

Clemson University, SC 29634 USA – hkwak@clemson.edu

***Abstract* — The 1-Ω/150-Ω direct coupling method described in IEC 61967-4 can be used to identify possible noise problems with specific ICs. However, the measurements described in this test procedure do not yield data that can be used to build source models of the IC sufficient for conducted or radiated emissions modeling. Accurate source models are required for system-level emissions simulations. This paper describes the errors associated with attempting to characterize a conducted emissions source with a single measurement and discusses alternative test procedures that could be used for this purpose.**

1. INTRODUCTION

Test procedures for measuring the conducted noise coupled from integrated circuits are described in the IEC 61967-1 and IEC61967-4 standards [1, 2]. IEC 61967-4 describes a method for measuring the supply current through a 1-Ω resistor in order to give an indication of the noise injected into the power distribution network by the IC. This measurement method can be useful for determining the amount of decoupling capacitance required or determining the effects of different decoupling configurations. The IEC 61967-4 standard also describes a method for measuring the voltage on I/O pins across a 150-Ω load. The standard describes 150 Ω as *a typical antenna impedance*; suggesting that the procedure is designed to estimate how strongly an unloaded IC pin might be able to drive an antenna. This can be useful for determining the ability of an IC output to be the source of an electromagnetic interference problem or for comparing the relative noise producing potential of two ICs independent of their intended application.

Prior to the introduction of IEC6197-4, there was no standardized test procedure for characterizing the conducted emissions from integrated circuits. Data from this test procedure can be helpful for selecting an IC, but the procedure has significant limitations and does not fully characterize the IC output drivers. Circuit board or system-level EMI models require more information than just the voltage delivered to a 150-Ω load. The following sections discuss some of the limitations of the IEC61967-4 standard and possible enhancements that would provide information about the IC required for system-level emissions modeling.

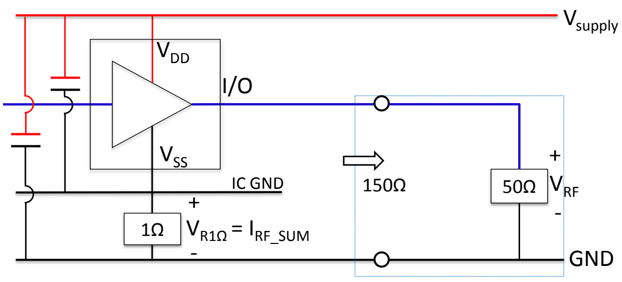

Fig. 1. IEC 61967-4 test configuration.

2. THEVENIN EQUIVALENT SOURCE MODEL

According to Thevenin's theorem, a linear circuit source can be fully characterized by two measurements; an open-circuit voltage measurement and a short-circuit current measurement. A Thevenin equivalent source model can be built using these impedance measurements.

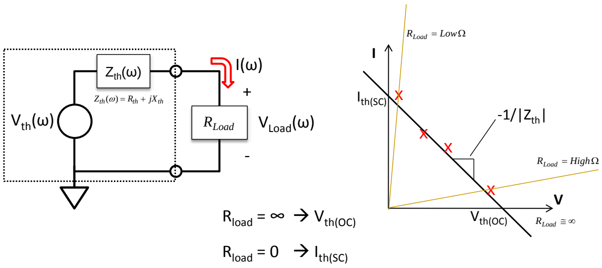

Fig. 2. Thevenin equivalent circuit and V-I curve.

At high frequencies, it can be difficult to measure the Thevenin open-circuit voltage, V_{oc}, and short-circuit current, I_{sc}, directly. However, we can estimate V_{oc} and I_{sc} with adequately high- and low-valued load impedances as indicated on the right in Figure 2. Note that sources with real-valued source impedances can be characterized by magnitude-only measurements. Sources with complex source impedances generally require magnitude and phase measurements.

