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

Sponsor

Industrial Control Committee of the
IEEE Industrial Applications Society

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Foreword

(This foreword is not part of IEEE Std 518-1977, Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.)

The rapidly expanding use of solid-state controllers 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 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.

At the time it approved the guide, the Industrial Control Systems Subcommittee had the following membership:

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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 standard 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 installation of controllers and control systems so that proper operation can be achieved in the presence of electrical noise. This standard is not intended to be a guide for the internal design of electrical controllers or for the prevention of 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 is 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 which can be measured, correlated to the process, and subsequently controlled; the controlled variable may be temperature, pressure, liquid level, speed, or other 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 devices and equipment to monitor the controlled variable and adjust the manipulated variable to keep the process at the desired condition.

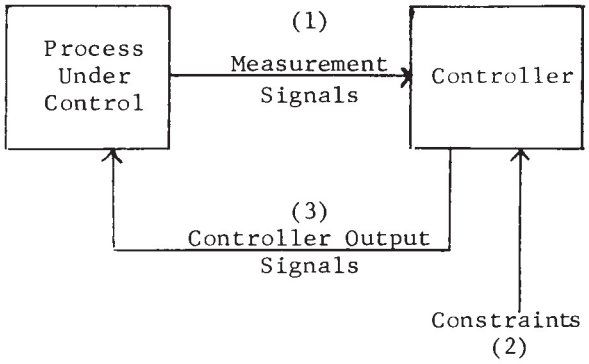


Fig 1
Signal Flow in Control System

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 this signal, 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 associated control system is dependent on the process characteristics.

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 man 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

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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 Section 3.3).

(2) Coupling of noise from source to control circuit (see Section 3.4).

(3) Susceptibility of the control circuit to electrical noise (see Section 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 devices which are known to be sources of noise is given below:

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

There are other sources of noise which appear in a control circuit due to the method of connection of 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 will be discussed in this section. (Whether this voltage which appears in the control circuit actually results in noise, as defined in this guide, is dependent upon the susceptibility of the control circuit.) (See Section 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. Fig 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, AR2 are being used to amplify the output of an iron-constantan thermocouple TC. A load operated by contact 1a is also associated with the circuit. The lead A—B is 50 ft of AWG #12 wire which has a resistance of 1.6 Ω per thousand ft.

$R_{AB} = 50/1000 \times 1.6 = 0.08\ \Omega$

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

$V_{AB} = 0.5 \times 0.08 = 0.040$ V

Assume that the amplifier AR1 close to the thermocouple TC will amplify by 100. This will mean that 0.040 V from A to B will appear to AR2 just like a 0.04/100 (or 0.40 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 1a it could change (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 Section 7.1, Ref [1].

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

where ℓ is the length of wire in centimeters and r is the radius of conductor in centimeters.

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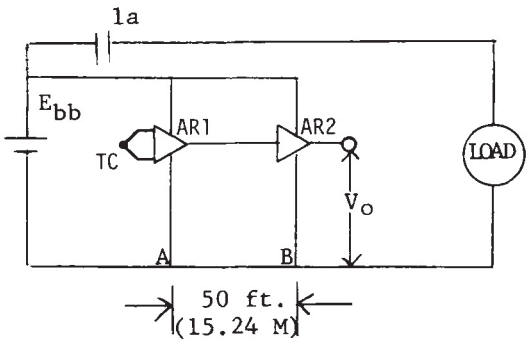


Fig 2
Single-Ended Circuit with Long Common Wire

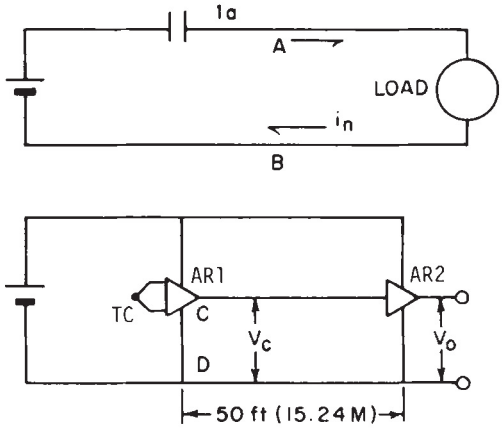


Fig 3
Circuit Showing Magnetic Coupling

For wire A—B this would be

$\ell = 1524$ cm
$r = 0.205$ cm

$$L = 3.05 \log_e \left[\frac{2 \times 1524}{0.205} - \tfrac{3}{4}\right] \mu H$$

