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IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

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of the
IEEE Industrial Applications Society**

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Foreword

(This Foreword is not a part of IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.)

The rapidly expanding use of computers and solid-state controllers in industry requires consideration of many factors not previously important in the design, installation, and operation of other forms of controllers. Many portions of the control circuits of computers and solid-state controllers designed for operation at low-energy low-voltage signal levels are susceptible to disturbances by excessive electrical noise. Erratic controller operation may result unless suitable precautions are taken. The following recommendations are intended as an installation guide for industrial controls involving low-energy-level equipment to minimize electrical noise inputs from external sources.

The electrical noise guide is comprised of six sections. Sections 1 and 2 state the scope and service conditions. Sections 3 through 5 provide the technical foundation for the recommendations given in Section 6. Section 6 is intended to stand alone as the working section of the electrical noise guide.

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IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources

1. Scope

The purpose of this document is to develop a guide for the installation and operation of industrial controllers to minimize the disturbing effects of electrical noise on these controllers.

2. Service Conditions

This guide is limited to techniques for the installation of controllers and control systems so that proper operation can be achieved in the presence of electrical noise. This guide is not intended to be a guide for the internal design of electrical controllers or for the prevention of the generation of electrical noise resulting from their operation.

3. Identification of Electrical Noise in Control Circuits

3.1 Definition of Noise (for the purpose of this guide)

electrical noise. Unwanted electrical signals, which produce undesirable effects in the circuits of the control systems in which they occur.

3.2 Significance of Electrical Noise

In any process under control there are at least two variables.

- 1) The *controlled* variable is a condition or characteristic that can be measured, correlated to the process, and subsequently controlled. The controlled variable may be temperature, pressure, liquid level, speed, or another similar physical quantity.
- 2) The *manipulated* variable is the electrical power, energy, or material supplied to the process to keep the process under control.

The control system includes all the devices and equipment to monitor the controlled variable and to adjust the manipulated variable to keep the process at the desired condition.

The signal flow in a control system is shown in Fig 1. A primary element of some sort detects the condition or magnitude of the controlled variable and produces an electrical signal. These measurement signals ① are directed to the *controller*, which accepts the signal, modifies or amplifies it, or does both, in relation to the constraints ② which define the range of the controlled variable directly or indirectly. The controller output signal ③ is directed to the final control elements, which receive the signal and, in response to it, adjust the manipulated variable to maintain the process at the desired value or within the allowable tolerance. The complexity of the controller and the associated control system is dependent on the process characteristics.

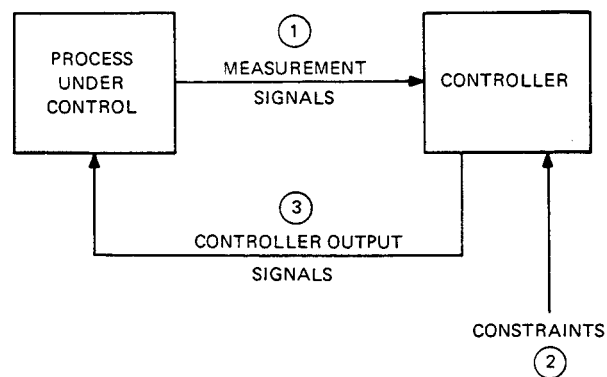


Figure 1—Signal Flow in Control System

In early control systems the controller function was performed by a person who was capable of using judgment in maintaining the process under control. As the state of the art progressed, it was possible to design more functional control systems so that humans could be removed from the control loop. The required precision in industrial processes, coupled with advances in electronic devices, has led to the development of the all-electronic solid-state controller. These controllers, which are usually more complex, may operate at very low power levels. Electrical disturbances are more likely to affect them because of the lower power levels. In addition to this, the system must operate at high speeds in order to provide the required speed of response. These factors tend to make noise a more important factor in the operation of the system.

If the definition and concept of electrical noise in control circuits is examined, it is possible to divide the problem into three subdivisions:

- 1) Sources of electrical noise (see 3.3)
- 2) Coupling of noise from the source to the control circuit (see 3.4)
- 3) Susceptibility of the control circuit to electrical noise (see 3.5)

3.3 Sources of Electrical Noise

Typical sources of electrical noise are electrical or electromechanical devices which cause or produce very rapid or large amplitude changes in voltage or current. A partial list of the devices known to be sources of noise is given below:

- 1) Switches operating inductive loads
- 2) Thyristors or other semiconductors used in the switching mode
- 3) Welding machines
- 4) Heavy current conductors
- 5) Fluorescent lights
- 6) Thyatron and ignitron tubes
- 7) Neon lights

There are other sources of noise which appear in a control circuit due to the method of connecting the control wires. In general these noise sources are in series with the control signal and can be controlled by careful attention to connections. Some of these sources are:

- 1) Thermal voltages between dissimilar metals
- 2) Chemical voltages due to electrolyte between poorly connected leads
- 3) Thermal noise of resistors

3.4 Coupling of Electrical Noise

If some type of electrical coupling exists between the source of the noise voltage or current and one or more wires or elements of the control circuit, a voltage will appear in the control circuit. The four possible types of coupling are discussed in this section. (Whether the voltage that appears in the control circuit actually results in noise, as defined in this guide, is dependent upon the susceptibility of the control circuit; see 3.5.)

3.4.1 Common Impedance Coupling

This type of noise can produce problems any time two circuits share any common conductors or impedances (even in the case of common power sources in extreme cases). Probably one of the most usual methods of common impedance coupling is the use of long common neutral or ground wires. Figure 2 shows an example of this in a circuit which is described as *single ended* because the signal voltage appears as a voltage between a single wire and the neutral. In Fig 2 two amplifiers AR1 and AR2 are used to amplify the output of an iron-constant, an thermocouple TC. A load operated by contact 1a is also associated with the circuit. The lead A-B is 50 ft of AWG No 12 wire, which has a resistance of 1.6Ω per 1000 ft. Thus

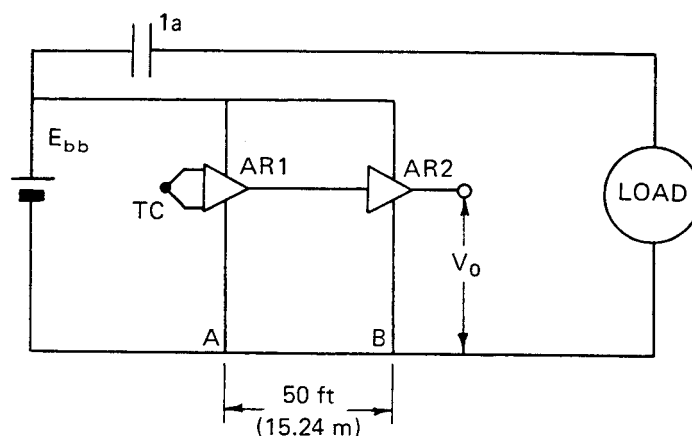


Figure 2— Single-Ended Circuit with Long Common Wire

$$R_{AB} = \frac{50}{1000} \cdot 1.6 = 0.08 \Omega$$

If the load requires 0.5 A from the source E_{bb} , the voltage between points A and B will be

$$V_{AB} = 0.5 \cdot 0.08 = 0.04 \text{ V}$$

Assume that the amplifier AR1 close to the thermocouple TC will amplify by 100. This will mean that 0.04 V from A to B will appear to AR2 just like a 0.04/100 V (or 0.4 mV) change in the input voltage to AR1. For an iron-constantan thermocouple this would be equivalent to a 14°F temperature change near 100°F.

When the current through the load is interrupted by contact la, it could change from 0.5 A to 0 in less than 1 μs. With this rapid change in current in line A-B the effect of the self-inductance must also be considered. Normally inductance is a property attached to a complete circuit, but it is possible to attach a value of inductance to each segment making up a circuit. This results in a way of calculating the voltage induced in a portion of a circuit (such as line A-B) by a change in current in the circuit. The formula for the self-inductance of a straight wire at high frequency is derived in [1]¹:

$$L = 0.002l \left[\log_e \frac{2l}{r} - \frac{3}{4} \right] \mu\text{H}$$

where l is the length of wire in centimeters and r is the radius of the conductor in centimeters. For wire A-B in Fig 2 this would be

$$l = 1524 \text{ cm}$$

$$r = 0.205 \text{ cm}$$

$$\begin{aligned} L &= 3.05 \left[\log_e \frac{2 \cdot 1524}{0.205} - 0.75 \right] \mu\text{H} \\ &= 3.05 [9.6 - 0.75] \mu\text{H} \\ &= 3.05 \cdot 8.85 = 27 \mu\text{H} \end{aligned}$$

When the current through the load is interrupted, it could change from 0.5 A to 0 in 1 μs, and the voltage between points A and B becomes

$$\begin{aligned} V_{AB} &= L \frac{\Delta i}{\Delta t} \\ &= 27 \cdot 10^{-6} \cdot \frac{0.5}{10^{-6}} = 13.5 \text{ V}_{\text{peak}} \end{aligned}$$

This disturbance is over in a short time, but it could cause trouble in a control circuit.

Many times it is possible to recognize obvious common impedance paths in a control circuit and eliminate them. A good example is to use two distinct wires for each transducer feeding into a control element. However, there are other

¹The numbers in brackets correspond to those of the references listed in 3.6.

common impedance paths which are not as obvious. Some of these can be listed to present a better understanding of this problem:

- 1) Common power supply
- 2) Inductance of capacitors at high frequency
- 3) Inductance of lead wires
- 4) Stray capacitance from the enclosure to ground
- 5) Inductance of busbars on the common or neutral in a building
- 6) Resistance of the earth or ground

3.4.2 Magnetic Coupling

This type of coupling is often called inductive because it is proportional to the mutual inductance between a control circuit and a source of interference current. Its magnitude also depends upon the rate of change of the interference current. This type of coupling does not depend upon any conductive coupling between the noise source and the control circuit. Figure 3 illustrates the nature of magnetic coupling.