3. LIMITATIONS OF IEC 61967-4 STANDARD

3.1 Sensitivity to measurement error

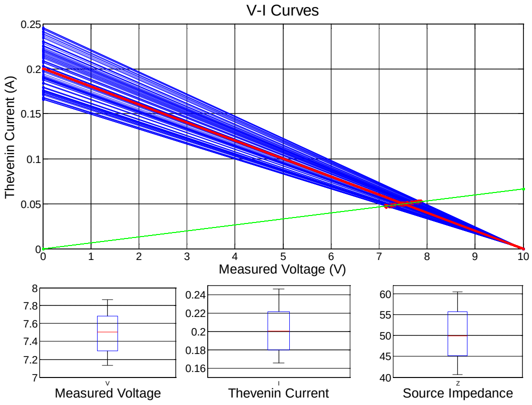

Fig. 3. Sensitivity to V_{RF} measurement error.

A 150-Ω RF voltage measurement as described in IEC 61967-4 could theoretically be used to determine the magnitude of the source impedance if the open-circuit voltage were already known. The upper plot in Figure 3 shows a V-I curve obtained from a single 150-Ω measurement of a 50-Ω source with an open-circuit voltage of 10 V. The known open-circuit voltage provides one fixed point that falls on the horizontal axis. The 150-Ω measurement provides the second point needed to draw a line. The slope of the (red) line indicates that the source impedance is 50 Ω. The blue lines in Fig. 3 represent the effect of a plus or minus 5% error in the voltage measurement. As indicated in the box plot in the lower right-hand side of the figure, the error in the slope corresponds to a source impedance that varies from 40 Ω – 60 Ω (plus or minus 20% error). In each box plot, the central red mark represents the median value; the blue edges of the box indicate the limits within which 50% of the data points closest to the median fall; and the whiskers indicate the most extreme data points. In this example, if the source impedance had been lower than 50 Ω, the error sensitivity would have been even greater.

3.2 Sensitivity to the assumed V_{oc}

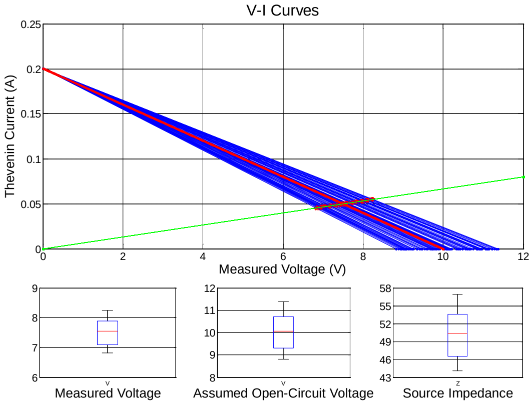

Fig. 4. Sensitivity to the assumed open-circuit voltage.

In the frequency domain, the open circuit voltage is a function of frequency and depends on the waveform generated by the IC. At low frequencies, we might be able to measure this or infer its value from published waveforms; but at moderate to high frequencies the open circuit voltage cannot be determined accurately. The upper plot in Figure 4 shows the V-I curves obtained for a fixed 150-Ω measurement and an assumed open circuit voltage that varies by plus or minus 10% as shown in the middle of lower box plots. In this case, the slope of the line varies dramatically and the calculated source impedance ranges between 43 Ω and 58 Ω as shown in the lower right box plot.

3.3 Sensitivity to ωL

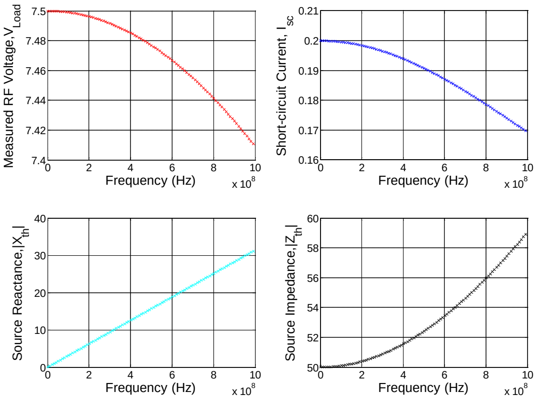

Fig. 5. Slope of V-I curve is $-1/|Z_{th}|$.

