ELECTROMAGNETIC SUSCEPTIBILITY

Background

Once an almost completely neglected aspect of EMC/EMI, susceptibility has within the past few years assumed extremely important status. The earliest military rf interference specifications (such as AN-I-24 and Navy 16E4) had no susceptibility requirements at all. Not until the appearance of MIL-I-6181 in 1950 was there a document with susceptibility limits and test methods. Progressive expansion of susceptibility requirements in military EMI documents paralleled that of the emission aspects thereof. However, in the civilian sector, susceptibility considerations were essentially ignored, except in a few documents covering commercial airline avionics equipments. The Federal Communications Commission (FCC) Rules and Regulations contain emission limits and test methods for receivers in Part 15; but requirements for susceptibility have never been established for consumer equipment in the U.S. This has led to a near-chaotic situation within the past few years; in which, by the beginning of 1977, the FCC will have been presented with about 200,000 complaints of interference to consumer-owned electronic equipments in two years. Efforts in the Congress to alleviate the situation by specifically authorizing the FCC to establish susceptibility requirements for civilian electronic equipment have come to nought thus far.

Definitions of Susceptibility

Susceptibility has been defined variously in a number of the government and other requirements documents. MIL-STD-463 (Military Standard Definitions and System of Units, Electromagnetic Interference Technology) defines it as "the characteristic of electronic equipment that permits undesirable responses when subjected to electromagnetic energy." Somewhat more specifically, the Society of Automotive Engineers' ARP 937 uses the following definition: "That characteristic which causes an equipment to malfunction or exhibit an undesirable response when its case of any external lead or circuit is subjected to electromagnetic voltages or fields." However defined, susceptibility is, indeed, a highly significant aspect of EMC/EMI engineering.

Origins of Susceptibility

Susceptibility may originate in many ways. Some of these are:

1. Receiver front-end overload.
2. Intermodulation product generation in non-linear elements, both intentional (such as mixers) and unintentional (such as audio IC's).
3. Demodulation of environmental rf signals in low-level audio circuits.
4. Spurious system resonances in sub-audio to gigahertz frequency ranges.
5. Power line noise and transients.
6. Electrostatic discharge.

Table 1 summarizes the various conducted and radiated susceptibility test frequency ranges and briefly describes the basic test methods used.

Particularly for military equipments and systems, requirements which are more stringent and/or in frequency ranges not covered by a particular document may be imposed by the system or equipment specification.

Conducted Susceptibility

Electronic devices and many equipments usually considered electrical may be vulnerable to external signals or noise entering their circuits on their power leads. The low-frequency 30Hz - 50 kHz conducted susceptibility requirements, CS01 of MIL-STD-461, are intended primarily to assure that a particular equipment item will perform satisfactorily when operated from power sources which may be contaminated with spurious emanations; for example, power frequency harmonics, motor commutator ripple, or DC/DC converter oscillator powerline modulation.

Figures 1 and 2 indicate the relationship between conducted susceptibility requirements and power characteristics for aircraft 28-volt DC systems as defined in MIL-STD-704.

It is obvious that a margin of safety is provided between the maximum permissible 28-volt/DC bus ripple voltage envelope and the susceptibility test voltages specified. It should also be noted that Figure 2 shows that equipment designed for supplies other than 28 volts should be able to function properly with up to 10 percent of the nominal supply voltage (to a maximum of three volts) applied to its power leads at frequencies up to 1500Hz with decreasing levels above that point.

Spike-type susceptibility is covered by Requirement CS06 of MIL-STD, which specifies the characteristics of the transients to be applied to the power input leads. As an example of vulnerability of presumably well-designed equipment to spikes injected on power input leads, a few years ago one of the more widely used computing systems (this one installed at a non-military facility) was found to be susceptible to transients at levels significantly below the specified 100 volts of CS06. Reduction of susceptibility to transients is rapidly becoming of importance in commercial and consumer electronic equipment. Micro- and mini-computers are entering the market, in vehicular and household applications. For instance, a fine roast could be overcooked when the solid-state controller in a microwave oven malfunctions becaue of its vulnerability to transients generated by the SCR speed regulator in a hair dryer being used in the same house. Quantitative information on spike susceptibility requires the use of a transient generator with controllable repetition rate and amplitude; however, some qualitative idea of the vulnerability of an item to transients may be obtained by connecting a relay "multivibrator" across the input to the device. This is a relay wired so that its coil is in series with one of its normally-closed contacts.