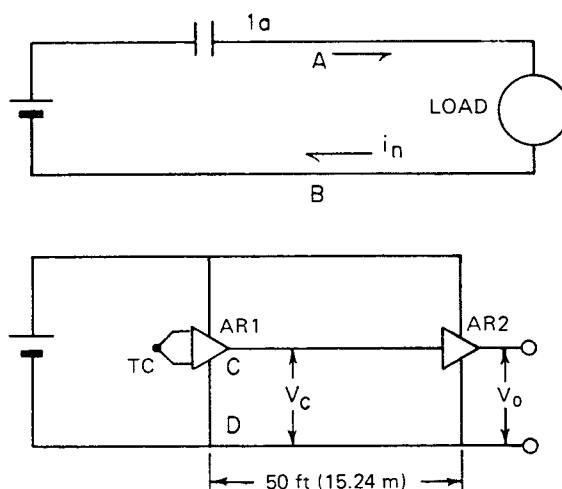
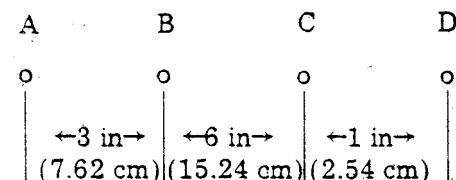


Figure 3— Circuit Showing Magnetic Coupling

In the circuit of Fig 3 assume that an four wires, A, B, C, and D are placed in the same nonmetallic raceway with a separation of 3 in between A and B, 6 in between B and C, and 1 in between C and D. Under these conditions the mutual inductance between the noise-producing circuit (A and B) and the control circuit (C and D) can be calculated from [2], p 57, eq (2-107). For the given distances



we have

$$M_{nc} = \frac{140.4}{10^9} \cdot l \cdot \log_{10} \left[\frac{d_{AC} \cdot d_{BD}}{d_{BC} \cdot d_{AD}} \right] \mu\text{H}$$

$$M_{nc} = 7020 \cdot 10^{-9} \cdot \log_{10} \left[\frac{9}{6} \cdot \frac{7}{10} \right] \mu\text{H}$$

$$= 0.149 \mu\text{H}$$
$$\begin{aligned} V_{\text{CD}} &= M_{\text{nc}} \frac{\Delta i_{\text{n}}}{\Delta t} \\ &= 0.149 \cdot 10^{-6} \cdot 0.5 / 10^{-6} \\ &= 0.0745 \text{ V} \end{aligned}$$
$$C = \frac{3.68 \epsilon_R}{\log_{10} \left(\frac{2s}{d} - \frac{d}{2s} \right)} \text{ pF/ft}$$

A diagram of a four-point bending test setup. A horizontal beam is supported at points A and B, with a load applied at point C. Point D is the right end of the beam. The distance between A and B is 3 inches (7.62 cm). The distance between B and C is 6 inches (15.24 cm). The distance between C and D is 1 inch (2.54 cm).

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$$C_{AD} = \frac{3.68 \cdot 50}{\log_{10}\left(\frac{20}{0.08} - \frac{0.08}{20}\right)} - \frac{184}{2.398} = 76.7 \text{ pF}$$

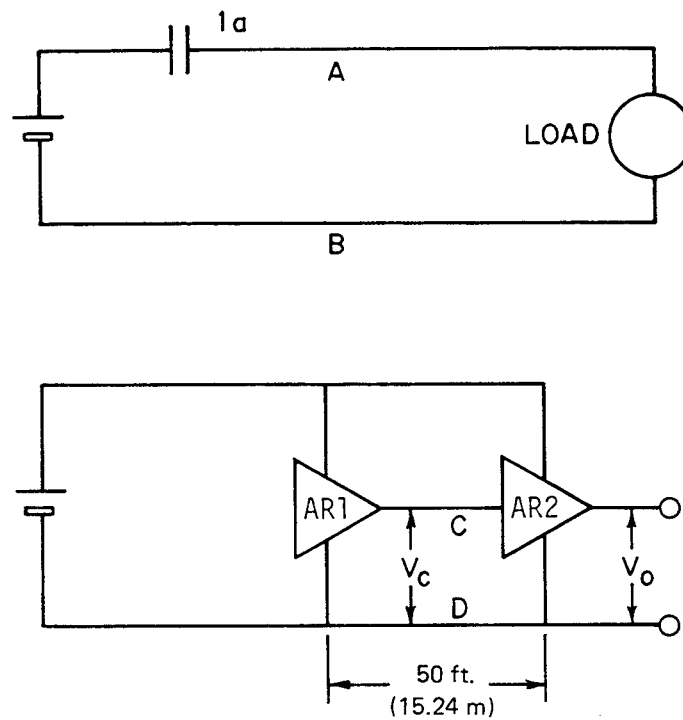


Figure 4— Circuit Showing Electrostatic Coupling

$$C_{AC} = \frac{3.68 \cdot 50}{\log_{10}\left(\frac{18}{0.08} - \frac{0.08}{18}\right)} = \frac{184}{2.351} = 78.3 \text{ pF}$$

$$C_{BD} = \frac{3.68 \cdot 50}{\log_{10}\left(\frac{14}{0.08} - \frac{0.08}{14}\right)} = \frac{184}{2.242} = 82.1 \text{ pF}$$

$$C_{BC} = \frac{3.68 \cdot 50}{\log_{10}\left(\frac{12}{0.08} - \frac{0.08}{12}\right)} = \frac{184}{2.176} = 84.6 \text{ pF}$$

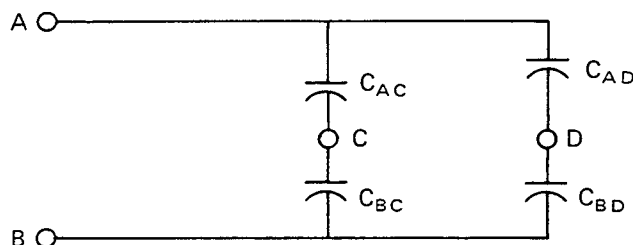


Figure 5— Equivalent Circuit

These are the important capacitors in this case, but it must be realized that all objects have capacitance to all other objects resulting at times in unexpected *sneak* circuits. For instance, an isolated oscilloscope used for trouble-shooting might have a capacitance to a conducting grid in a concrete floor of 150 pF.

When interrupting the current to the load, it is possible for the voltage between lines A and B to rise to 2000 V. (This is representative of the showering arc voltage resulting from opening a relay coil with double break contacts.) The coupling mechanism between lines A-B and C-D is very complex, but the following simplistic analysis will illustrate a principle. Assume the equivalent circuit shown in Fig 5. Using the relationship of voltage division by capacitors,

$$V_1 = \frac{V_2 C_2}{C_1}$$

we have

$$\begin{aligned} V_{BC} &= \frac{V_{AB}}{C_{BC}} \frac{C_{AC} \cdot C_{BC}}{C_{AC} + C_{BC}} \\ &= \frac{2000}{84.6} \frac{78.3 \cdot 84.6}{78.3 + 84.6} = 961.32 \text{ V} \end{aligned}$$

Similarly,

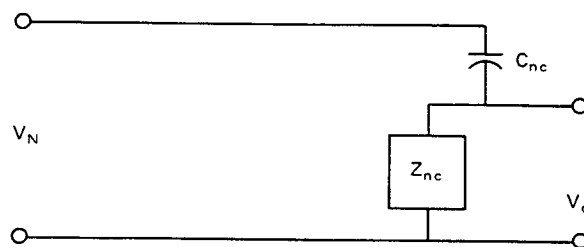
$$\begin{aligned} V_{BD} &= \frac{V_{AB}}{C_{BD}} \frac{C_{AD} \cdot C_{BD}}{C_{AD} + C_{BD}} \\ &= \frac{2000}{82.1} \frac{76.7 \cdot 82.1}{76.7 + 82.1} = 965.99 \text{ V} \end{aligned}$$

and

$$\begin{aligned} V_{CD} &= V_{BD} - V_{BC} \\ &= 965.99 - 961.32 = 4.67 \text{ V} \end{aligned}$$

Thus a considerable voltage can be induced in leads D and C, resulting in a voltage difference of 4.67 V at the input to amplifier AR2. This example was chosen to illustrate a serious condition. In practice this voltage difference would not be as great due to impedance paths to common, as explained in the following paragraph.

The process of electrostatically inducing a voltage in a lead wire can be summarized by the following equation (Fig 6). For this illustration assume rms voltages.



$$\frac{V_c}{V_n} = \frac{1}{1 + j\omega_n C_{nc} Z_{nc}}$$

Figure 6—

where

V_c = voltage induced in control wire

V_n = noise voltage source

ω_n = frequency of noise voltage

C_{nc} = capacitance between noise circuit and control wire

Z_{nc} = impedance between noise voltage reference and control signal wire

In order to keep the ratio V_c/V_n as low as possible, the product $\omega_n C_{nc} Z_{nc}$ must be kept as low as possible. Thus anything that can be done to reduce the coupling capacity C_{nc} or the impedance Z_{nc} will be helpful. A well-grounded shield on a control wire will do both.

3.4.4 Coupling by Electromagnetic Radiation

The voltages induced by magnetic or electrostatic induction are sometimes called near-field effects because this type of interference is produced close to interference sources. Further from the source, fields are associated with propagating radio waves or radiation fields. In general, radio waves are produced at distances greater than 1/6 wavelength from the source of interference. For reference purposes the following chart can be used:

Frequency	1/6 Wavelength
1 MHz	1970 in (5000 cm)
10 MHz	197 in (500 cm)
100 MHz	19.7 in (50 cm)
1 GHz	1.97 in (5 cm)

This type of interference is particularly difficult to eliminate if present, because any shielding must be 100% complete, and any ground connection is only effective for immediately adjacent circuit elements. In most controllers this is not a problem. However, sources of these types of noise voltages, such as radio transmitters, high-frequency brazing equipment, and television stations, have been known to cause noise problems in control systems. The threshold of concern for ambient electromagnetic field strength will depend upon the level of susceptibility of the control system

and whether it is susceptible directly to the incident continuous-wave signal, to a direct current which may be produced by rectification of the carrier, or to audio or video modulation frequencies which may appear as a result of demodulation in a system component. Whenever the field strength exceeds 1 V/m, a determination of susceptibility at the frequency of interest is advisable. This is the approximate field strength that would be produced by a 50 kW transmitter at a distance of 1.3 km (0.8 mi) or by a 5 W transmitter at 13.1 m (43 ft).

An approximation of the ambient field strength due to a known source can be calculated as

$$FS = \frac{0.173 \sqrt{P}}{D}$$

where

FS = field strength, in V/m
 P = radiated power, in kW
 D = distance from source, in km

This equation is based on free-space propagation, and in a specific case the actual field strength may be considerably more or less than that calculated by its use.

The coupling of electromagnetic radiation into a control circuit is via any incompletely shielded conductor, which will act as a receiving antenna for the signal. The received signal voltage will appear between the receiving conductor and ground. If the noise cannot be eliminated at the source by proper shielding, capacitors can be used to shunt these noise signals to ground, in many cases without reducing the performance of the system.

3.5 Susceptibility of Control Circuits

How well a control circuit can differentiate between noise and desired signals is a measure of its susceptibility. The susceptibility of a given control circuit is a function of the design of the circuit and can vary widely, even within a given class of devices. In general, high-power-level systems such as relay control systems have low susceptibility, while low-power-level systems such as those using integrated circuits have high susceptibility.