A non-zero source reactance increases the apparent magnitude of the source impedance, $|Z_{th}|$, which affects the value of short circuit current on the vertical axis of the V-I curve. As long as ωL << (R_{th}+150 Ω), this effect can be neglected. For example, Figure 5 illustrates how 5 nH of parasitic inductance would affect various measured circuit parameters in a circuit with a 50-Ω source impedance. The measured the reactance value at 150 kHz is about 4.7 mΩ, which doesn't have much effect on the RF voltage measurement. However, the reactance value at 1 GHz would be about 31.4 Ω. This would seriously compromise the measurement of a 50-Ω source and would completely obscure the source resistance of most high-speed digital outputs that typically have source resistances of a few ohms or less.

3.4 Measurement requirements

A single RF voltage measurement can't be used to characterize an unknown source. For sources with a real source resistance, a minimum of two voltage measurements are required to determine the two unknown quantities, V_{OC} and R_{TH}. These values can be determined with minimal sensitivity to measurement error by measuring with one low-impedance load and one high-impedance load. The low impedance should be a resistance that is a small as possible, but greater than the parasitic inductive reactance at the highest frequencies of interest. The high impedance should be as large as possible, but less than the parasitic capacitive reactance at the highest frequencies of interest [3].

4. ALTERNATIVE MEASUREMENTS

4.1 1/50/500-ohm measurement

Theoretically, three magnitude-only measurements are required to fully characterize sources with complex source impedances. This is because there are three real-valued unknowns: the Thevenin resistance, R_{th}, the amplitude of the Thevenin reactance, X_{th}, and the open-circuit voltage, V_{OC}. At least one of these magnitude-only measurements would have to be made with a complex load. In practice, attaching a reactive load to a reactive source impedance and accurately measuring the voltage across the reactive load would be very difficult. However, we are often not interested in the sign of the source reactance; or if we are, it can be determined separately. In this case, measurement of the magnitude of the voltage induced across three real-valued load resistances is sufficient.

To demonstrate this, we measured various sources using the three load resistances: 1, 50 and 500 Ω. Fixtures were built to terminate the source with the appropriate resistance and connect to a 50-Ω oscilloscope or spectrum analyzer as shown in Figure 6.

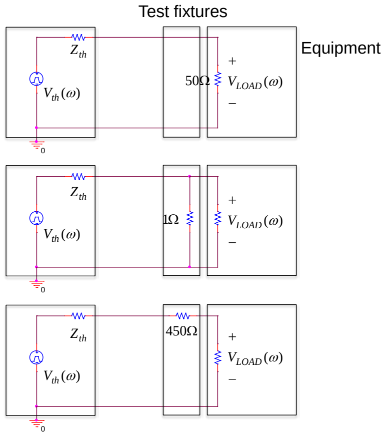

Fig. 6. Three load conditions for characterizing conducted EMI sources.

4.2 Estimation of Thevenin equivalent circuit

Figure 7 illustrates the source with the three unknown source parameters connected to the three different loads.

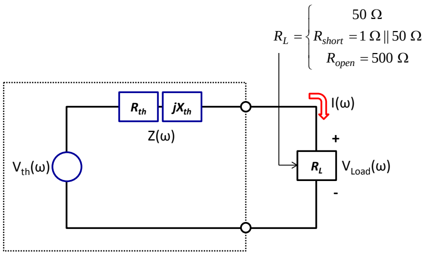

Fig. 7. Thevenin equivalent circuit for three load conditions.

The following equations express the expected value of the measured voltage for the three load conditions as a function of the source parameters, V_{th} and Z_{th};

$$\left|V_{50\Omega\_Load}\right| = \left|V_{th}\right| \left|\frac{50\Omega}{50\Omega + Z_{th}}\right| \tag{1}$$

$$\left|V_{short\_Load}\right| = \left|V_{th}\right| \left|\frac{R_{short}}{R_{short} + Z_{th}}\right| \tag{2}$$

$$\left|V_{open\_Load}\right| = \left|V_{th}\right| \left|\frac{R_{open}}{R_{open} + Z_{th}}\right| \tag{3}$$

where,

$$Z_{th} = R_{th} + jX_{th} \tag{4}$$

$$R_{short} = 1\Omega \parallel 50\Omega,\ R_{open} = 500\Omega \tag{5}$$

Equations (1) – (5) can be algebraically manipulated to express the source parameters V_{th}, R_{th} and $|X_{th}|$ as a function of the measured voltages,