Conducted rf susceptibility (50 kHz and above) requirements are aimed at assuring that an equipment item will be able to function properly in typical environments. Powerlines act as antennas and will pick up any rf signal which impinges on them. Such signals can, in turn, propogate along the lines and arrive at the power input terminals of the device.

Once inside, coupling of the spurious signal into vulnerable circuits can occur by many different paths. The recent explosive growth of both communications and non-communications rf sources in public and private use means that this aspect of susceptibility can no longer be considered as only of importance in complex military systems. One point which should be emphasized in connection with rf susceptibility testing - both conducted and radiated - is the requirement of Paragraph 5.5.1 of MIL-STD-461, which states: "Susceptibility signals shall have characteristics

The family of conducted susceptibility requirements represented by CS03, CS04, CS05 and CS07 is intended to assure that receivers are capable of operating compatibly in radiated rf environments in which they will be used. Although rf ambient levels are much higher in most military usage situations, the proliferation of communications transmitters mentioned above has resulted in a corresponding increase in interference incidents involving receivers used by the general public and by the numerous municipal, county and state government agencies. CS03 establishes intermodulation requirements; while CS05 sets out those for cross-modulation (which is generally considered to be a special case of intermodulation). CS04 requirements cover front-end rejection of undesired signals. It is quite important that both the testing and the analyses of results for the above three sets of requirements be performed by competent personnel. Differentiation between true spurious responses (e.g., a higher-order image or an IF feed-through) and the more complex intermodulation products may be difficult, indeed, even for relatively experienced engineers and technicians. Computer or programmable-calculator analytical techniques must be resorted to in this area in many situations. The CS07 requirements apply only to receivers having squelch circuits, and are intended to

TABLE 1
SUSCEPTIBILITY TESTS AND TEST METHODS

TESTS	METHODS
Conducted	
Powerlines	
30 Hz to 50 kHz	Injection from audio source via special transformer (1)
15 kHz to 150 MHz	Injection from signal generator via current probe (2) (6)
50 kHz to 400 MHz	Injection from signal generator via low-reactance capacitor (6)
Spike	Injection from spike generator via integral transformer (3)
Intermodulation	Receiver front-end injection from two signal generators with isolation network(s)
Undesired signal rejection	Receiver front-end injection from two signal generators with isolation network(s)
Cross-modulation	Receiver front-end injection from two signal generators with isolation network(s)
Squelch circuits	
Impulse input only	Receiver front-end injection from impulse generator
Sub-threshold signal, plus impulse input	Receiver front-end injection from impulse generator and signal generator
Radiated	
Magnetic field, loop	Equipment case exploration with special loop energized from audio source (4)
Magnetic induction	
Cases	Equipment case wrapped with several turns of wire, energized with power frequencies and with spike generator
Cables	Interconnecting cables wrapped with several turns of wire and energized as for cases
Electric field (5) (6) (7)	
14 kHz to 10 GHz	Rod, dipole and conical log-periodic antennas energized from signal generators/amplifiers
14 kHz to 30 MHz	Parallel-plate line energized from signal generators/amplifiers (8)
14 kHz to 30 MHz	Longwire antenna in shielded enclosure, energized from signal generators/amplifiers (9)
	Crawford Cells, energized from signal generators/amplifiers (10)

NOTES:

(1) The special transformer may also be used to obtain conducted emission data. See the Analysis, Recording and Measurement section of ITEM for procedures.

(2) Method approved for use in testing commercial avionics equipments per RTCA Document DO-160 (Obtainable from Radio Technical Commission for Aeronautics, 1717 H St., NW, Washington D.C. 20006)

(3) 50-ampere secondary winding on the integral output transformer is standard. Available from at least one manufacturer with 100-ampere secondary on special order.

(4) Instructions for the fabrication of this loop appear in MIL-STD-461.

(5) See footnote under Radiated Susceptibility in this section.

