Interpreting Antenna Performance Parameters for EMC Applications
Part 1: Radiation Efficiency and Input Impedance Match

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Antenna performance parameters and the language used to describe antennas can be confusing and sometimes even misleading. While much can be said in general about what constitutes a good antenna, most designs reflect some sort of compromise or trade off between the various desirable attributes because antenna design involves conflicting goals. Therefore, it is crucial that antenna specifications be reviewed in light of the intended application. A more complete understanding of the terminology associated with antennas allows the engineer to specify the most appropriate antenna for a given task.

A great deal of effort has been made over the years to standardize antenna terminology. The de facto standard is the *IEEE Standard Definitions of Terms for Antennas* published in 1983. The EMC community has developed its own distinct vernacular with terms not included in the IEEE standard. While some of these terms are superfluous, they elucidate some important antenna characteristics and are convenient to those working in the field.

This tutorial paper is the first in a series in which we will discuss antenna terminology. In this first part we will cover two widely used terms that have perhaps not received adequate attention: antenna radiation efficiency and input impedance match.

Strictly speaking, an antenna is a device which can radiate or receive electromagnetic energy. An ideal transmitting antenna accepts power from a source (perhaps a power amplifier) and *radiates* the power into space. That is, electromagnetic energy escapes from the antenna and, unless reflected or scattered, does not return. This is in contrast to a non-radiating electric or magnetic field generator, such as a Helmholtz coil, which generates primarily non-radiating fields. Such a device accepts energy from the source and then either returns it to the source (on alternate half cycles) or dissipates it in a resistive load. A practical antenna generates both radiating and non-radiating field components.

In the EMC area, quasi-static field generators are usually lumped together with true antennas. Moreover, in EMC testing, antennas are often used in configurations that (intentionally or otherwise) make use of both their radiating and non-radiating field components.

Antenna Efficiency or Radiation Efficiency

It is appropriate to first address the issue of antenna efficiency. If an antenna is taken as a device which accepts power from a source and radiates it into space, the ratio of the power radiated into space to the power accepted from the source is the efficiency [1, 2],

$$\eta_{radiation},$$

sometimes termed the radiation efficiency. Radiation efficiency is defined in the above IEEE reference as “the ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter.” Thus antenna efficiency is an easy concept to grasp; it is exactly the same as the definition of efficiency for essentially any power conversion device.

$$P_{radiated} = P_{input}\,\eta_{radiation}$$

The power that is accepted by an antenna but not radiated is dissipated in the form of heat. The reader will notice that radiation efficiency is rarely, if ever, published in any antenna manufacturer’s literature. There are several reasons for this: First, radiation efficiency is exceedingly difficult to measure accurately; techniques for experimentally determining radiation efficiency are the subject of ongoing research (especially for portable telecommunication devices). Second, the radiation efficiency of an antenna is implicitly contained in the complete specification of the *gain* of an antenna (to be discussed in Part 2 of this article). We point out here that the radiation efficiency of any of the non-radiating field generators mentioned above is essentially zero. The electric or magnetic field at a given point or in a particular region might be large, but essentially no power is radiated. For the transmission-line type electric field generator shown in Figure 1 and the stripline shown in Figure 2, the RF power from the amplifier travels through the electric field generator to a high-power load located in the opposite end of the device. Essentially all of the power from the amplifier is dissipated in the load with the exception of a small amount absorbed by the DUT or in nearby absorbing material. For this particular electric field generator, the power handling capability is 4 kW. Thus, 4,000W of waste heat is generated in the load, thereby requiring special thermal considerations. The electromagnetic field of a non-radiating device such as this is much more localized than that of an antenna; far away from the device the field decays with the inverse square of the distance from the device. This localization can be a desirable feature when the device must be operated in a shielded chamber exhibiting high-Q modes (most chambers, even those lined with ferrite absorber, exhibit modes below 30 MHz). The localization of the fields greatly reduces the interaction between the field generating device and the chamber. There are other types of electric field generators. However, in any case, the radiation efficiency of such a device is practically zero.

Figure 1: Transmission-Line Type E-Field Generator

(*Photo Courtesy of TDK RF Solutions*)

Figure 2: Stripline for Radiated Immunity Testing

(*Photo Courtesy of TDK RF Solutions*)

It is important not to confuse radiation efficiency with impedance mismatch. The radiation efficiency is simply the ratio of the power *radiated* by an antenna to the power *accepted* by the antenna. An antenna can be very nearly 100 percent efficient but still function very poorly if it reflects power back into the source.