$$V_{th} = \sqrt{\frac{R_{short} - 50\Omega}{2(A-B)}} \tag{6}$$

$$R_{th} = \left|V_{th}\right|^2 \times B - \frac{R_{open} + 50\Omega}{2} \tag{7}$$

$$\left|X_{th}\right| = \sqrt{\frac{\left|V_{th}\right|^2 \times 50\Omega^2}{\left|V_{50\Omega\_Load}\right|^2} - (50\Omega + R_{th})^2} \tag{8}$$

where,

$$A = \frac{\left(\dfrac{R_{open}}{\left|V_{open\_Load}\right|}\right)^2 - \left(\dfrac{R_{short}}{\left|V_{short\_Load}\right|}\right)^2}{2(R_{open} - R_{short})} \tag{9}$$

$$B = \frac{\left(\dfrac{R_{open}}{\left|V_{open\_Load}\right|}\right)^2 - \left(\dfrac{50\Omega}{\left|V_{50\Omega\_Load}\right|}\right)^2}{2(R_{open} - 50\Omega)} \tag{10}$$

These equations can be used to determine the source parameters of a complex source based on three relatively simple measurements. However, preliminary measurements and simulations indicate that, for some sources, measurement errors of a few percent can result in much larger errors in the estimation of the Thevenin impedance. This is particularly true for sources with very low or very high source impedances. Alternative formulations and adjustments to the test procedure are being evaluated. Possible solutions involve:

- making more than three measurements to do a “best fit” calculation,
- using known physical information about the source to further constrain the calculations,
- or, using a controlled reactive load for one of the measurements.

The ultimate goal of this investigation is to develop a reliable and accurate method for fully characterizing conducted EMI sources and producing source-models that can be used in system-level simulations [4].

4.3 Direct impedance measurement

As illustrated in Figure 8, the Thevenin source impedance can be measured directly using a network analyzer or impedance analyzer when the source voltage can be set to zero. The open-circuit voltage can then be determined by magnitude-only measurements across one or two real-valued loads. With this method swept-frequency characterization of the Thevenin impedance is possible, which facilitates a more accurate characterization of this impedance using lumped circuit elements. This technique is only practical when it is possible to turn the source off without changing the impedance looking into the source terminals. In some cases it may also be possible to use a method like this to characterize sources while they are operating at frequencies different from the frequencies being measured.

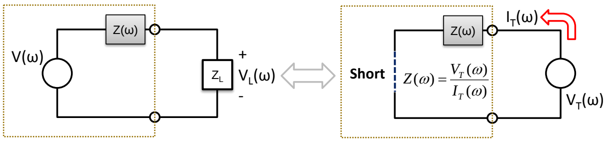

Fig. 8. Direct measurement of the Thevenin impedance.

5. CONCLUSIONS

The IEC 61967-4 conducted emissions measurements are useful for identifying potentially noisy ICs, but they do not provide the information necessary to characterize the ICs as emissions sources in system-level simulations. At least two magnitude-only measurements are required to characterize a linear source with a resistive source impedance. At least three magnitude-only measurements are required to characterize a linear source with a complex source impedance. Some options have been discussed in this paper; however more work is required to develop an accurate and robust conducted emissions measurement capable of fully characterizing linear IC outputs over a wide range of frequencies.

6. REFERENCES

[1] IEC 61967-1 Integrated circuits - Measurement of Electromagnetic Emissions, 150 kHz to 1 GHz - Part 1: General Conditions and Definitions, International Electrotechnical Commission, Geneva, Switzerland, March 2002.

[2] IEC 61967-4 Integrated circuits - Measurement of Electromagnetic Emissions, 150 kHz to 1 GHz - Part 4: 1Ω/150Ω Direct Coupling Method, International Electrotechnical Commission, Geneva, Switzerland, July 2006.

[3] T. Hubing, “Building IC Models Based on Measurements and Using these Models Productively,” *EMCCompo 2007, 6th International Workshop on Electromagnetic Compatibility of Integrated Circuits*, Torino, Italy, November 2007.

[4] H. Kwak, H. Ke and T. Hubing, “Characterizing Conducted EMI Sources with A 1/50/500-Ohm Measurement,” *Clemson Vehicular Electronics Laboratory Technical Report*, CVEL-09-002, April 2009.