(6) Amplifiers are required to obtain the field levels specified by certain of the Notices to MIL-STD-461. Octave-band low pass filters will usually be necessary to reduce harmonic and other spurious outputs to levels which will prevent false indications of susceptibility within a particular frequency octave.

(7) Field levels at location of EVT should be checked, using a sensor/remote readout arrangement such as the Instruments for Industry type EFS-1/LMT/LDI.

(8) Fabrication instructions for a widely-used parallel-plate line and a "transmission-line" (or "loop-line") antenna are given in Air Force Design Handbook DH1-4. Directions for making another parallel-plate type are contained in MIL-STD-462. The former will accommodate larger equipment case sizes and accept higher excitation powers.

(9) Directions for installation and adjustment of a suitable radiating line are contained in Notice 3 to MIL-STD-462. CAUTION: If this test setup is to be used for generating field levels in the tens to hundreds of volts ranges, consideration should be given to using larger conductors than those mentioned in Notice 3, and to using symmetrical, radial arrangements of paralleled non-inductive resistors at the line input and end terminations. Depending on shielded enclosure dimensions, some difficulties may be encountered in adjusting the terminations. Under such conditions, a slight change in the excitation frequency will usually make it possible to perform the required checks and adjustments.
WARNING: POWER LEVELS REQUIRED TO OBTAIN THE HIGHER FIELDS SPECIFIED IN CERTAIN REQUIREMENTS DOCUMENTS WILL RESULT IN THE RADIATION OF ENERGY AT LEVELS SUFFICIENT TO CAUSE HARMFUL INTERFERENCE TO COMMUNICATIONS AND OTHER SERVICES AT CONSIDERABLE DISTANCES FROM THE TEST LOCATION. ALL SUCH TESTING MUST BE PERFORMED IN SHIELDED ENCLOSURES OF ADEQUATE ATTENUATION CAPABILITIES. THE SPECIFIED LEVELS ARE ALSO ABOVE THE LIMITS ESTABLISHED BY SOME AGENCIES FOR HUMAN EXPOSURE. TEST PERSONNEL SHOULD NOT BE INSIDE THE ENCLOSURE DURING SUCH TESTING.

(10) Frequency ranges dependent on cell dimensions. Consult manufacturers for recommended usable ranges.

establish reasonable levels of resistance to radiated impulse noise. Test 1 of CSO7 uses only an impulse generator as the imput; while Test 2 uses both an impulse generator and a signal generator (applied simultaneously via isolation networks), with the output of the latter set at a level below the squelch-break point.

Radiated Susceptibility

Almost any electronic device - not merely intentional receivers - may be vulnerable to electromagnetic fields. This has become especially apparent as more and more consumer-oriented electronic devices have come into use. The majority of the cases of interference reported to the F.C.C. within recent years have involved, as victims, equipments not intended to act as receivers.

The magnetic field susceptibility requirements of RSO1 and RSO2 of MIL-STD-461 are primarily of interest to designers of equipment for military and other rigorous environments. RSO1 testing involves use of a specified multiturn coil energized from a variable-frequency source. The coil is used to probe all surfaces of an equipment case. RSO2, Test 1 requirements are aimed at ensuring that the inter-connecting cables of an equipment or system will not be adversely affected by the relatively constant-amplitude magnetic fields set up by ac powerlines, or by the high-level transient magnetic fields incident to energization or de-energization of large inductive loads (e.g., solenoids and motors). RSO2 requirements are intended to accomplish similar ends for the equipment "black boxes" themselves. The cable and case tests are performed both with a power-frequency source and with a spike generator source.

The tests of RSO3 and RSO4 involve exposure of equipments to rf electric (nominally) fields.[1].

It is interesting to note that orders-of-magnitude increases in the levels specified for these tests have been implemented since the original V/meter given in MIL-STD-461 in 1967. Notice 3 to MIL-STD-461A, issued in May 1970, raised the test levels to from 5 to 200V/m, depending on frequency and usage location, for U.S. Air Force procurements. The U.S. Army Electronics Command in Notice 4, dated February 1971, established test levels of up to 50V/m also frequency- and usage- dependent. The above changes reflect military experience in typical deployment situations.

Considerably more detailed treatment of susceptibility requirements with respect to category of usage has been written into the proposed revision MIL-STD-461B. Tables 2, 3 and 4 show the classes of equipments and the conducted spike and radiated E-field levels associated with the different categories.