$$L = 3.05 \left[9.6 - \tfrac{3}{4}\right] \mu H$$

$$L = 3.05 \times 8.85 = 27\ \mu H$$

When the current through the load is interrupted, it could change from 0.5 ampere to 0 in 1 μs.

$$V_{AB} = L \frac{\Delta i}{\Delta t}$$

$$V_{AB} = 27 \times 10^{-6} \times \frac{0.5}{10^{-6}} = 13.5 \text{ V peak}$$

Of course 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 common impedance paths which are not as obvious. Some of these can be listed in order 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 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 interference current. This type of coupling does not depend upon any conductive coupling between the noise source and control circuit. Fig 3 illustrates the nature of magnetic coupling.

In the circuit in Fig 3 assume that, all 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 equation (2-107) found in Section 7.1, Ref [2].

A o — ←3 in→ — B o — ←6 in→ — C o — ←1 in→ — D o
(7.62 cm) (15.24 cm) (2.54 cm)

$$M_{nc} = \frac{140.4}{10^9} \times \ell \times \log_{10} \left[\frac{d_{AC} \times d_{BD}}{d_{BC} \times d_{AB}}\right]$$

where ℓ is the length of wire in feet and d is the distance between wires (any units may be used)

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

$$M_{nc} = 0.149\ \mu H$$

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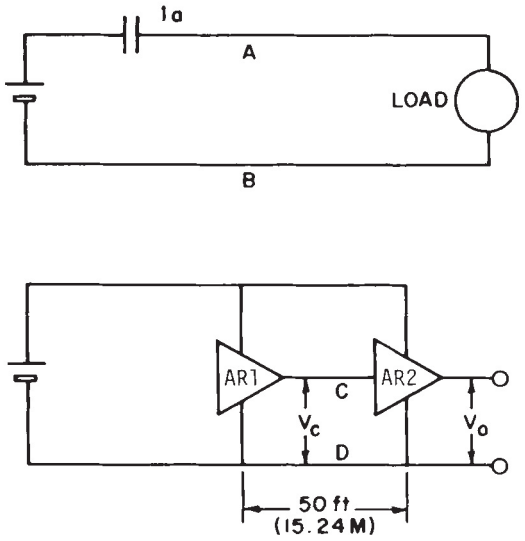


Fig 4
Circuit Showing Electrostatic Coupling

If the rate of current decay $\Delta i_n/\Delta t$ is 0.5 A/μs as assumed for the example in Section 3.4.1, the voltage induced in the control circuit would be:

$$V_{cD} = M_{nc}\frac{\Delta i_n}{\Delta t}$$

$$V_{cD} = 0.149 \times 10^{-6} \times 0.5/10^{-6} = 0.0745 \text{ V}$$

For an amplifier gain AR1 = 100 as assumed in the example in Section 3.4.1, this would be equivalent to a voltage at the thermocouple of 0.745 mV (26°F at the TC).

3.4.3 *Electrostatic Coupling.* This type of coupling is often called capacitive coupling because it is proportional to the capacitance between a control lead and a source of interference or "noise" voltage. Its magnitude depends upon the rate of change of the "noise" voltage and the impedance between elements of the "noise" circuit and elements of the control circuit.

The same circuit used to illustrate magnetic coupling can be used to illustrate electrostatic coupling (see Fig 4). However, the voltage between the wires and the capacitance is now important. The formula for the capacitance between two parallel wires in air is given by the following formula from an equation in Section 7.1 Ref [3]:

$$C = \frac{3.68\,\epsilon_R}{\log_{10}\left(\frac{2s}{d} - \frac{d}{2s}\right)} \text{ pF/ft}$$

where d is the diameter of wires (0.08 in for AWG #12), s is the distance between wires (in same units as "d"), and ϵ_R is the relative permittivity of the medium between conductors. (For this example, it is sufficient to assume the relative permittivity to be that of air, which is 1. In actual practice, the equivalent permittivity will be somewhere between 1 and 3 depending on the distribution and type of insulation on the wire.)