Input Impedance, Input Match, Matching Efficiency, and Input VSWR

The ability of an antenna to accept power from a source (such as an amplifier) is determined by the input impedance the antenna presents. For maximum power transfer, the input impedance should exactly match the output impedance of the source. Strictly speaking, for maximum power transfer the input impedance of the antenna must be the complex conjugate of the amplifier's output impedance. However, essentially all amplifiers and other RF sources exhibit real output impedances, with the vast majority having output impedances of 50 Ω. The 50 Ω system impedance level, in turn, was chosen as a standard coaxial cable impedance and represents a good compromise between dissipative loss and power handling. On the other hand, over a broad bandwidth, the complex input impedance of an antenna will differ greatly from 50 Ω. The complex reflection coefficient at the input of the antenna is

$$\Gamma = \frac{Z_{input} - Z_0}{Z_{input} + Z_0}$$

where

$$Z_{input}$$

is the antenna's complex input impedance and

$$Z_0$$

is the source/system impedance. The power reflected is equal to the incident or forward power multiplied by the square of the magnitude of the complex input reflection coefficient

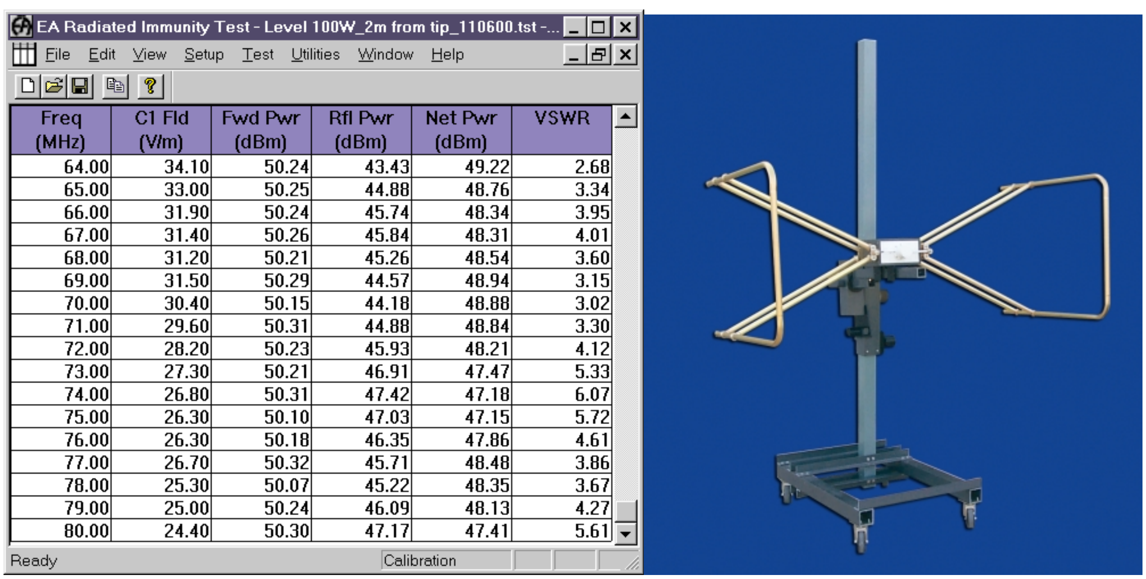
$$P_{reflected} = P_{forward} \left| \Gamma \right|^2 .$$

Thus, the power accepted by the antenna, sometimes referred to as the net power, is given by

$$P_{input} = P_{net} = P_{forward} - P_{reverse}$$

$$P_{input} = P_{forward} (1 - \left|\Gamma\right|^2) .$$

These parameters can be measured by a software-driven automated test system. Figure 3 shows the user interface for radiated immunity test software set up to monitor frequency, forward power, reflected power, net power, VSWR, as well as the field produced by the antenna (in this case, a high power broadband antenna).



Freq (MHz)	C1 Fld (V/m)	Fwd Pwr (dBm)	Rfl Pwr (dBm)	Net Pwr (dBm)	VSWR
64.00	34.10	50.24	43.43	49.22	2.68
65.00	33.00	50.25	44.88	48.76	3.34
66.00	31.90	50.24	45.74	48.34	3.95
67.00	31.40	50.26	45.84	48.31	4.01
68.00	31.20	50.21	45.26	48.54	3.60
69.00	31.50	50.29	44.57	48.94	3.15
70.00	30.40	50.15	44.18	48.88	3.02
71.00	29.60	50.31	44.88	48.84	3.30
72.00	28.20	50.23	45.93	48.21	4.12
73.00	27.30	50.21	46.91	47.47	5.33
74.00	26.80	50.31	47.42	47.18	6.07
75.00	26.30	50.10	47.03	47.15	5.72
76.00	26.30	50.18	46.35	47.86	4.61
77.00	26.70	50.32	45.71	48.48	3.86
78.00	25.30	50.07	45.22	48.35	3.67
79.00	25.00	50.24	46.09	48.13	4.27
80.00	24.40	50.30	47.17	47.41	5.61