Recognition of the substantial increases in rf environmental levels in recent years has not been confined to military situations. The Scientific Apparatus Manufacturers Association (SAMA), in March 1974, issued a proposed standard covering radiated rf susceptibility of industrial and process control instrumentation. Three basic classes, each with three subclasses, are established; for low-, moderate-, and high-level rf environments. Field strengths to which the equipment is to be exposed are 3, 10 and 30 volts per meter, respectively. To offset increased costs of providing the required modifications to obtain the necessary degree of protection, some manufacturers are offering the susceptibility fixes as an extra-cost option package. Even the highest of the above levels is not at all unrealistic, considering that in many industrial facilities, a number of employees will be using VHF transceivers with 5-watt output capability within intimate distances of sensitive monitoring and controlling devices.

Another area which has received much attention recently is that of hospital and other medical electronics equipment. The Food and Drug Administration (FDA) has sponsored development of a medical device EMC standard, which is expected to be released some time in 1977. Figure 3 will show the tentative conducted susceptibility limits which will appear in this document. A 150-volt powerline transient susceptibilty test is also specified. It will be noted that two different levels are shown, one for "critical parameter" and one for "non-critical parameter". Critical parameters are defined as "those operational characteristics or functions of a device for which an electromagnetic induced malfunction would place a patient in immediate jeopardy"; while

