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Interaction Notes

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SYSTEM-GENERATED TRANSIENTS

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ABSTRACT

One bound on the amount of transient interference reduction required of an electromagnetic barrier or shield is the interference level generated in the protected volume. When the environment in the protected volume is dominated by transients generated inside that volume, improvements in the barrier will not improve the internal environment. Transients are produced inside facilities and vehicles by power switching and by processes such as rectification and conversion. In this note, the transients produced by some of these processes are examined to obtain an estimate of the level of system-generated transient activity. It appears that peak voltages on the order of the power supply voltage can be expected inside typical facilities.

ACKNOWLEDGEMENT

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SYSTEM GENERATED TRANSIENTS

I. INTRODUCTION

One of the important characteristics of an effectively impervious barrier is that it reduces the effect of sources on one side of the barrier to a level smaller than system generated interference on the other side of the barrier. Thus the effects of these sources are masked by the ambient noise produced by the system and are either undetectable or produce less stress on the system than the routinely generated system transients. It is important therefore, to estimate the magnitude of these routinely generated transients, since these transients set an upper bound on the amount of imperviousness required of the barrier.

Power switching and processing (rectification, inversion, conversion, regulation) probably produce the largest transients that occur routinely inside a facility. Therefore, switching phenomena will be analyzed to demonstrate the nature of these transients. Heavy loads such as air conditioners, space heaters, water heaters, etc., are switched on and off several times each day to regulate temperature. Inductive loads such as solenoid actuated devices, relay coils, motor and transformer windings are also energized and deenergized frequently. Other devices, such as rectifiers, converters, inverters, and even fluorescent lights, produce switching transients at the 60 Hz (or some multiple thereof) rate. In the following paragraphs, some of these switching transients are analyzed.

II. EARLY-TIME SWITCHING TRANSIENTS

Consider the internally generated interference caused by ac power switching and processing. Such noise originates in the space between the facility barrier and the equipment barrier -- it is not reduced by either barrier in reaching this volume of interest. Transients are generated on power conductors whenever an appliance is turned on or off. This action is illustrated in Figure 1, where the circuit, the slow 60 Hz wave, and the transient charging and discharging waves are shown. Because the 60 Hz wavelength is 5000 km, the entire energized part of the circuits is at approximately the same potential before the switch closes. If the 120 V (170 V peak) circuit is energized at the peak of the 60 Hz wave, as illustrated in Figure 1(b), an 85 V charging step propagates down the energized circuit and an 85 V discharge wave propagates toward the 60 Hz source [as illustrated in Figure 1(c)]. When the discharging wave reaches the branch point in Figure 1(a) where other circuits are connected to the supply system, part of the discharge wave will propagate to these other circuits. Thus, both the circuit being energized and other circuitsserved by the same supply will experience a transient as a result of this switched load.

A similar analysis can be made using circuit currents. Observe that the current in the charging wave will be V/Z_0, where V is the charging voltage (85 V in Figure 1) and Z_0 is the characteristic impedance of the wiring to the circuit being energized. A discharge current wave flowing in the same direction will propagate toward the 60 Hz source, as illustrated in Figure 1(d). When the charging waves reach the end of the circuit being energized, a reflection occurs and the reflected wave sweeps across the circuit. A similar action occurs with the discharging wave and, after many reflections from the circuit ends and discontinuities, a steady state is reached.

For a simple circuit consisting of a resistive source, wiring of length ℓ, and a resistive load, two time regions (illustrated in Figure 2) are of interest. In the early time regions, individual reflections from the load and source impedances are apparent as the current builds up in the load. The steps last $2\ell/c$ (approximately 67 ns for a 10 m wiring circuit). In the intermediate time region the wiring can be represented as a lumped capacitance $C \simeq \ell/Z_0c \simeq 333$ pF for a 100 Ω line which is 10 m long. (The line behaves as a capacitor because