A control circuit is sensitive to a potential difference applied between two input terminals, whether that potential be noise voltage or a useful signal. Any voltage appearing between these input terminals is called a *normal-mode* voltage. Any voltage difference appearing between both terminals and some common point is called a *common-mode* voltage.

A major factor in the susceptibility of control and signal circuits is their ability to reject common-mode interference. Such interference may be introduced into a control signal circuit through inductive or capacitive coupling with the source of interference, or through electromagnetic radiation. Common-mode conversion is the process by which normal-mode interference is produced in a signal circuit by common-mode interference applied to the circuit. The amount of the common-mode conversion that occurs is a function of the balance of the signal circuit, that is, the electrical similarity (series impedance) of the two sides of the signal transmission path, and their symmetry with respect to a common reference plane, usually ground. For best balance, the requirement for symmetry must also be satisfied by the output of the signal source and the input of the signal receiver. These terminating impedances are generally determined by the equipment designer, not the user. However, the susceptibility of the system due to common-mode conversion may be reduced by judicious equipment selection and the use of balancing networks at equipment inputs and outputs.

Single-ended amplifiers have one of the input terminals at a common potential; they are thus more sensitive to noise. Differential amplifiers have both input terminals at some impedance level to ground. As such, any common-mode voltage (a voltage appearing on both input terminals simultaneously) will not normally result in an output signal (provided the impedance to noise voltage reference Z_{nc} is kept balanced for both input terminals). How well a

differential amplifier rejects a common-mode voltage is usually indicated in amplifier specifications. Thus the use of differential amplifiers is a well-known method of decreasing circuit susceptibility when proper care is used in the design of input terminations.

Susceptibility is of concern to the user in the selection of the control system. However, once a control system has been chosen, the principles of noise reduction are the same, although the magnitude of the problem will depend upon the susceptibility of the chosen system. The installation of a control system must be made in such a way that noise sources present in the environment will not induce into the control circuit electrical signals of greater magnitude than the susceptibility of the circuit will permit.

3.6 References

[1] GROVER, F.W. *Inductance Calculations*. New York: Van Nostrand, 1944, p 35, eq (7).

[2] KNOWLTON, A.E., Ed. *Standard Handbook for Electrical Engineers*, 8th ed. New York: McGraw-Hill Book Co, 1949.

4. Classification

4.1 Electrical Noise Classification

Noise sources are listed here in the order of their importance. Noise will be characterized by *noise prints* (oscillograms of voltage and current versus time) or other data when available.

The voltage values listed in this section are intended to describe the characteristics of the particular phenomenon under discussion. The maximum voltage values listed could be limited to smaller values in any given system by the voltage breakdown of conductor spacing through air or over insulation surface [9].²

4.1.1 Showering Arc

The showering arc is caused by current chopping in electrical contacts. During circuit interruption, arc current will *chop* (suddenly cease to flow) at some value of current, which depends on the circuit constants, but is not less than the minimum arcing current [44]. This current chopping, in association with the circuit inductance (such as relay magnets) and shunt capacitance (such as coil self-capacitance and wiring capacitance), generates electrical noise transients, called showering arc [51], [70], where the peak voltages are a function of the contact gap breakdown, which in turn depends on the number and size of the contact gaps, contact material, atmosphere, and so on.

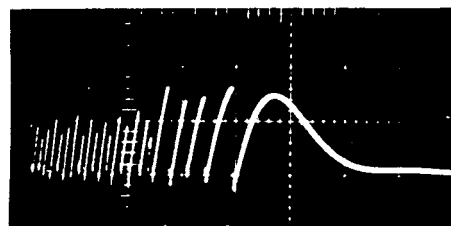


Figure 7— Showering Arc Voltage across Double Break Contacts Interrupting 120 V AC, 60 Hz Machine Tool Magnet

²The numbers in brackets correspond to those of the references listed in 4.6.

4.1.1.1 Electromagnetic Current Interruption

Typical noise prints, taken from [67], are shown in Figs 7–9 and in the following text. Each transient is unique. However, typical values of characteristics are as follows:

dv/dt (rise) up to 1000 V/ μ s

dv/dt (fall) > 10 000 V/ μ s

(In [54] the fall is stated to be 2 000 000—6 000 000 V/ μ s.)

The repetition rate is up to 2 MHz. The duration is up to 1 ms during contact break, but will also occur during contact bounce on contact make.

Typical voltage peaks for a 120 V magnet are

1000 V for 1 contact gap in air

1500 V for 2 contact gaps in air

2500 V for 4 contact gaps in air

17000 V for 1 contact gap in vacuum

Typical voltage peaks for a 600 V magnet are 5600 V for 4 contact gaps in air

See 6.5.1.1 for methods for suppressing showering arc transients.

Most of the following noise sources are listed in outline form only. Information will be added as it becomes available in suitable form.

4.1.1.2 AC Motors

4.1.1.3 DC Motor Commutator

4.1.2 Solid-State Switching Devices

Power-line voltage transients can be initiated by switching power loads. For example, if a switch is closed to a resistive load when the voltage is not zero, the current will rise to the normal value as rapidly as the circuit parameters will permit. While this current is rising to its normal value, there will usually be a voltage transient associated with the expression

$$e = L \frac{di}{dt} \quad V$$

where

L = circuit inductance.

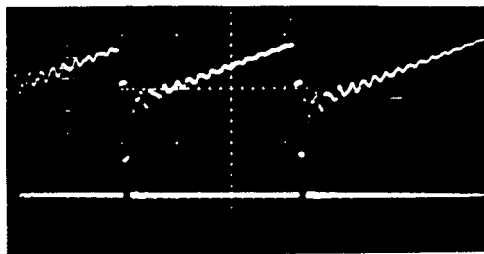


**Figure 8— Upper Trace — Similar to Fig 7, but Expanded Time Scale;
Lower Trace — Current in Contacts**
(Contacts connected by 100 ft, 300 Ω transmission line.)

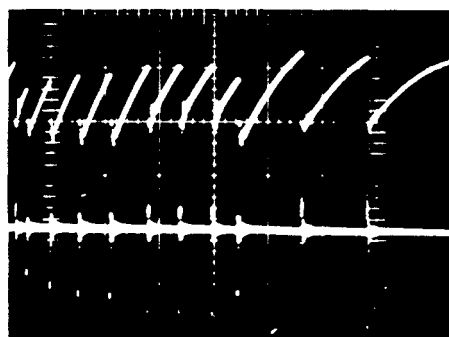


Figure 9— Upper Trace — Similar to Fig 7, but Expanded Time Scale; Lower Trace — Voltage Induced in Adjacent 100 ft, 300 Ω Line Terminated in Its Characteristic Impedance (Note 300 V peaks coincident with Current Pulses in Fig 8.)

While solid-state switching devices are limited to switching speeds less than those for hard contacts (manufacturers specify that the thyristor maximum permissible di/dt must initially be limited to approximately 10 A/ μ s), the total effect can be very disturbing because these devices are commonly used to control power by performing switching operations repeatedly, such as every half-cycle (commonly called phase control).

It is difficult to produce typical noise prints because of the wide variations in inductance, capacitance, and resistance, which affect the resultant transient due to switching; however, some examples follow.

4.1.2.1 Resistive Load

Phase control for lamp dimmers or heater control can be a source of noise. An example is shown in Figs 10–12.

4.1.2.2 Motor Load [65]

Semiconductor controlled rectifier (SCR) drives are capable of producing power-line noise. Figure 13 is a schematic diagram of an SCR control for a dc motor. In general, current flows through the dc motor from two of the three power lines selected by the SCRs to provide the proper motor terminal voltage. The SCR firing order is shown in the figure; this sequence is completed each cycle.

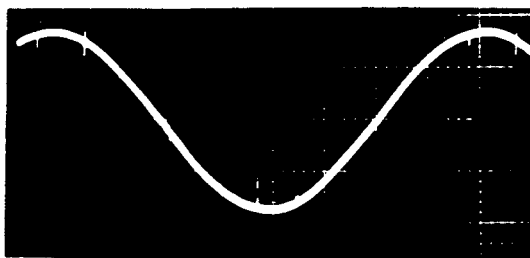


Figure 10— Noisy 30 A, 120 V, 60 Hz Laboratory Power Line
(The transients occurring just before voltage peak are caused by a $20\ \Omega$ resistive load phase controlled by a triac.)

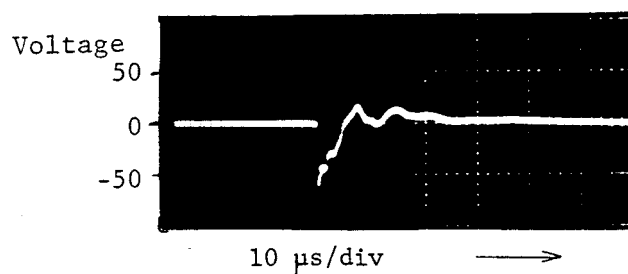


Figure 11— Same as Fig 10, but Expanded Time Scale and High-Pass Filter Used to Eliminate 60 Hz Voltage

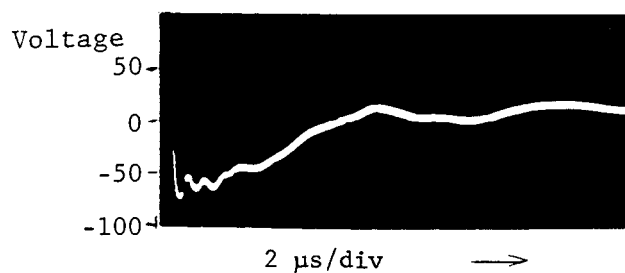


Figure 12— Same as Fig 11, but Further Expanded Time Scale to Show High-Frequency Ringing

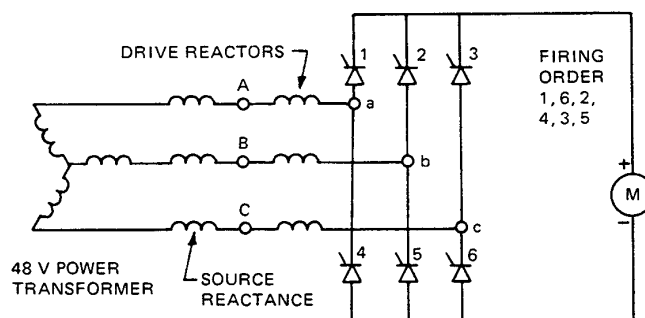


Figure 13— Three-Phase Full-Wave Rectifier Motor Control Power Circuits

The noise is produced when the current flowing in one line must suddenly stop and this same current must suddenly be established in another line. For example, assume that SCRs 1 and 6 have fired and are carrying the motor current, and now it is time for SCR 2 to fire and transfer the current from line A to line B. The lines have inductance preventing sudden changes in current, and so SCRs 1 and 2 are both conducting (short-circuited together) until this transfer is completed.