A o — ←3 in→ — B o — ←6 in→ — C o — ←1 in→ — D o
(7.62 cm) (15.24 cm) (2.54 cm)

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

$$= 76.7 \text{ pF}$$

$$C_{AC} = \frac{184}{\log_{10}\left(\frac{18}{0.08} - \frac{0.08}{18}\right)} = \frac{184}{2.351}$$

$$= 78.3 \text{ pF}$$

$$C_{BD} = \frac{184}{\log_{10}\left(\frac{14}{0.08} - \frac{0.08}{14}\right)} = \frac{184}{2.242}$$

$$= 82.1 \text{ pF}$$

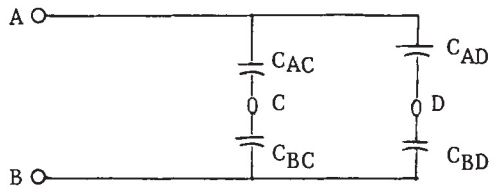
$$C_{BC} = \frac{184}{\log_{10}\left(\frac{12}{0.08} - \frac{0.08}{12}\right)} = \frac{184}{2.176}$$

$$= 84.6 \text{ pF}$$

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 troubleshooting might have capacity to a conducting grid in a concrete floor of 150 pF.

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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 principal. Assume this equivalent circuit:



Using The Relationship of voltage division by capacitors

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

$$V_{BC} = \frac{V_{AB}}{C_{BC}} \frac{C_{AC} \times C_{BC}}{C_{AC} + C_{BC}}$$

$$V_{BC} = \frac{2000}{84.6} \frac{78.3 \times 84.6}{78.3 + 84.6} = 961.32 \text{ V}$$

Similarly

$$V_{BD} = \frac{V_{AB}}{C_{BD}} \frac{C_{AD} \times C_{BD}}{C_{AD} + C_{BD}}$$

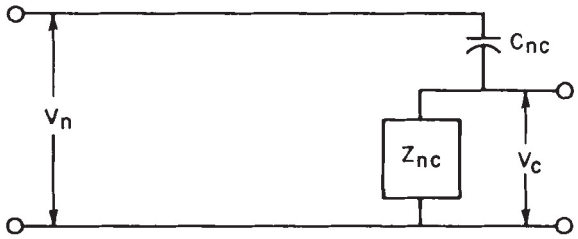
$$V_{BD} = \frac{2000}{82.1} \frac{76.7 \times 82.1}{76.7 + 82.1} = 965.99 \text{ V}$$

$$V_c = V_{BD} - V_{BC}$$

$$V_{cD} = 965.99 - 961.32 = 4.67 \text{ V}$$

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

The process of electrostatically inducing a voltage in a leadwire can be summarized by the following equation. For this illustration assume rms voltages.



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

V_c = Voltage induced in the control wire
V_n = Noise voltage source
ω_n = Frequency of the 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 $Z_{nc}\omega_n C_{nc}$ must be kept as low as possible. Thus anything that can be done to reduce 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 percent 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

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problems in control systems. 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 given control circuit can differentiate between noise and desired signals is a measure of the susceptibility of a control circuit. 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 a 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.

Single-ended amplifiers are amplifiers with one of the input terminals at a common potential and 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 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 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.

4. Classification

4.1 Electrical Noise Classifications. 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, or both, when available.

The voltage values listed in this section are intended to describe 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. (See Section 7.2, Ref [10]).

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, depending upon circuit constants, not less than the minimum arcing current. (See Section 7.2, Ref [4].) This current chopping in association with circuit inductance (such as relay magnets) and shunt capacitance (such as coil self-capacitance and wiring capacitance) generate electrical noise transients, called the showering arc (see Section 7.2 Refs [5] and [6]), having peak voltages as a function of the contact gap breakdown, which depends upon number and size of the contact gaps, contact material, atmosphere, etc.