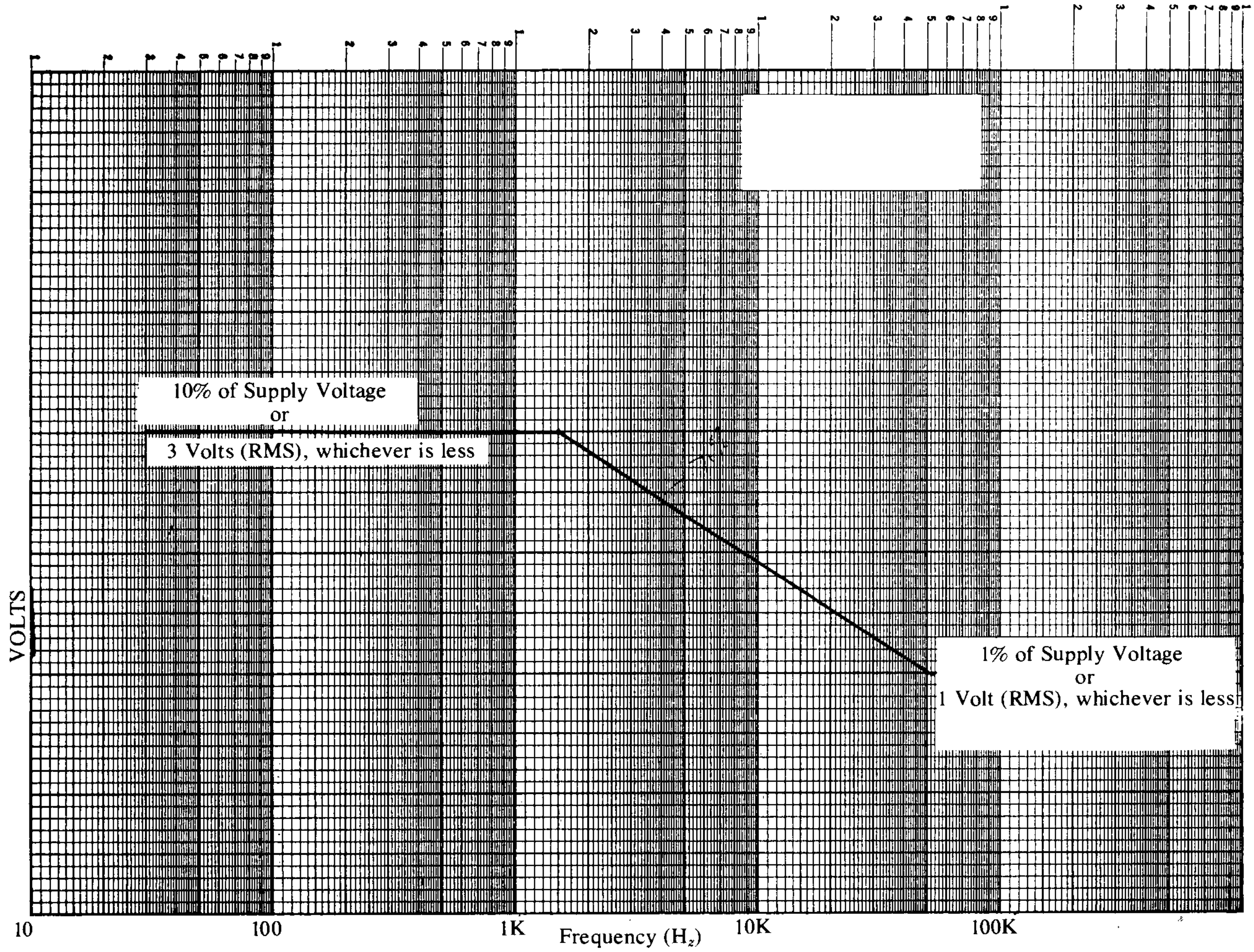

Figure 1. Conducted Susceptibility Limits CSO1

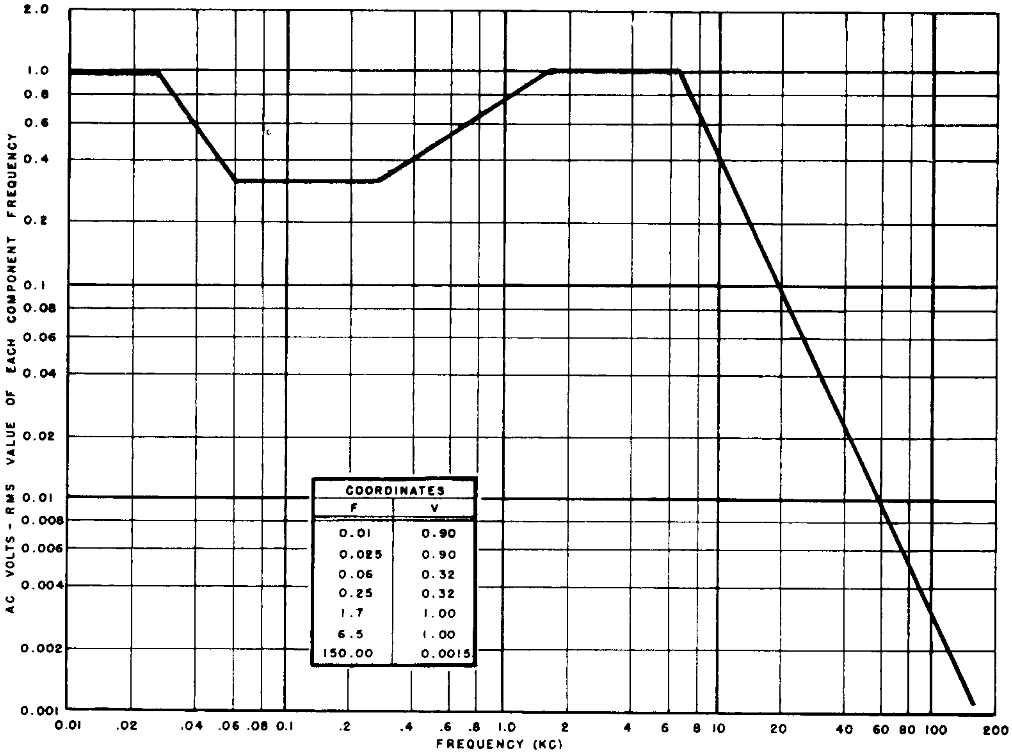

FIGURE 2. Frequency characteristics of ripple in 28 volt dc electric systems

non-critical parameters are those which would not result in imminent hazard to the patient. Radiated rf susceptibility limits proposed are shown in Figure 4. Again, the critical/non-critical differentiation is made. Also of interest is the fact that both the emission and susceptibility limits of this document were based on comprehensive studies made in several hospitals.

1. With the test setup geometries specified in requirements documents, the equipment under test (EUT) is in a region in which the predominant electromagnetic field components over most of the specified frequency ranges are the magnetic induction field and the static dipole field (also known as the electric induction field or radial electric field). Refer to Chapter 6 of "Noise Reduction Techniques in Electronics Systems", Henry W. Ott, Wiley-Interscience, 1976; for a discussion of wave impedance variations in the near field region.