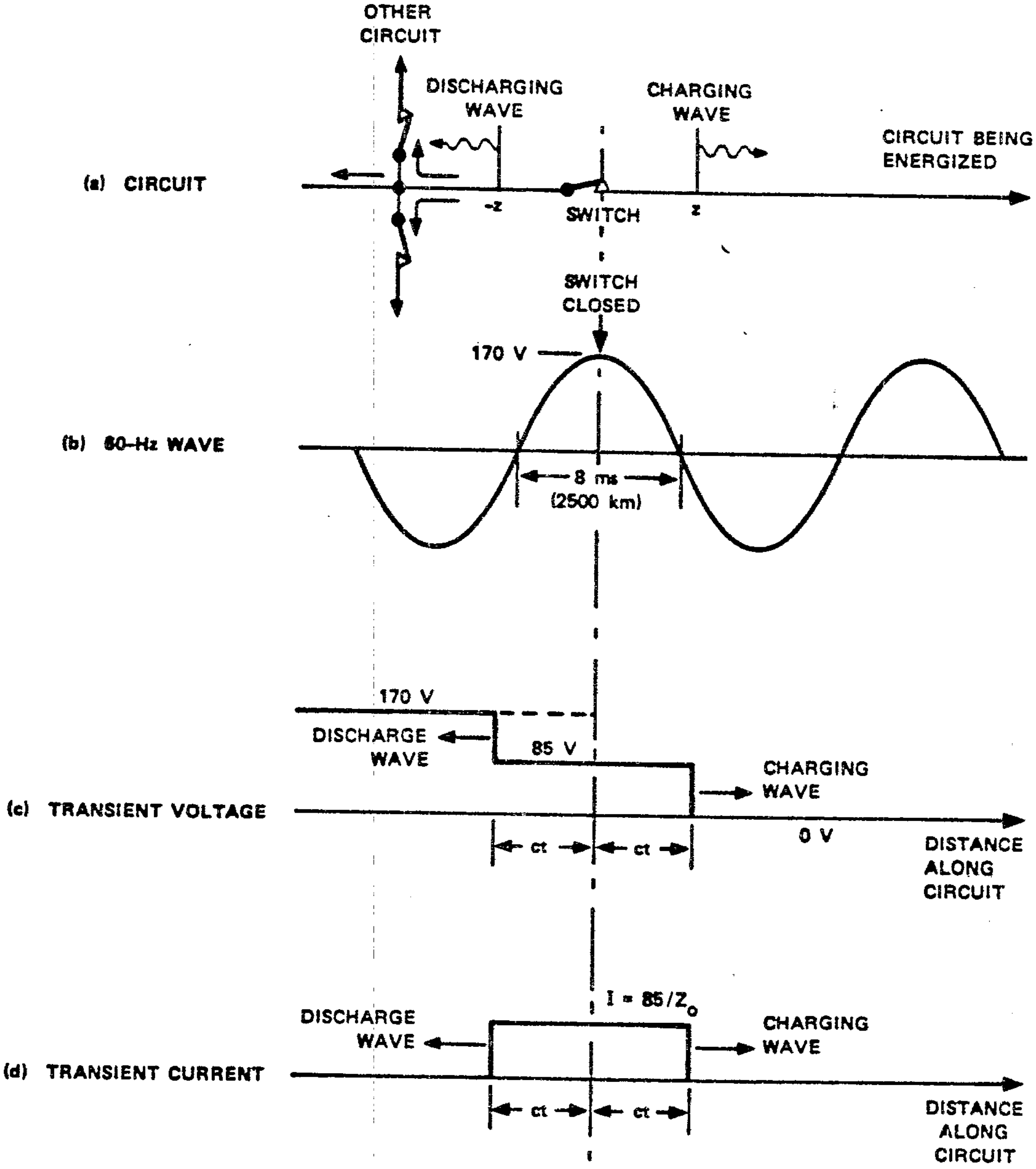


FIGURE 1 INTERNALLY-GENERATED INTERFERENCE CAUSED BY ac POWER SWITCHING AND PROCESSING

the impedances R_1 and R are assumed to be much larger than the characteristic impedance Z_o; had they been smaller than Z_o, the line would have behaved as a lumped inductance.) This capacitance is exponentially charged toward $V_oR/(R+R_1)$ through the resistor R_1 in