Figure 14 shows an oscillogram of the voltage ab going to zero as this transfer takes place. This phenomenon is called *line notching*. The notches are not as wide at reduced current, as shown in Fig 15. These noise prints were made on a 400 A line which had power factor correction capacitors on the power transformer secondary, resulting in a very small source impedance power system. For this reason the drive reactors were included as part of the source impedance to demonstrate line notching. In normal operation this 50 hp drive produces line disturbance on this power system, as shown in Fig 16.

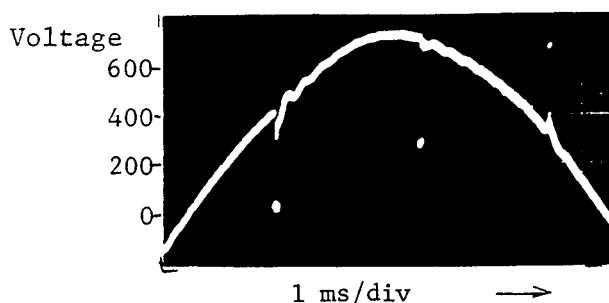


Figure 14— Typical Line Notching Transients Produced by Three-Phase Full-Wave Rectifier Motor Control

(Half-cycle of voltage ab in Fig 13 with motor loaded to produce 50 A rms in each ac line.)

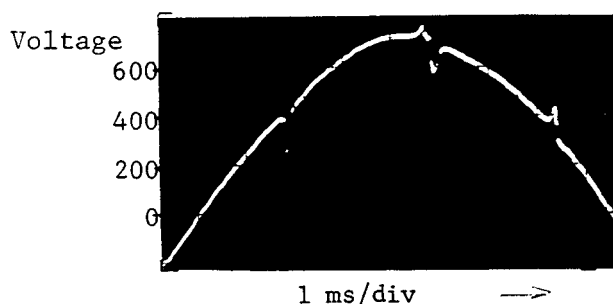


Figure 15— Voltage ab in Fig 13 with Motor Load Reduced to 15 A rms in Each AC Line

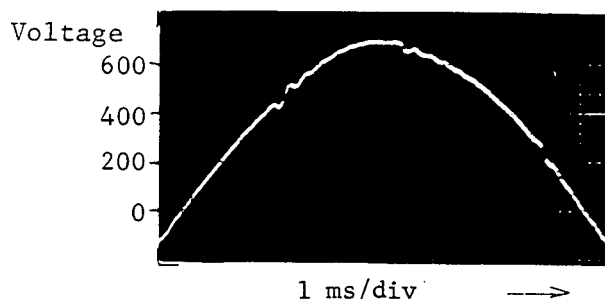


Figure 16— Voltage ab in Fig 13 with Motor Load to Produce 50 A rms in Each AC Line

For a further discussion of the effects of source reactance versus feeder and load reactance, load current, and firing angle, see [65].

Details of the line notch are shown in Figs 17 and 18. Current transfer details of the notch are illustrated in Fig 19.

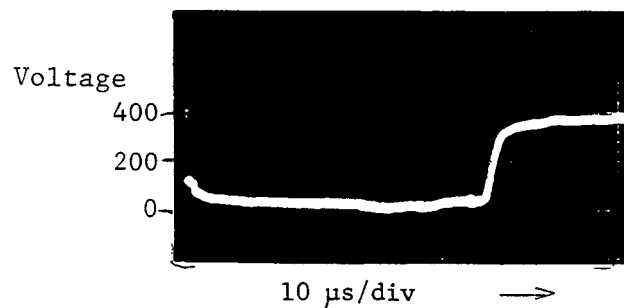


Figure 17— Same as Fig 14, but Expanded Time Scale to Show Notch Detail

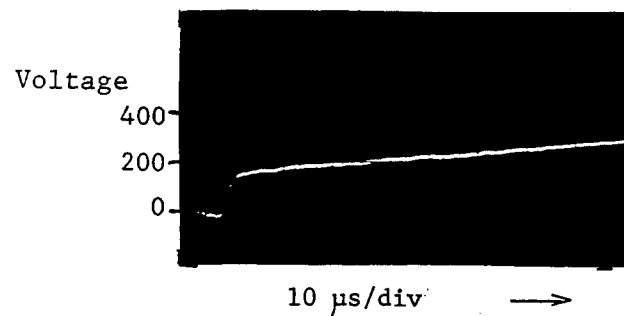


Figure 18— Same as Fig 15, but Expanded Time Scale to Show Notch Detail

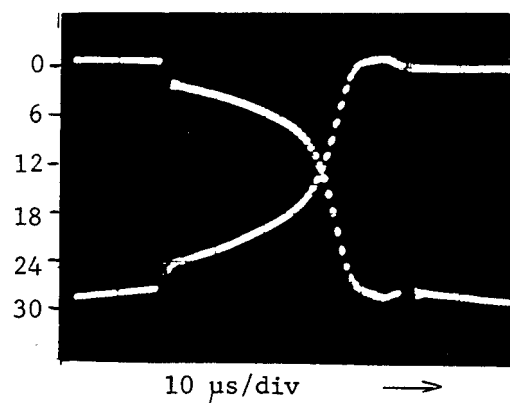


Figure 19— Current Transfer from Line a to Line b during Line Notch Shown in Fig 17

(Maximum $di/dt = 2.53 \text{ A}/\mu\text{s}$; initial $di/dt = 0.156 \text{ A}/\mu\text{s}$. Measurement was made with two 1200/5 Weston model 327 type 2 current transformers with 4Ω resistance as secondary load.)

4.1.2.3 Inductive Load**4.1.3 Circuit Switching****4.1.3.1 Multispeed Motors****4.1.3.2 Capacitor Banks****4.1.3.3 Transformer****4.1.3.4 Distribution Circuitry****4.1.3.5 Fluorescent Lights****4.1.4 Faults****4.1.4.1 Current-Limiting Fuses****4.1.4.2 Arcing Faults****4.1.4.3 Restrikes on Switching****4.1.5 Power-Frequency Electric and Magnetic Fields****4.1.5.1 Resistance Welding Machines****4.1.5.2 Power Lines****4.1.6 High-Frequency Narrowband Generators****4.1.6.1 Plastic Heating****4.1.6.2 Induction Heating****4.1.6.3 Diathermy****4.1.6.4 Arc Starters for Arc Welders****4.1.6.5 Radio Transmitters (Transceivers)****4.1.7 Radio-Frequency Broadband Generators**

Most radio-frequency sources generate broadband noise. Of these, the characteristics of only a few have been well documented, for example, power transmission lines, automotive ignition, and radio-frequency-stabilized arc welders. Solid-state devices, for example, thyristors, are known to be great offenders in the generation of radio-frequency noise. The radio-frequency characteristics of these devices have been under investigation.

The radio-frequency disturbance is transmitted to susceptible systems by conduction through power input lines and by radiation through space. Transmission of radio-frequency noise by radiation is complicated by the presence of environmental radio noise, which is composed of both atmospheric and man-made sources. The environmental radio noise varies from place to place as well as from time to time for the same place. Figure 20 shows the median values of radiated radio noise for various areas [3]. Table 1 is an example of the variation of radio noise with time [63].

An example of radiated radio noise from power lines, automotive traffic, and radio-frequency-stabilized arc welders is shown in Fig 21 [64]. It was concluded in [64] that below 25 MHz lower voltage transmission lines and radio-frequency-stabilized arc welders are the major incidental noise sources when the observer is within 100 ft of the source, and that above 40 MHz automotive traffic and lower voltage transmission lines are the major radio noise sources, with neither appearing to be consistently the greater when an observer is within 50 ft or less of the source.

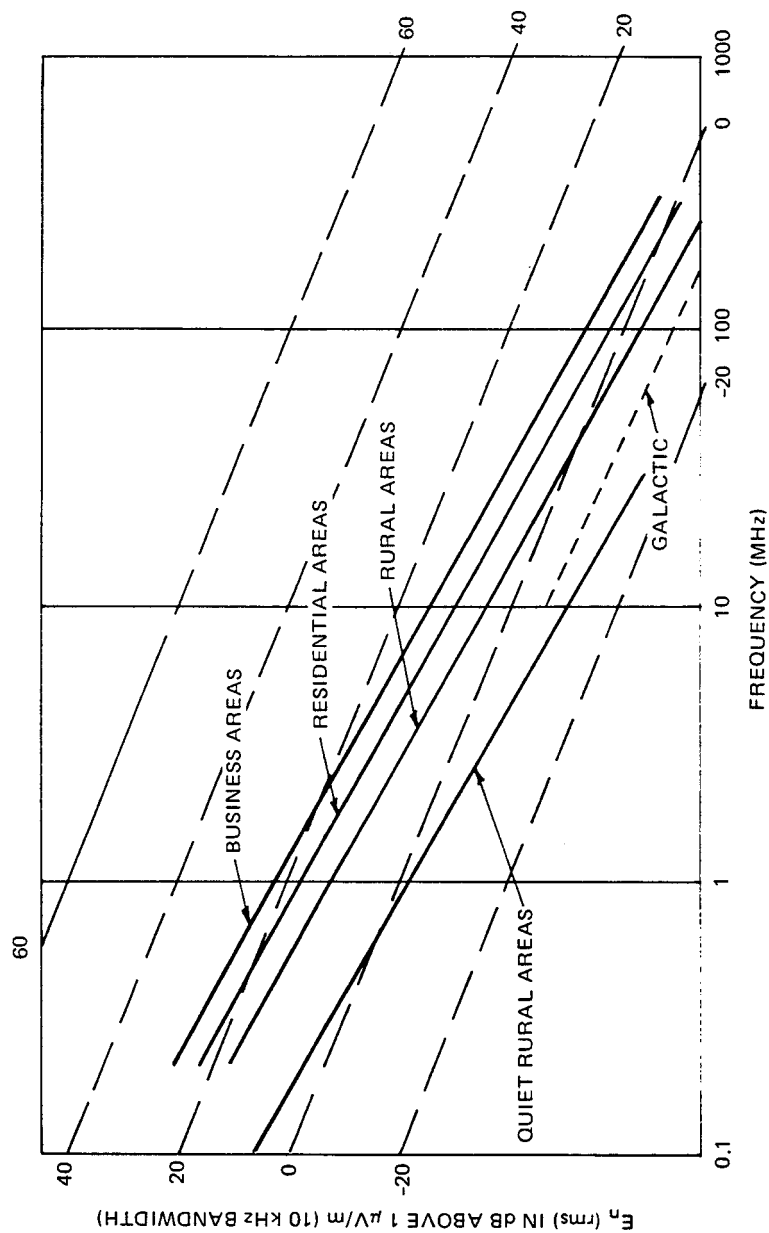
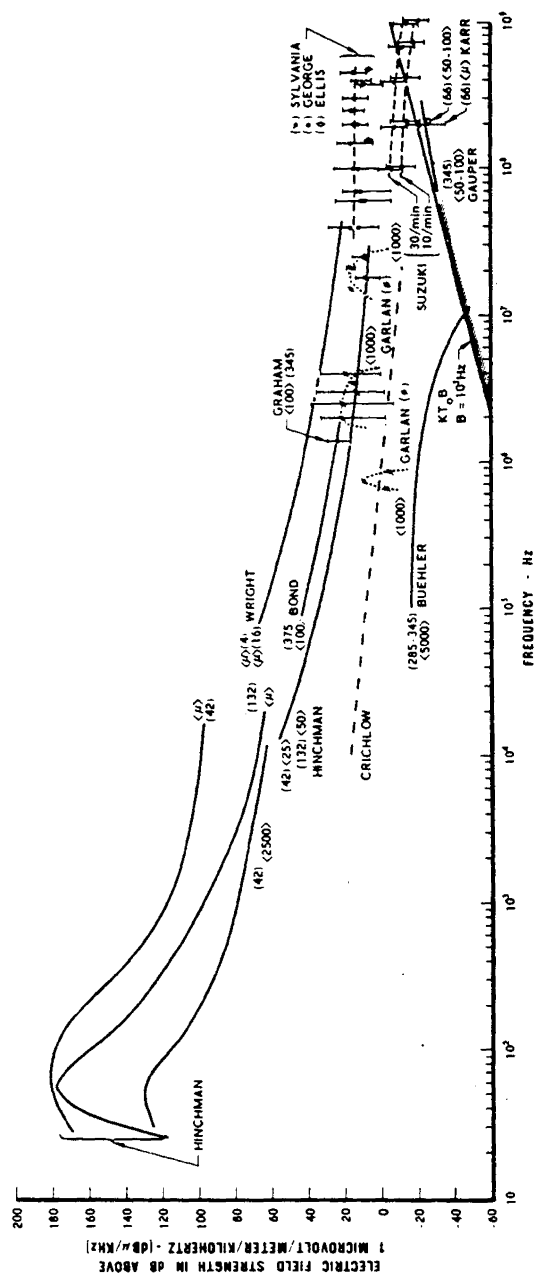