4.1.1.1 *Electromagnetic Current Interruption.* Typical noise prints taken from Section 7.2, Ref [8] are shown in Figs 5, 6, and 7 and in the following text. Each transient is unique. However, typical values of characteristics are as follows:

dv/dt (rise) up to 1000 V/μs
dv/dt (fall) $>$ 10 000 V/μs

(Section 7.2, Ref [7] states that the fall is 2 000 000 to 6 000 000 V/μs.)

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.

Voltage peaks (typical) (120 V magnet)

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

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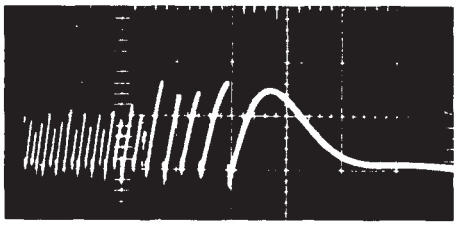


Fig 5
Showering Arc Voltage Across Double Break Contacts Interrupting 120 V AC 60 Hz Machine Tool Relay Magnet

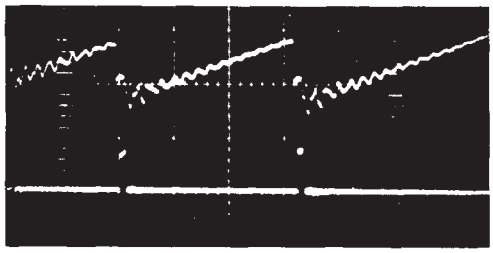


Fig 6
Upper Trace Similar to Fig 5 but Expanded Time Scale; Lower Trace Is Current in Contacts (Contacts Connected by 100 ft 300 Ω Transmission Line)

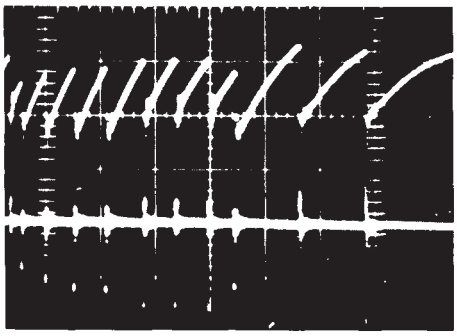


Fig 7
Upper Trace Similar to Fig 5 but Expanded Time Scale: Lower Trace Is Voltage Induced in Adjacent 100 ft 300 Ω Line Terminated in Its Characteristic Impedance
(Note 300 V Peaks Coincident with Current Pulses in Fig 6)

Voltage peaks (typical) (600 V magnet)
5600 V 4 contact gaps in air
See Section 6.4.1.1 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:

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

where L is the circuit inductance.

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

It is difficult to produce typical noise prints because of the wide variation in inductance, capacitance, and resistance which affects 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 8, 9, and 10.

4.1.2.2 *Motor Load* (see Section 7.2, Ref [11]). Semiconductor Controlled Rectifier (SCR) drives are capable of producing power line noise. Fig 11 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.

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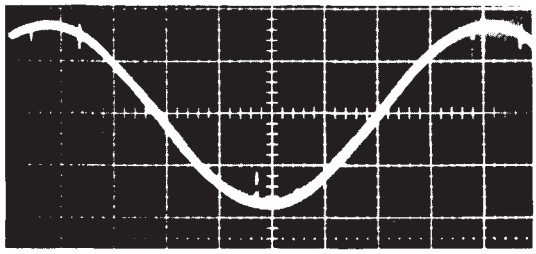


Fig 8
Noisy 30 A 120 V 60 Hz Laboratory Power Line
(The Transients Occurring Just Before Voltage Peak Are Caused by a 20 Ω Resistive Load Phase Controlled by a Triac)