Figure 3: Software Monitoring the Behavior of a High Power Broadband Antenna

(Screen capture and photo courtesy of TDK RF Solutions)

We can now define a "mismatch efficiency" as

$$\eta_{mismatch} = 1 - |\Gamma|^2 .$$

Now,

$$P_{radiated} = P_{forward}\ \eta_{mismatch}\ \eta_{radiation} .$$

Notice that while the mismatch efficiency does not have the same thermodynamic implications as the radiation efficiency (it does not indicate any power dissipated as heat), it is a quantity which ranges from 0 to 1 with 1 being the ideal value. The quality of the input impedance match for an antenna is generally not specified in terms of either reflection coefficient or mismatch efficiency. Rather, it is specified by one of two other parameters: return loss or Standing Wave Ratio (SWR), sometimes called Voltage Standing Wave Ratio (VSWR). The return loss (a term originally coined for telephone systems) [3, 4] indicates how much of the incident power is not reflected or does not return from a load. In other words, it is the square of the magnitude of the reflection coefficient, usually expressed logarithmically as

$$R.L. = 10\log_{10}\left(|\Gamma|^2\right) = 20\log_{10}\left(|\Gamma|\right).$$

Thus, a return loss of –3.0103 dB indicates that half of the incident power is reflected (for example, forward power = 100W, reverse power = 50W, net power = 50W). The standing wave ratio is defined as the ratio of voltage minimum to maximum on the input transmission line. It is partly a carry-over from days when slotted transmission lines were used to experimentally determine input impedance. The slotted line was capable of measuring the magnitude of the voltage along a transmission line. In terms of the reflection coefficient, the standing wave ratio is given by

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}.$$

One utility in VSWR for describing input match is that while the magnitude of the reflection coefficient will range from 0 to 1 for a passive device such as an antenna, the VSWR will range from 1 to infinity. The VSWR then is particularly useful for describing input match when the match is not very good. Note that a VSWR of 5.83 corresponds to 3.01 dB return loss or a reflection coefficient magnitude of

$$\frac{1}{\sqrt{2}}.$$

The equipment used for EMC testing is significantly different from that used for communications and broadcasting. The reason for this is that much greater bandwidth demands are made on the EMC test equipment. Therefore, constraints on input match must be relaxed to some extent. Many power amplifiers operating over frequency bands under 1 GHz will drive loads (such as antennas) with VSWRs of 6:1 or more; some manufacturers claim their equipment will operate into any VSWR. A common high-VSWR situation is the use of the standard 1.37 meter biconical antenna at frequencies below 80 MHz. This arrangement is often used for MIL-STD 461 radiated susceptibility testing. Because the testing is performed at 1 meter distance, the reactive near field components of the biconical antenna can provide intense fields. Nevertheless, these are really the quasi-static fields, and most of the power is returned to the amplifier. Not all amplifiers are tolerant of mismatched loads. In particular, some amplifiers, such as Traveling Wave Tube Amplifiers (TWTAs), must have very well-matched loads or employ some sort of non-reciprocal device such as an isolator or circulator to prevent reflected power from returning to the amplifier. Furthermore, high VSWR results in high voltages and high currents on the feed coaxial cable. For a VSWR of 5.83:1, the maximum voltage on the input transmission line is 1.707 times the matched output voltage of the amplifier. The maximum current, which occurs at points one-quarter wavelength away from the maximum voltage points, is 1.707 times the matched output current of the amplifier. This can result in arcing or thermal damage. Good engineering practices dictate that both connectors and cables must be de-rated from their matched power ratings if used in high VSWR situations.

In Figure 4, the VSWR for a typical log periodic dipole antenna (LPDA) is plotted. Over its operating frequency range the LPDA exhibits a VSWR < 2:1. This would be acceptable even for most communications systems, which are much less tolerant than EMC test systems.