Figure 20— Median Values of Radio Noise [3] (Omnidirectional antenna was near surface.)



(Line voltages in kV—(40), (60), etc; observation point locations relative to sources in ft < μ >—<25>, <50>, <50-100>, etc; beneath conductor — power lines; ••• radio-frequency-stabilized arc welders at 1000 ft; - - - - - automotive ignition.)

Figure 21— Radiated Noise from Power Lines, Automotive Traffic, and Radio-Frequency-Stabilized Welders [64]

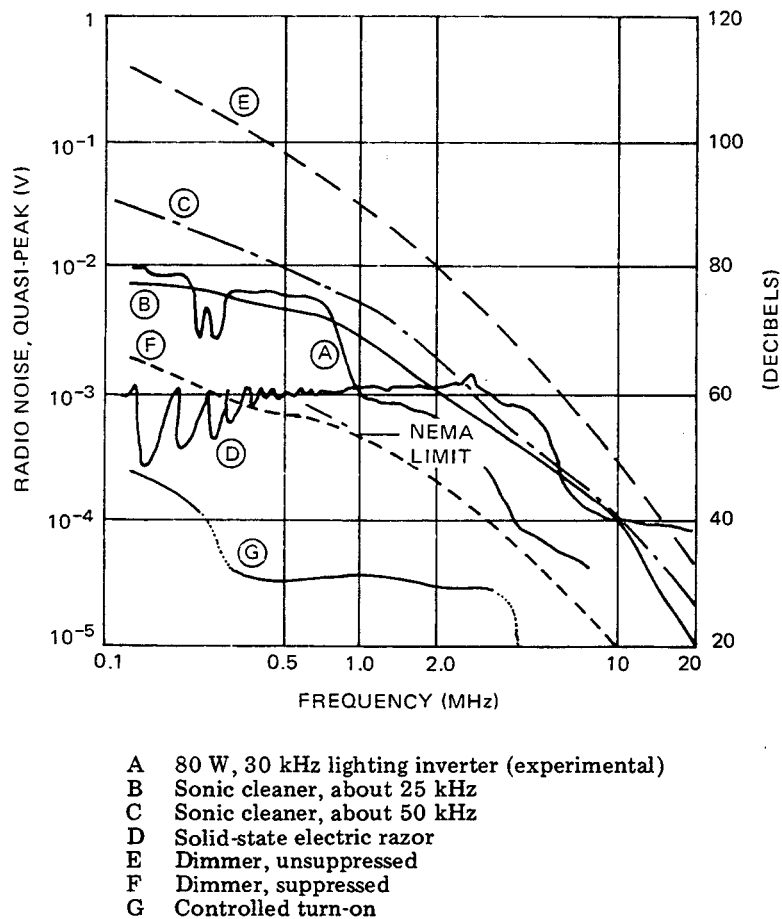
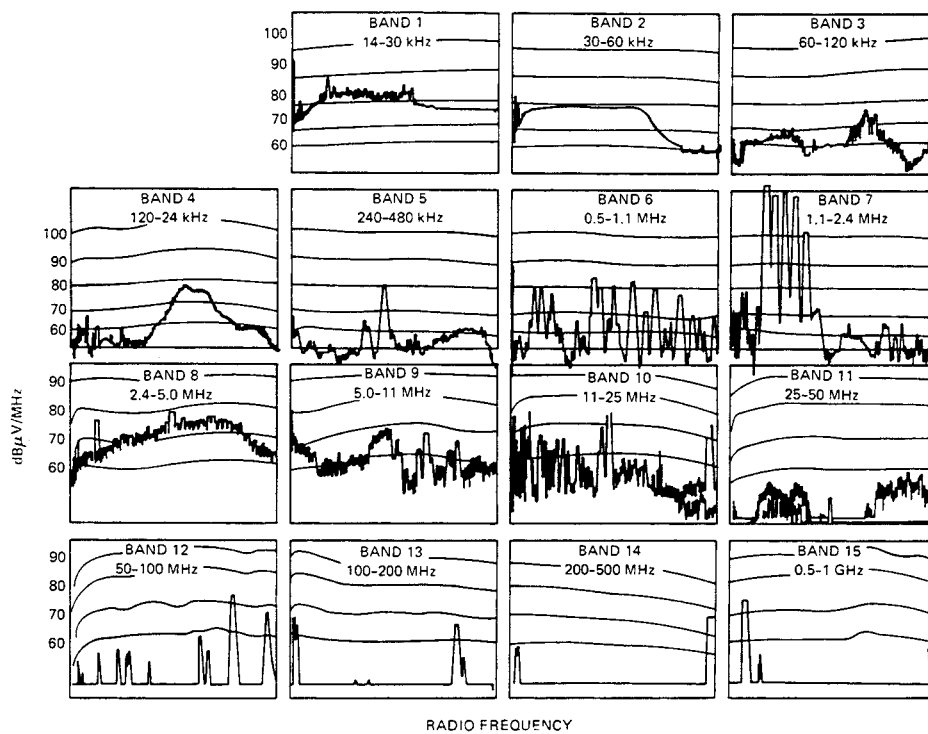
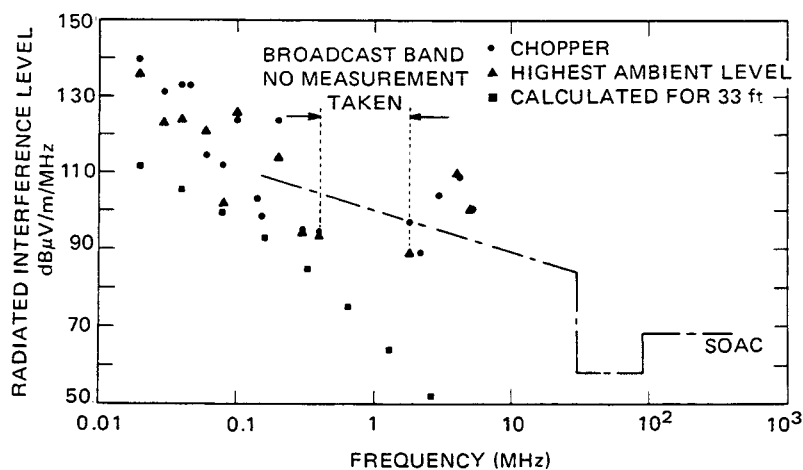


Figure 22— Conducted Interference for *Power Conditioned* Equipment up to 100 W [35]

Figure 22 shows examples of conducted interference from solid-state-controlled consumer equipment [35]. Figure 23 shows an example of radiated radio-frequency noise from a thyristor-controlled dc propulsion system of a transit car [31], and Fig 24 is another example of radiated radio-frequency noise from a thyristor-controlled propulsion system [48].



(a)

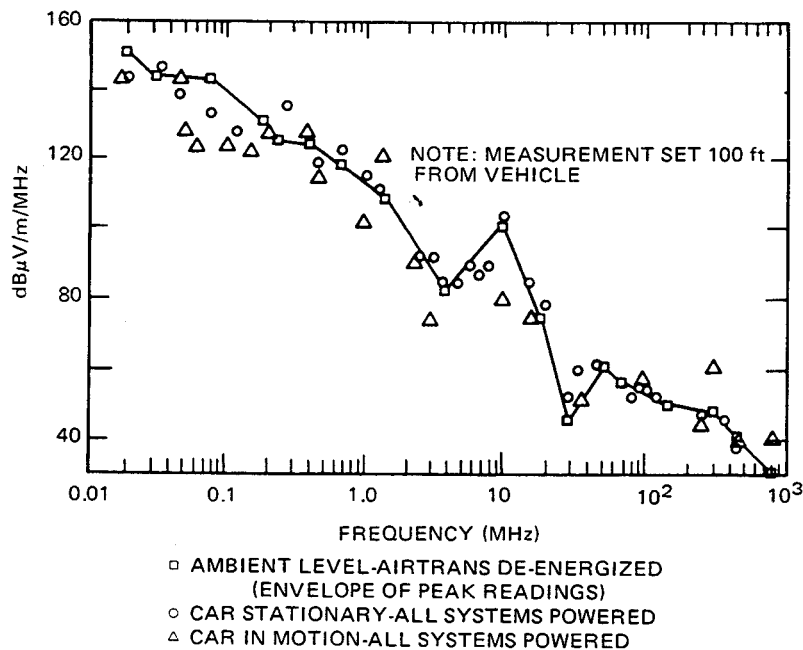


(b)

Figure 23— Radiated Peak Interference Levels from Chopper Car Running at 11 mi/h (17.6 km/h); Measurement Distance 33 ft (10 m) [31].
 (a) As Measured. (b) Corrected for Antenna Factors

Table 1— Data Measured in Hybla Valley, Fairfax County, Virginia, on August 15 and August 25, 1955 [63]

Frequency		Signal Level	
(MHz/s)	Time	($\mu\text{V}/\text{m}$)	dBm/kHz)
236	Day	30	-115
	Night	1	—
273	Day	60	-108
	Night	1	—
291	Day	8	-129
	Night	1	—
350	Day	90	-107
	Night	1	—

**Figure 24— Radiated Peak Interference from AIRTRANS; Measurement Distance 100 ft (30 m) [48]**

4.1.8 Ferroresonance

4.1.9 Lightning and Electromagnetic Pulse

4.1.9.1 Lightning

An abundance of literature is available on lightning and protection against lightning of high-voltage apparatus of electrical power systems [22], [40], [41], [68]. Although research on the lightning protection of telephone cables started at Bell Laboratories in the 1940s [24] [66], interest in the effects of lightning on low-voltage systems in general

started only about 20 years ago, when solid-state devices, such as diodes, transistors, and thyristors, were being used in control and communications systems.