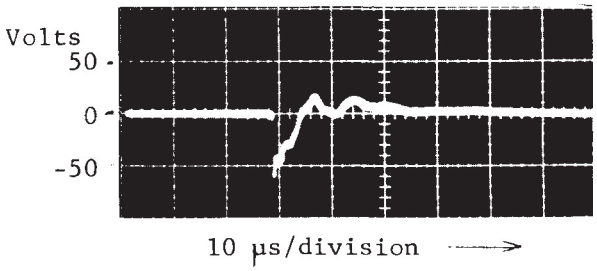


Fig 9
Same as Fig 8 but Time Scale Expanded and High Pass Filter Used to Eliminate 60 Hz Voltage
(See Section 4.1.12.1 for Measurement Method)

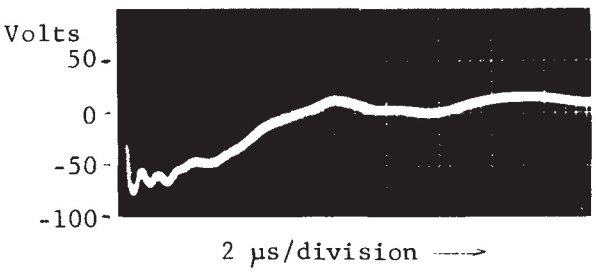


Fig 10
Same as Fig 9 but Time Scale Further Expanded to Show High-Frequency Ringing

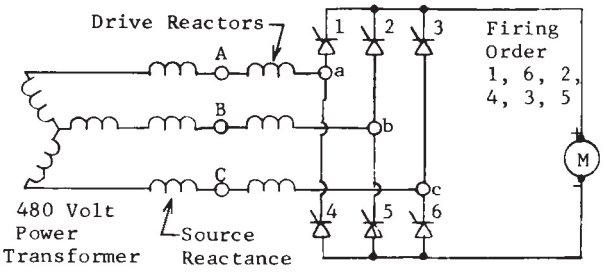


Fig 11
Three-Phase Full-Wave Rectifier Motor Control Power Circuits

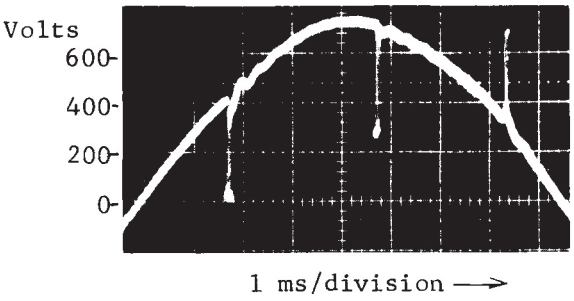


Fig 12
Typical Line Notching Transients Produced by Three-Phase Full-Wave Rectifier Motor Control
(Half Cycle of Voltage *ab* in Fig 11 with Motor Loaded to Produce 50 A RMS in Each AC Line. See Section 4.1.12.2 for Voltage Measurement Method)

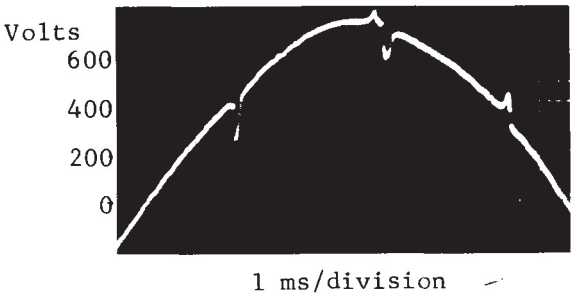


Fig 13
Voltage *ab* in Fig 11 with Motor Load Reduced to 15 A RMS in Each AC Line
(See Section 4.1.12.2 for Voltage Measurement Method)

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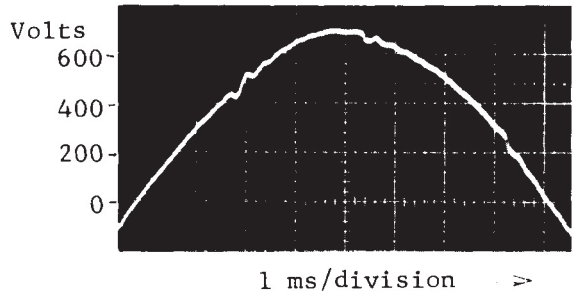