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STRAY RADIATION REDUCED BY GOOD TRANSMITTER DESIGN

Although microwave radiation provides mankind with many benefits, it can also play havoc with devices susceptible to electromagnetic interference (EMI) and radio frequency interference (RFI), and create human safety hazards as well. With use of microwave energy increasing almost exponentially in recent years, the potential for EMI/RFI disruption has increased dramatically, heightening awareness of the problem.

In an effort to prevent the annoying and possibly dangerous effects of microwave interference, a variety of regulatory agencies -- including the U.S. Department of Defense, the National Security Agency, Department of Commerce, NASA, the FCC, FAA, FDA and SAMA plus the Department of Health, Education and Welfare -- are tightening their requirements on a broad range of consumer, industrial and military products that must be tested for susceptibility to RF interference, and have formulated exacting specifications governing test procedures. As a result, susceptibility testing is becoming a fact of life for many suppliers who didn't need to be concerned about it before.

One of the major problems in such testing is setting up the microwave source to prevent stray radiation. Microwave devices are inherently leaky, so unless proper safeguards are employed, spurious RF signals can invade the test environment and distort test results, endanger test personnel, interfere with nearby or distant unrelated systems, and cause many needless hours of troubleshooting.

The focal point of the problem is the microwave transmitter, which generates both desired and unwanted RF energy. Here, the challenge is two-fold: first, to protect internal circuitry of the transmitter from EMI/RFI produced by other components; and second, to keep stray radiation from entering the test environment.

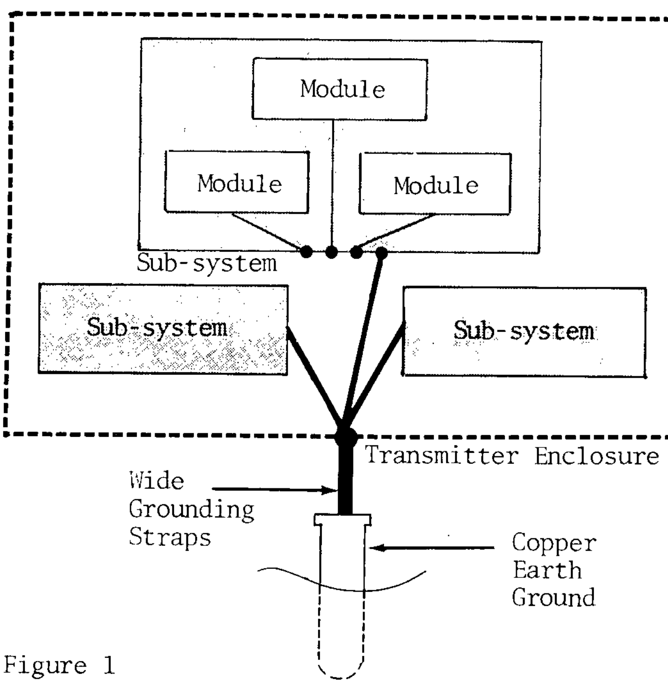
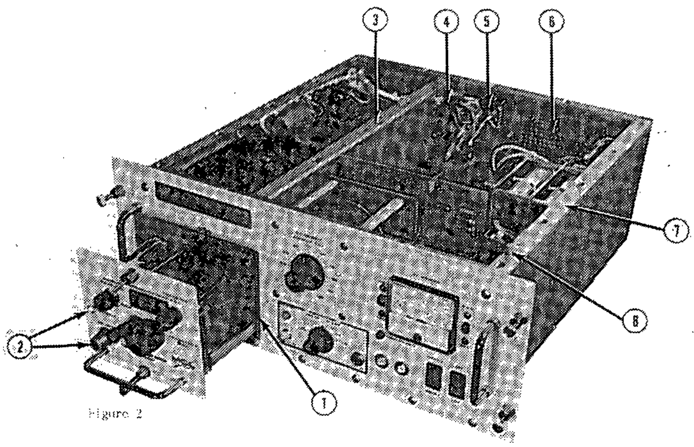