The Telephone Association of Canada conducted a field investigation of lightning voltages induced in outside plant toll facilities at ten selected sites across Canada during the 1968 and 1969 lightning seasons [23]. Their results indicate that a standard test wave, with 1000 V peak and 10/1000 μ s wave shape, simulates 99.8% of the lightning surges encountered in paired and coaxial cables, where 10 μ s is the front time of the wave and 1000 μ s is the decay time to half the peak voltage. Similarly, for open-wire circuits a more suitable test wave with 2000 V peak amplitude and 4/200 μ s wave shape is required to simulate 99.8% of the lightning surges.

The General Electric Company performed transient-voltage measurements on two transit systems, the Chicago Transit Authority and the Long Island Railroad, during 1970-1972 [28]. The transient voltages were measured on the 600 V dc third-rail systems. Although switching surges and lightning surges were not differentiated, the measurements at the Chicago Transit Authority showed a significant increase in the number and magnitude of transient voltages during thunderstorm periods. Transient voltages exceeding 3000 V were attributed to lightning.

International standards efforts (for example, the International Electro-technical Commission) favor the 1.2/50 μ s wave shape as the standard for testing the transient-voltage withstand capability of low-voltage apparatus and systems. This wave shape has long been the standard wave shape for impulse testing of high-voltage apparatus.

4.1.9.2 Electromagnetic Pulse [25], [38], [43], [461], [49], [52], [53]

Radiation effects of nuclear explosions have long been recognized as harmful to humans, animals, and vegetation. However, electromagnetic pulses, although biologically harmless, can play havoc with communications, electronic, and electrical systems by inducing current and voltage surges through electrically conducting materials. In some cases the surges trip circuit breakers, shutting down a piece of equipment or power line. In other cases, individual components, such as semiconductor devices, or circuits are destroyed.

The electromagnetic pulse (EMP) has three transient effects. First, a pulse of ground current flows radially from the point of explosion. Second, a magnetic-field pulse propagates away from the point of explosion with the same vector components as those from a vertical dipole. Third, a corresponding pulse of electric field is propagated.

Results of extensive analyses on electromagnetic pulses are available. However, actual test results are classified. When considering the effects rather than the electromagnetic-pulse generation, one may replace the nuclear model with the more common phenomenon of a lightning stroke, which also produces the same three components of the electromagnetic-pulse effect. However, to make the lightning model simulate nuclear electromagnetic-pulse magnitudes equidistant from nuclear explosions in the megaton range would assume a lightning current far greater than has ever been measured. The electromagnetic field of lightning reaches its peak value in a few micro-seconds, while the electromagnetic field of an electromagnetic pulse rises to peak in a few nanoseconds.

4.1.10 Static Discharge

4.1.11 Cable Noise

4.1.12 Electrical Noise Measurement

Electrical noise is measured in both the time domain and the frequency domain. Time-domain measurements are usually performed on transient voltages and currents which are destructive to an apparatus or to a system. Frequency-domain measurements are generally performed on electric, magnetic, and electromagnetic fields which cause malfunction (or interference) on radio and television receivers and other electronic equipment.

Measurement of electrical noise is an extensive area, which is beyond the scope of this guide. However, for the sake of completeness, several references are cited for both time-domain [12], [6], [61] and frequency-domain [1], [2], [7], [13]—[15], [19] measurements.

4.2 Electrical Noise Susceptibility Classification

4.2.1 Introduction

Electrical noise is an unwanted voltage or current, or both, which appears in an electrical system. Commensurate with the characteristics of the system, electrical noise may be innocuous to the proper functioning of the system, or it may force the system to malfunction, or it may even lead to damage and destruction.

The electromagnetic compatibility (EMC) of an electrical system is its ability to perform its specified functions in the presence of electrical noise generated either internally or externally by other systems. In other words, the goal of electromagnetic compatibility is to minimize the influence of electrical noise.

Every electrical device or system has some immunity to electrical noise which is its inherent characteristic. If the strength of the oncoming electrical noise is below the threshold level of the receiver, be it a device or a system, special precaution is not necessary. However, if the strength of the electrical noise is above the threshold level, then techniques need to be applied to attenuate the electrical noise to a level below the threshold level of the receiver.

To be able to predict the degree of electromagnetic compatibility of a given system, one should know the following:

- 1) Characteristics of the sources of electrical noise
- 2) Means of transmission of electrical noise
- 3) Characteristics of the susceptibility of the system
- 4) Techniques to attenuate electrical noise

The purpose of this section is to define the criteria of susceptibility of electrical control systems to electrical noise. This discussion is based on [32].

4.2.2 System Boundaries

Electrical noise can reach the system through four different paths (Fig 25):

- 1) Power feed lines
- 2) Input signal lines
- 3) Output signal lines
- 4) Radiation

The susceptibility level of the system will be different for the four paths of entry of the electrical noise. Furthermore, even for the same path of entry, the susceptibility will depend upon the type of electrical noise. For instance, for the first three entry paths, the susceptibility will be different for common-mode noise from that for normal-mode noise. For radiated noise the susceptibility may depend upon the type of wave—electric, magnetic, or electromagnetic.

4.2.3 Malfunction Characteristics

4.2.3.1 Nondestructive Malfunction

The primary result of a nondestructive malfunction is malfunction of the system without necessarily leading to destruction of the control system, that is, the system stops malfunctioning and returns to normal operation after the electrical noise is removed. For instance, an electrical noise pulse injected between the base and the emitter of a transistor may inadvertently switch the transistor on or off. Similarly, an electrical noise between the gate and the cathode of a thyristor may turn the thyristor on; or a forward voltage of high dv/dt may switch the thyristor on without necessarily damaging it. As another example, an electrical noise coupled through the power supply into the amplifier stage of an analog regulator may cause a disturbance to the controlled parameter, without any actual damage to the regulator itself.

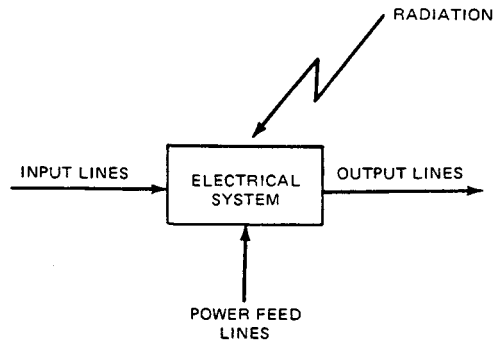


Figure 25— System Boundaries for Penetration of Electrical Noise

4.2.3.2 Destructive Malfunction

A destructive malfunction causes damage to the system irreversibly, that is, the system continues to malfunction even after removal of the destructive electrical noise, until the damaged components are replaced. For instance, a reverse voltage of sufficient magnitude across the base-emitter junction of a transistor can lead to destruction of the device. Similarly, a still higher voltage across the anode and the cathode of the thyristor would lead to irreversible breakdown of the device.

4.2.3.3 Nondestructive versus Destructive Malfunction

It may seem that once a system is protected against the nondestructive malfunction, it would also be protected automatically from the destructive malfunction. This is not always true. The characteristics of the electrical noise sources for these two types of malfunctions are generally quite different from one another. Furthermore, the suppression techniques may be quite different for these two types of electrical noise sources.

As an illustration, consider a pair of control lines running parallel to a power line. The pair of control lines are twisted to minimize pickup caused by the 60 Hz magnetic field of the power line. However, high-voltage transients may appear on the power line caused by power switching during faults or lightning. The induced voltage across the control lines may be high enough to cause a breakdown. The destructive electrical noise may be attenuated even below the nondestructive threshold level by elaborate shielding and grounding. However, this will be expensive. Alternatively, the destructive electrical noise may be attenuated below the destructive level by inexpensive surge suppression techniques, thereby letting the system temporarily malfunction for the duration of the transient.

As a second illustration, a conducted nondestructive electrical noise may be attenuated by a filter at the input of the equipment so that no malfunction occurs. The filter size will be larger, and hence the filter more expensive, if it is specified to make a destructive electrical noise innocuous to the system. The combination of a surge suppressor and a filter will be optimal in this case.

4.2.4 Electrical Noise Characteristics

Electrical noise can, in general, be divided into two classes: continuous wave and transient.

4.2.4.1 Continuous-Wave Electrical Noise

A continuous-wave electrical noise can further be subdivided into narrowband and broadband.

A narrowband continuous-wave electrical noise is, ideally, a disturbance at a single frequency with zero bandwidth. The single-frequency disturbance from an oscillator or a transmitter is a narrowband continuous-wave electrical noise.

A broadband continuous-wave electrical noise is a disturbance which contains energy covering a wide frequency range. A repetitive rectangular pulse is a broadband electrical noise (Fig 26).