Fig 14
Voltage *AB* in Fig 11 with Motor Load to Produce 50 A RMS in Each AC Line
(See Section 4.1.12.2 for Voltage Measurement Method)

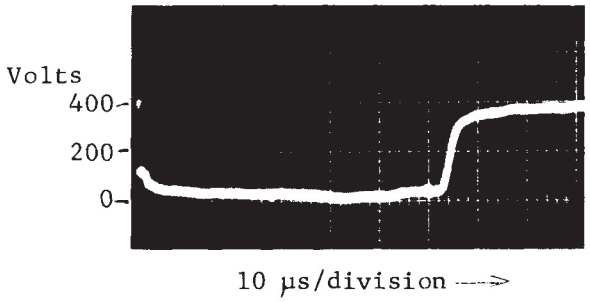


Fig 15
Same as Fig 12 but Time Scale Expanded to Show Notch Detail

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 SCR 1 and SCR 2 are both conducting (shorted together) until this transfer is completed.

Fig 12 shows an oscillogram of the voltage *ab* going to zero as this transfer takes place. This phenomena is called line notching. The notches are not as wide at reduced current as shown in Fig 13. These noise prints were made on a 400 A line having 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 14.

For further discussion of the effects of source reactance versus feeder and load reactance, load current, and firing angle, see Section 7.2 Ref [11].

Details of the line notch are shown in Fig 15 and 16. Current transfer details of the notch are in Fig 17.

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*

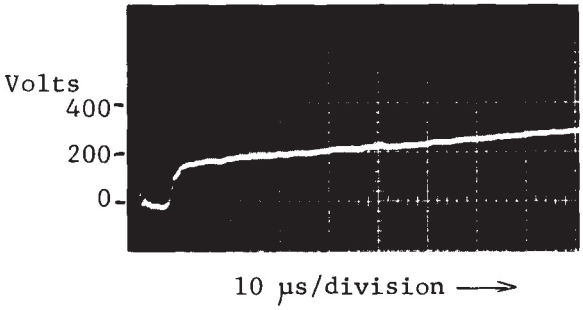


Fig 16
Same as Fig 13 but Time Scale Expanded to Show Notch Detail

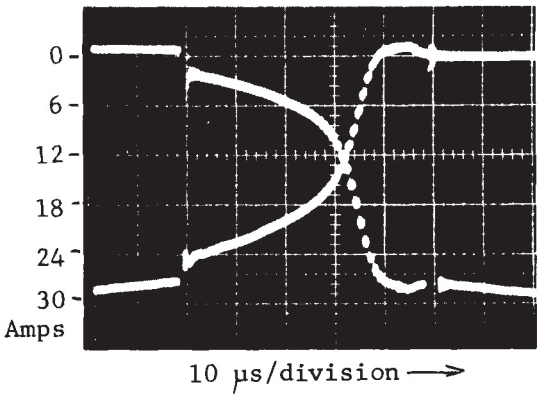
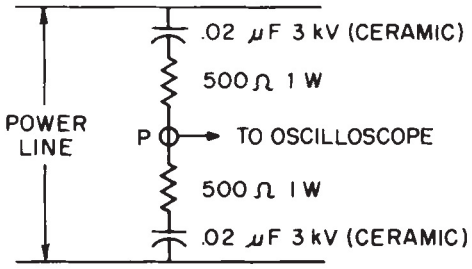


Fig 17
Current Transfer from Line *A* to Line *B* During Line Notch Shown in Fig 15
(Max di/dt = 2.53 A/μs; Initial di/dt = 0.156 A/μs. Measurement Made with Two 1200/5 Weston Model 327 Type 2 Current Transformers with 4 Ω Resistance as Secondary Load.)