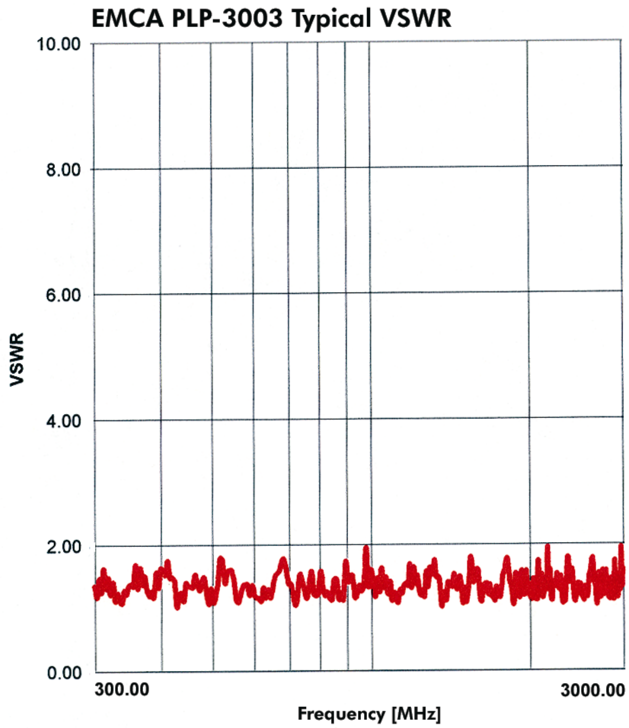


Figure 4: Typical VSWR for Precision Log Periodic Antenna

(*Antenna data and photo courtesy of TDK RF Solutions*)

In Figure 5, the input VSWR for a typical 1.37 meter biconical antenna is plotted. The VSWR is quite low from 80 to 300 MHz. However, these antennas are routinely used from 20 to 80 MHz as well. Below 80 MHz (roughly the fundamental series resonance of a 1.37 meter biconical antenna), the VSWR increases precipitously with decreasing frequency. This is a natural consequence of the decreasing electrical size of the antenna as frequency decreases. While it is possible to reduce the VSWR of this antenna in the range of 20 to 80 MHz, it is not possible to do so without compromising the match elsewhere. Thus, the VSWR behavior shown in Figure 5 is a reasonably good compromise.

This behavior is more or less typical of any 1.37 meter biconical antenna employing a 4:1 balun and not utilizing any resistive components to pad the VSWR down. While the impedance match is poor below 50 MHz, the response of the antenna is generally useable down to 20 MHz. A glance at the various manufacturers' catalogs will show that the antenna factors of such biconical antennas are similar, at least in their gross behavior, over the 20 to 80 MHz range.

The most important attribute of such an antenna in the range of 20 to 80 MHz is the balance (to be discussed in the next article). The reason for this is that the balance depends in part on the ratio of the choking impedance of the balun to the antenna's input impedance. As the antenna's input impedance becomes large in magnitude (and capacitive in nature) as the frequency decreases below 80 MHz, the balancing task of the balun becomes *much* more difficult. Note that if providing a good impedance match is critical, a 6 dB attenuator placed at the input of the antenna will provide essentially 12 dB better return loss while causing only a 6 dB reduction in overall gain or a 6 dB increase in antenna factor. In fact, a 3 dB attenuator will usually provide an acceptable match for most systems. Given that path loss over 3 meters at 300 MHz (the high end of the 1.37 meter biconical's operating frequency range) is over 30 dB, an additional 3 to 6 dB loss may have little effect on an emission system's dynamic range.

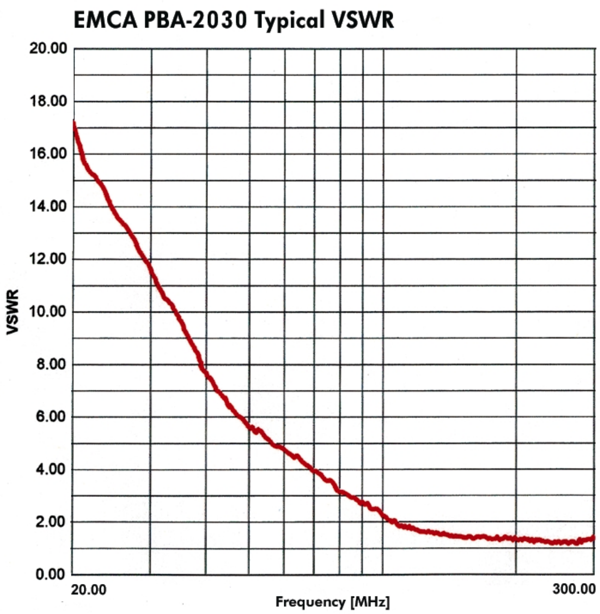


Figure 5: Typical VSWR for Precision Biconical Antenna
(*Antenna data and photo courtesy of TDK RF Solutions*)

Conclusion

Both radiation efficiency and input impedance match affect the ability of an antenna to generate far field electromagnetic radiation. Input impedance match determines how much incident power is reflected back into the source, while radiation efficiency determines how much incident power is dissipated as heat in the antenna. The intensity of the far field radiation produced by an antenna also depends on the tendency of the antenna to radiate power in a particular direction. This property is known as gain and will be discussed in a our next article.

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