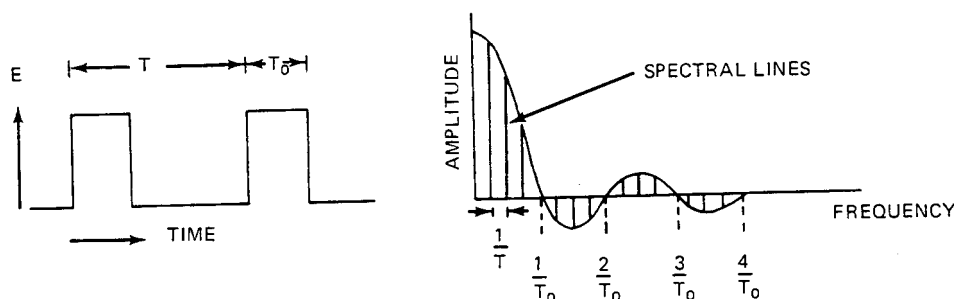


Figure 26— Spectrum of Rectangular Pulse Train

A broadband electrical noise can be mathematically expressed, by Fourier series, as the summation of narrowband continuous-wave functions whose amplitudes are frequency dependent. For instance, the repetitive rectangular pulse of Fig 26 can be expressed as

$$F(t) = \frac{ET_0}{T} + \sum_{n=1}^{\infty} \frac{2E}{n\pi} \sin\left(\frac{n\omega T_0}{2}\right) \cos(n\omega t)$$

$$= \frac{ET_0}{T} + \sum_{n=1}^{\infty} S(\omega, n) \cos(n\omega t)$$

where

$$\omega = 2\pi/T.$$

The plot of $S(\omega, n)$ as a function of frequency f is called the spectrum of the function $F(t)$ in the frequency domain.

4.2.4.2 Transient Electrical Noise

In many cases, electrical transients are the main cause of control system malfunctions, both destructive and nondestructive. Most transients are broadband and occur at random. Of the four transients shown in Fig 27, the first three are broadband and the last one is narrowband.

Figure 27(a) illustrates a rectangular pulse which is sometimes used as an approximation of actual transients for the sake of simplicity in analytical work. Figure 27(b) is a standard transient voltage specified in military specifications [19]—[21]. The duration of the first loop is 10 μ s. The front time is not specified. Figure 27(c) shows an industry standard transient voltage [5]. It has a front time of 1.2 μ s, a time to half-value of 50 μ s, and is designated a 1.2/50 μ s wave.

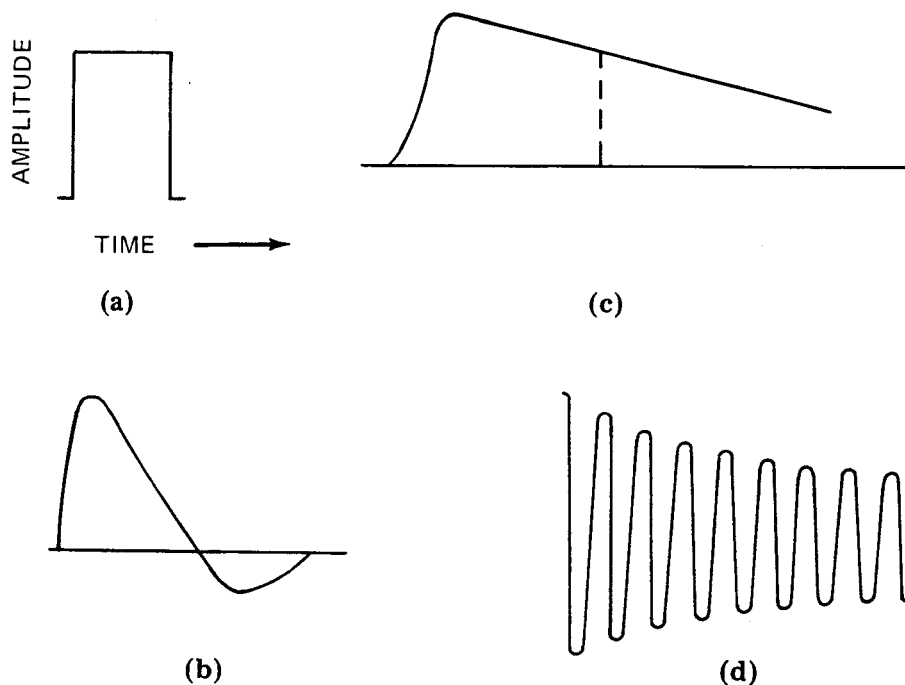


Figure 27— Illustration of Transient Electrical Noise

This wave shape is an approximation of the transient voltage generated by a lightning discharge on a power transmission line or a distribution line. The basic impulse insulation level (BIL) of high-voltage apparatus is specified by this wave shape, the actual magnitude being dependent on the voltage class of the apparatus. Figure 27(d) has been proposed as the surge withstand capability (SWC) test for solid-state relays [4]. This is an oscillatory wave of 1.5 MHz nominal frequency, with the envelope decaying to 50% of crest value in not less than 6 μ s, and a pulse repetition rate of 50 pulses per second for a period of not less than 2 μ s.

Transients can be represented in the frequency domain by Fourier integrals for analytical purposes. For instance, a rectangular pulse can be represented in the frequency domain, as in Fig 28, by

$$S(\omega) = \left(\frac{2}{\omega}\right) \sin\left(\frac{\omega T}{2}\right)$$

However, electrical transients are almost universally represented in the time domain because they are convenient to generate and measure in the time domain.

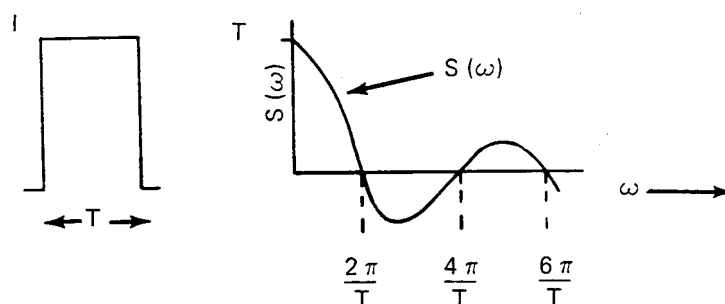


Figure 28— Spectral Density of Rectangular Pulse

4.2.5 Criteria of Susceptibility Measurement

It is known that the susceptibility of the most commonly used semiconductor devices (diodes, transistors, thyristors, integrated circuits) to electrical noise depends largely upon the magnitude of the voltage or current of the impressed electrical noise and its charge or energy content, or both [26], [27], [29], [37], [55], [71]. On the other hand, the characteristics of passive electrical circuits are primarily frequency dependent. The susceptibility of an analog control circuit is a function of the specified accuracy of the circuit, that is, of the deviation or output tolerance of the circuit without any external electrical noise present. As long as the control circuit output stays within this normal tolerance in the presence of an electrical noise, the circuit is considered to be not susceptible to the type and level of electrical noise. It is obvious then that an electrical system containing both the passive resistance-inductance-capacitance (RLC) elements and the active devices would have very complex susceptibility to electrical noise.

The rational approach appears to be to characterize system susceptibility in accordance with the characteristics of the impressed electrical noise, that is, continuous wave and transient.

4.2.5.1 Susceptibility to Continuous-Wave Electrical Noise

The conducted continuous wave susceptibility is generally measured by injecting a voltage of a certain frequency to the input of the receiver (or system) and determining the voltage level at which the receiver malfunctions [19]–[21]. This procedure is repeated over a specified range of frequencies. This method does not appear to be completely justified. The susceptibility of many systems to electrical noise depends upon the interaction between the impedances of the electrical noise source and the system. The lower the impedance of the system and the higher the impedance of the source, the lower will be the susceptibility of the system to an external electrical noise. This difference is not recognized in the present method of determining susceptibility. This is illustrated by an example. Let us consider two identical systems which have a conducted narrowband susceptibility of x V at a specified frequency. Let a capacitor be connected across one of the systems to improve its susceptibility. However, according to the present method of testing, both systems will still have the same susceptibility because the present method requires that equal voltages be impressed across the terminals of each of the two systems. In actuality, however, a lower voltage will appear across the input terminals of the system that has the capacitor connected across its input terminals for the same source of electrical noise.

This discrepancy may be corrected to some extent by standardizing both the source (signal generator) impedance and the system impedance, and reducing the required susceptibility limit in proportion to the actual system impedance. This procedure has the drawback that the source and system impedances are generally complex, having both active and reactive parts which are frequency dependent.

An alternate method is to specify the conducted narrowband continuous-wave susceptibility of a system in terms of volts and volt-amperes as a function of frequency. In other words, at each specified frequency of the electrical noise source, the susceptibility of the system should be measured in terms of the impressed voltage across the input terminals of the system and the voltamperes injected by the electrical noise source into the system. The requirements of volts and voltamperes do not have to be met simultaneously. To illustrate, let us consider again the example of the two systems, one having an input capacitor, but which are otherwise identical. To determine the susceptibility of the system with the input capacitor, the output voltage of the electrical noise source at a specified frequency is gradually increased, while the voltage across the input of the system as well as the injected voltamperes are monitored. If the input capacitance is high enough, then the limit of the input voltamperes is reached. For the second system, depending upon the input impedance, the required input voltage magnitude may be reached before the limit of the voltampere requirement. In this way the designer of the system will be free to reduce the system susceptibility either by increasing the threshold or by decreasing the system impedance, or both. The electrical noise source (signal generator) is also free from any constraints, except that it should have the capability to inject the required volts and voltamperes.

4.2.5.2 Susceptibility to Transient Electrical Noise

The susceptibility to transient electrical noise is another matter. The continuous-wave susceptibility cannot cover this area because of the limited energy contained in transient electrical noise. Moreover, the wave shape of transient

electrical noise is a significant parameter because the performance of many modern semiconductor devices depends upon the di/dt and dv/dt of the electrical noise. Therefore it is proposed that the susceptibility to transient electrical noise be specified by the following parameters:

- 1) Peak of transient voltage
- 2) Wave shape of voltage (front time and duration)
- 3) Energy

Similar to the case of continuous-wave susceptibility, it may not be possible (or necessary) to satisfy all the above three requirements simultaneously. The susceptibility to transient electrical noise will be governed by the designed threshold level and impedance level of the system. Many control systems contain semiconductor devices which are sensitive to di/dt and the dv/dt of the impressed source. Special networks are designed, either internally or externally to these systems, to minimize the dv/dt effects. Therefore insistence on the specified voltage wave shape across the input terminals of the system would be either to face an impossible situation or to disregard the merits of the special design features of the system.

The specifications concerning the transient electrical noise susceptibility of communications/control systems are relatively new. These are mostly required by military standards [19]—[20]. However, it is believed that these specifications are not complete. For instance, none of these specifications has any limit on the front time of the transient electrical noise. Moreover, the energy of the applied electrical noise is not explicitly specified. These standards recommend calibration of the transient-voltage generator by connecting a fixed resistor, for example, $5\ \Omega$, across its terminals. Although this implicitly specifies the energy-handling capability of the electrical noise source, the actual energy injected into the system is not known when the fixed resistor is replaced by the system under test, and the output voltage of the electrical noise source is readjusted to the specified value. The susceptibility of the system, as measured by this method, may depend considerably on the internal design of the transient-voltage generator.