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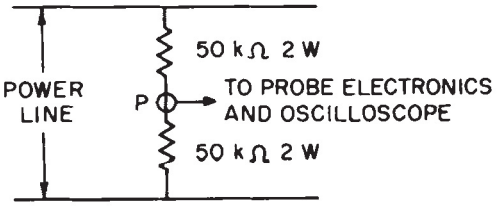
4.1.3.4 *Distribution Circuitry*
4.1.3.5 *Flourescent Lights*
4.1.4 *Faults*
4.1.4.1 *Current Limiting Fuses*
4.1.4.2 *Arcing Faults*
4.1.4.3 *Restrikes on Switching*
4.1.5 *Power-Frequency Electric and Magnetic Fields*
4.1.5.1 *Resistance Welding Machines*
4.1.5.2 *Power Lines*
4.1.6 *High-Frequency 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*
4.1.7 *High-Frequency Broadband Generators such as Electrical Discharge Machining (EDM)*
4.1.8 *Ferroresonance*
4.1.9 *Lightning and Electromagnetic Pulse (EMP)*
4.1.10 *Static Discharge*
4.1.11 *Cable Noise*
4.1.12 *Voltage Measurements*

4.1.12.1 High pass filter for voltage measurements using an oscilloscope isolated from the voltage being measured.



P is a 350 MHz current transformer type current probe or a 50 MHz clamp on type current probe.

4.1.12.2 Voltage measurement method providing oscilloscope isolation from the voltage being measured.



P is clamp-on 50 MHz current probe.

4.2 Electrical Noise Susceptibility Classification

4.2.1 *Introduction.* An 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 may force the system to malfunction, or even may 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 EMC 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, no special precaution needs to be taken. 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 EMC 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 the 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 Ref [12] in Section 7.3.

4.2.2 *System Boundaries.* Electrical noise can reach the system through four different paths (Fig 18).

(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

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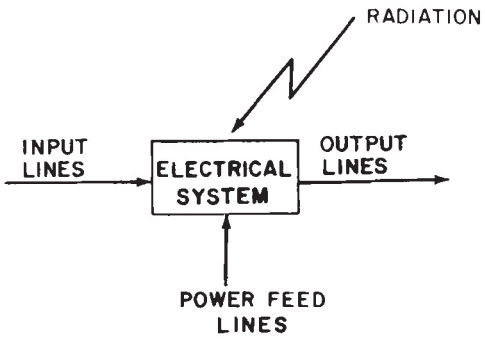


Fig 18
System Boundaries for Penetration of Electrical Noise

susceptibility will be different for the common-mode noise from that of the normal mode. For the 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 the nondestructive malfunction is the 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.

4.2.3.2 *Destructive Malfunction.* The destructive malfunction causes damage to the system irreversibly; that is, the system continues to malfunction even after the 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 (CW) and transient.

4.2.4.1 *Continuous Wave Electrical Noise.* A CW electrical noise can further be subdivided into narrowband and broadband.

A narrowband CW 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 CW electrical noise.

A broadband CW electrical noise is a disturbance which contains energy covering a wide

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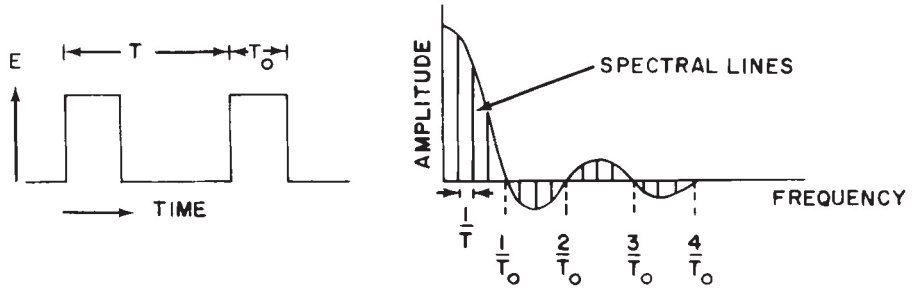