Figure 1



MCL Microwave Power Generator, with top removed and plug-in oscillator head opened to demonstrate design techniques needed to prevent stray RFI/EMI radiation:

1. Metal contact fingers, applied with conductive silver epoxy, encircle the oscillator plug-in opening to assure solid metal-to-metal contact between inserted head and mainframe chassis.
2. RF output and sample port installed with RF gasketing of rubber material woven through with metal fibers.
3. Metal divider wall completely separates oscillator compartment from low level PCB components.
4. RF suppressant feed-throughs on all wires passing through divider wall.
5. AC line filter keeps line noise out and prevents EMI/RFI from leaking back onto power line.
6. Metal honeycomb grid covers ventilation port and presents an electrically "solid" wall to microwave energy.
7. One-piece chassis forms bottom and sides to eliminate bottom side seams. Front panel, rear panel and top are secured with screws placed less than 1/4 wavelength apart, with adhesive-backed metal contact fingers to assure continuous contact, between panels and chassis.
8. Interlock switch de-energizes generator when top is removed.

Generally, the techniques for achieving these objectives involve good engineering practice in the design of the transmitters but due to cost considerations and the lack of industry-wide standards, the appropriate safeguards are not always built in. For this reason, a working knowledge of these techniques is essential in helping the buyer evaluate competitive transmitters as well as troubleshooting systems already installed.

There are two primary means of protecting internal circuitry, and both should be employed in any well-designed transmitter. The first is to provide a separate, direct ground path from each module or subsystem to a central ground terminal. The alternative, series or common grounds can allow spurious signals to be passed from one part of the transmitter to another, resulting in signal distortion or transmitter malfunction. (See Figure 1). Cabinet and chassis members should never be used as ground paths; all grounding should be done through wires with current capacity 5 times operating current. The second safeguard is to shield low-level circuitry components in the transmitter from high-level microwave energy by enclosing them in EMI/RFI-proof containers, complete with RF suppressant feedthroughs and shielded control signal leads. This will protect delicate components from stray radiation that could cause distortion or even destroy the circuitry.

Keeping stray radiation out of the test environment also requires a combination of several techniques. One is the design of the transmitter cabinet. Fastener spacing should be less than one-quarter of the wavelength of the highest frequency in the operating waveband, or else the gap between fasteners functions as a slot antenna, beaming stray energy out of the enclosure. In addition, adhesive-backed contact fingers or RF gasketing material should be used to improve metal-to-metal contact along the seams of the enclosure.

Necessary openings in the cabinet, such as ventilation holes, should be minimized. Rather than one large opening, several small ones should be used, since microwave energy "reads" the small-hole configuration as a solid wall and will not pass through efficiently.

Another preventative technique is to filter the AC primary power. This is an often-overlooked area and can be the source of many gremlin-type problems that defy diagnosis. Without an AC line filter, microwave energy can leak back onto the power line, from which it can radiate into the test environment, or be conducted into other test equipment that is powered by the same line.

Care must also be taken to prevent RF signal leakage in the transmission line (waveguide or coaxial cable) between the transmitter and the antenna or the test object. This is typically achieved by using heavily-shielded, multi-grounded transmission line that prevents radiation from escaping into the test environment.

Provided that these methods have been successful in preventing radiation from escaping into the test environment, there is then need for properly draining off stray radiation from the transmitter housing. This is done by connecting the transmitter's central ground terminal to a good earth ground that is large enough to provide an attractive path for the stray radiation to follow. Here, size is the key. An earth ground that is too small will function as a resistor, causing some of the grounded microwave energy to be radiated into the atmosphere. A wide copper grounding strap (one inch wide minimum if possible) is recommended. If the transmitter's grounding strap is connected to a grounding circuit built into the testing facility, care must be taken to assure that this circuit provides a comparably attractive ground path. Otherwise, the point of connection may become part of a radiating antenna network.

Despite all these precautions, a small amount of stray microwave energy will probably still be present in the test environment. To prevent it from distorting test results it must be kept out of both the test object and its monitoring devices. Good grounding techniques, filtering of the AC power, good RF shielding, selective RF filtering (bandpass, low pass, etc.) and even increasing the physical separation between the instruments and the test object will help achieve this objective.

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