A method is proposed which will measure the susceptibility of the system to transient electrical noise without any regard to the internal design of the transient-voltage generator. It is proposed that the generator be set up to produce the specified wave shape on open circuit. The generator is then connected to the system. The voltage across the system terminals as well as the energy injected into the system are simultaneously measured. The peak terminal voltage is adjusted until either the specified peak voltage is reached or the specified energy is injected into the system, whichever occurs first.

Transients in electrical systems occur at random. Two transients are seldom alike, either in wave shape or in amplitude. However, industry-standard wave shapes are already in existence which can be applied to test the susceptibility of equipment to transient electrical noise.

Transient voltages may last for microseconds as well as milliseconds. For microsecond transients a standard wave shape of $1.2/50\ \mu\text{s}$ is as shown in Fig 27(c) [5]. This wave shape in the *chopped* mode is represented by the vertical dashed line in Fig 27(c). Chopping denotes a flashover of an insulating path, such as a pair of separating contacts. Showering arc, as discussed in [67], can be represented by a thyatron or a thyristor, and the time to chop can be varied to produce the worst case by logic circuitry.

In [4] a damped oscillatory sine wave has been proposed, as shown in Fig 27(d). It has a frequency range of 1.0—1.5 MHz, the envelope decaying to 50% of the first crest in not less than $6.0\ \mu\text{s}$.

For representing millisecond transients, one half-cycle of the 60 Hz wave can be used. This type of transient-voltage wave shape has been successfully used to test semiconductor devices.

It is admitted that the proposed transient-voltage wave shapes will not represent all possible types of transient voltages which may be generated in the various electrical systems. As basically there are two types of transients, short duration and long duration, the proposed wave shapes would simulate a broad range of transients. Under special circumstances, other wave shapes should also be considered.

4.2.5.3 Overall Susceptibility

The susceptibility of a system will be different for the various means of entry (Fig 25) of the same type of electrical noise. This is not only due to the characteristics of the active devices, but it is also true because the incoming electrical noise encounters different impedance networks. The susceptibility of a system also depends upon the mode of propagation of the electrical noise, namely, common mode or normal mode. The susceptibility to electrical noise can be categorized as shown in Fig 29.

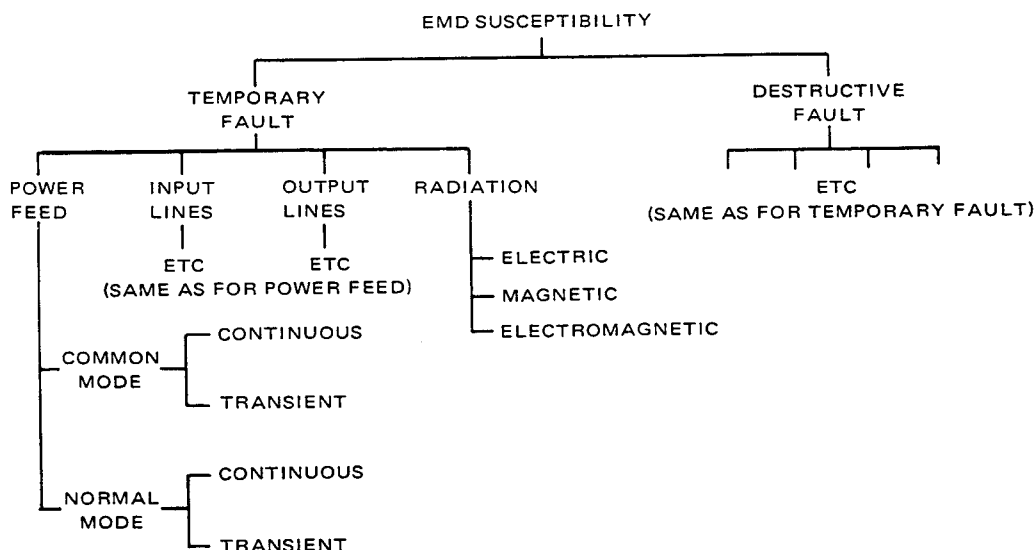


Figure 29— Classification of Susceptibility to Electrical Noise

4.2.6 Susceptibility of Control Systems

The classification in Fig 29 may appear to be formidable at first glance. However, it can be considerably simplified. Almost all destructive faults are caused by transient voltages. Therefore the susceptibility criterion of destructive faults caused by continuous waves may be eliminated.

The withstand capability of a system to common-mode electrical noise is generally much higher than that to normal-mode electrical noise, and the ratio of the two withstand capabilities can be expressed as a number A , as shown in Table 2.

Table 2— Transient Susceptibility Requirements (Temporary Fault)

Power Feed Lines		Input Lines		Output Lines	
Normal Mode	Common Mode	Normal Mode	Common Mode	Normal Mode	Common Mode
x (V)	Ax (V)	ax (V)	Aax (V)	βax (V)	$A\beta ax$ (V)
y (J)	A^2y (J)	a^2x (J)	A^2a^2x (J)	β^2a^2x (J)	$A^2\beta^2a^2x$ (J)

a = (highest input signal level)/(system voltage).
 β = system voltage gain.
 A = (withstand capability to common-mode noise)/(withstand capability to normal-mode noise).

The ratio of output signals to input signals is the gain of the system. It is logical to express the ratio of these withstand capabilities also in terms of the gain β , shown in Table 2. Similarly, the ratio of the withstand capabilities of the input lines to the power feed can be expressed as equal to the ratio of the highest input signal voltage level to the system voltage a , shown in Table 2.

Therefore, the only parameter to be specified is the withstand capability of the power feed lines; a , β , and A will be known from the requirements of the system.

An example is shown in Table 2. For a particular system the normal-mode withstand capability of the power feed lines is specified as x V for temporary faults. Once this is specified, the others will follow suit as shown in Table 2. Once the withstand capabilities for temporary faults are thus specified, the corresponding withstand capabilities for destructive faults can be obtained by multiplying by a factor to be determined by the system requirements.

Once the transient-voltage withstand capabilities are specified the transient-energy withstand capabilities can be similarly specified, starting with the normal-mode power feed withstand capability. For the transient-energy capabilities the multiplying factors are squared because energy is proportional to the voltage squared.

The same procedure should be used for both the short-duration and the long-duration transients.

The specifications on the continuous-wave withstand capabilities are similar. However, in this case instead of specifying a number x , a curve of voltages versus frequency has to be specified. The other steps are similar.

The numbers x and y and the voltage versus frequency curves will be different for different systems. It is recognized that this is a difficult task. It will be completed only when the characteristics of electrical noise in various systems can be estimated, and suppression to a known level can be obtained *economically*. Much work needs to be done in this area.

4.2.7 Methods of Measurement [30]

4.2.7.1 Measurement of Transient Susceptibility

Three apparatus are needed for the measurement of transient susceptibility:

- 1) Transient-voltage generator
- 2) Apparatus to measure transient voltage
- 3) Apparatus to measure transient energy

4.2.7.1.1 Generation of Transient Voltage

The schematic of a transient voltage generator for generating the 1.2/50 μ s voltage wave is shown in Fig 30. The wave shape is determined by the parameters C_1 , C_2 , R_1 , and R_2 . A fairly good estimate of the peak magnitude and the wave shape of the open-circuit output voltage can be made from the following equations:

$$\text{peak of output voltage} = V_1 \left(\frac{R_2}{R_1 + R_2} \right) \left(\frac{C_1}{C_1 + C_2} \right)$$

where

$$\begin{aligned} \text{time to crest} &= 3R_1C_2 \\ \text{time to half-value} &= 0.8R_2C_1 \\ V_1 &= \text{charging voltage of capacitor } C_1. \end{aligned}$$

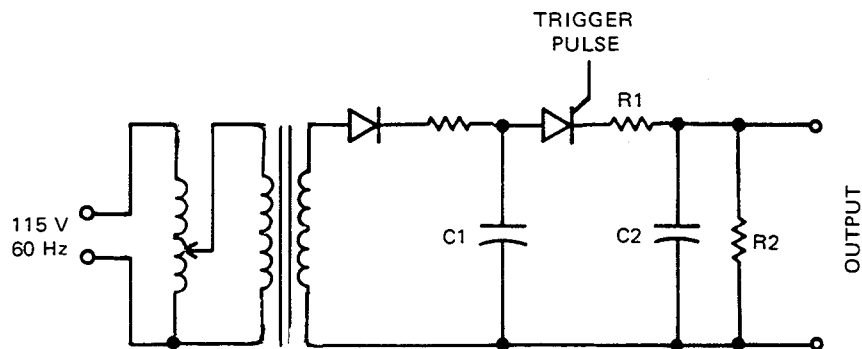


Figure 30— 1.2 / 50 μ s Oscillatory Transient-Voltage Generator

The transient voltage [Fig 27(d)] is an oscillatory wave having a frequency range of 1.0-1.5 MHz, a voltage range of 2.5-3.0 kV crest of the first half-cycle peak, and an envelope decaying to 50% of the crest value of the first peak in not less than 6.0 μ s from the start of the wave. The source impedance of the surge generator used to produce the test wave shall be 150 Ω . The test wave is to be applied to a test specimen at a repetition rate of not less than 50 tests per second for a period of not less than 2.0 s [4].

The test is a design test for relaying systems, in particular static relaying systems. The schematic of a typical test wave generator is shown in Fig 31. For its adaptation as a test voltage to determine the susceptibility levels of the various control systems, its magnitude has to be modified to suit the specific requirement.

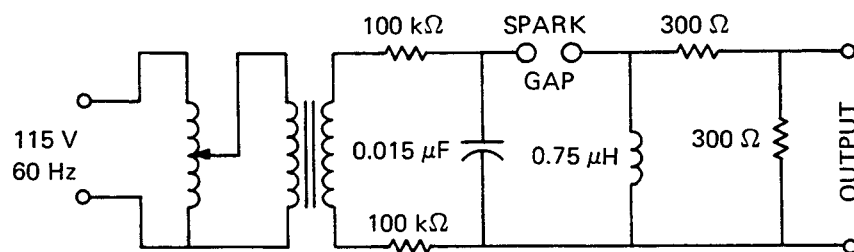


Figure 31— Oscillatory Wave Transient-Voltage Generator

The schematic of the 8 ms transient-voltage generator is shown in Fig 32. The open-circuit output voltage is given by the equation

$$V_0 = V_i \left(\frac{C_1}{C_1 + C_2} \right) \left[1 - \cos \left(\frac{t}{\sqrt{LC}} \right) \right]$$

where V_0 is the open-circuit output voltage, V_i is the charging voltage of capacitor C_1 , and $C = C_1 C_2 / (C_1 + C_2)$.