Fig 19
Spectrum of Rectangular Pulse Train

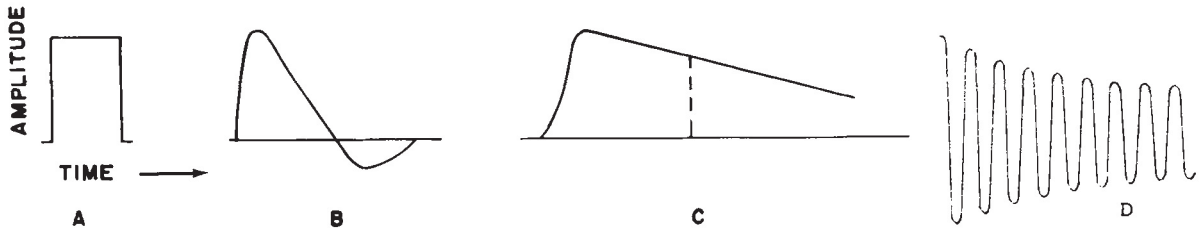


Fig 20
Illustrations of Transient Electrical Noise

frequency range. A repetitive rectangular pulse is a broadband electrical noise (Fig 19).

A broadband electrical noise can be mathematically expressed, by Fourier Series, as summation of narrowband CW functions whose amplitudes are frequency dependent. For instance, the repetitive rectangular pulse of Fig 19 can be expressed as:

$$F(t) = \frac{ET_o}{T} + \sum_{n=1}^{\infty} \frac{2E}{n\pi} \sin(n\omega T_o/2) \cdot \cos(n\omega t)$$

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

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 20, the first three are broadband and the last one is narrowband.

Fig 20A is a rectangular pulse which is sometimes used as an approximation of actual transients for the sake of simplicity in analytical work. Fig 20B is a standard transient voltage specified in MIL-SPECS. (See Section 7.3, Refs [13] — [15].) The duration of the first loop is 10 μs. The front time is not specified. Fig 20C is an industry standard transient voltage [16]. It has a front time of 1.2 μs, the time to half value of 50 μs, and is designated as the 1.2 × 50 μs wave.

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. Fig 20D has been proposed as the surge withstand capability (SWC) test for solid state relays [17]. This is an oscillatory wave of 1.5 MHz nominal frequency, with the

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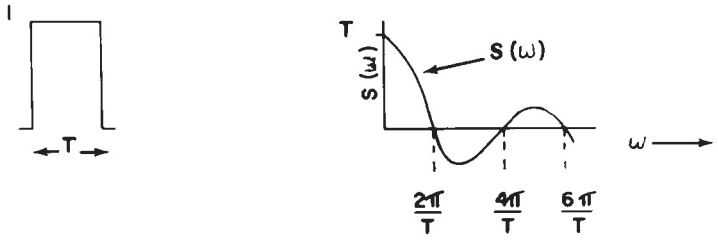


Fig 21
Spectral Density of Rectangular Pulse

envelope decaying to 50 percent of crest value in not less than 6 μs, and a pulse repetition rate of 50 pps for a period of not less than 2 μs.

Transients can be represented in the frequency domain by Fourier Integral for analytical purpose. For instance, a rectangular pulse can be represented in the frequency domain, as in Fig 21, by

$$s(\omega) = (2/\omega) \sin(\omega T/2)$$

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

4.2.5 *Criteria of Susceptibility Measurement.* It is known that the susceptibility of the most commonly used semiconductor devices (diodes, transistor, thyristor, integrated circuits) to electrical noise depends largely upon the magnitude of voltage or current of the impressed electrical noise and its charge or energy content or both [18]—[21]. 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 that 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 CW 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 [13]—[15]. 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 the systems will still have the same susceptibility because the present mode 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 which 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.

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An alternate method is to specify the conducted narrowband CW susceptibility of a system in terms of volts and voltamperes 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) 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 monitoring the voltage across the input of the system as well as the injected voltamperes. If the input capacitance is high enough, then the limit of the input voltampere 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 the transient electrical noise is another matter. The continuous wave susceptibility cannot cover this area because of the limited energy contained in a transient electrical noise. Moreover, the wave shape of the transient electrical noise is a significant parameter because the performance of many of the 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 specified requirements simultaneously. It will be governed by the designed threshold level and impedance level of the system. Many control systems contain semiconductor devices which are sensitive to the 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, the insistence on the specified voltage waveshape 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 on the transient electrical noise susceptibility of communications/control systems are relatively new. These specifications are mostly required by the military standards [13]—[15]. 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 Ω, 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-

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