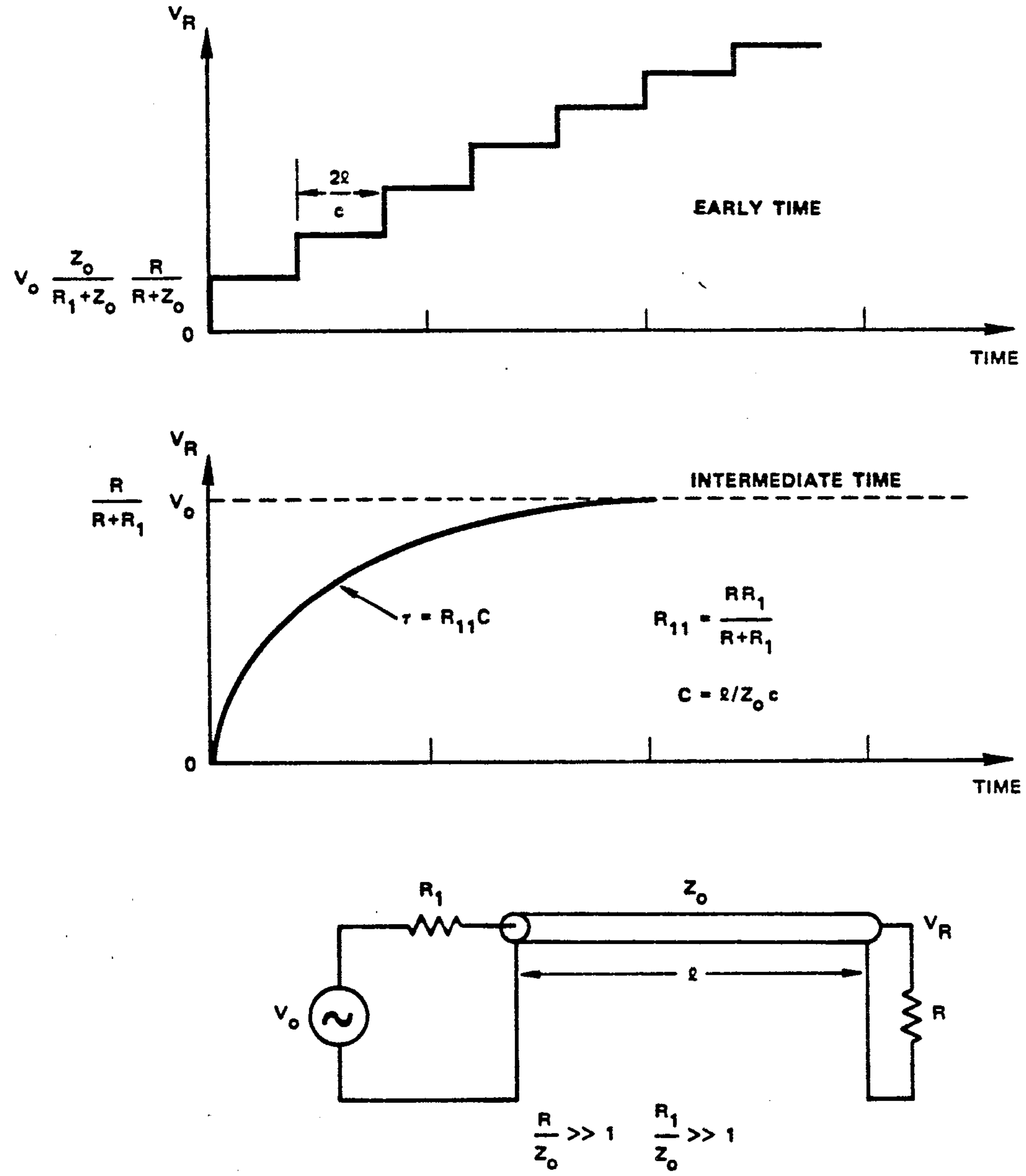


FIGURE 2 CHARGING TRANSIENTS ON SWITCHED RESISTIVE POWER CIRCUIT

parallel with R. The charging time constant is $\tau \simeq R_{11}C \simeq 0.17$ μs when $R_1 = R = 1000\ \Omega$ and

$$R_{11} = \frac{R\ R_1}{R + R_1} \simeq 500\ \Omega\ .$$

The example used here is easy to analyze and plot because the finite line length and high-resistance load and source impedances cause neat stairsteps in the early-time waveform. A more representative case encountered in practice, however, consists of a load that appears to be a small inductance in the early time regions. Then, if $L/Z_o < 2\ell/c$, significant decay occurs between reflections and a very complicated (but commonly observed) waveform such as that shown in Figure 3 results.

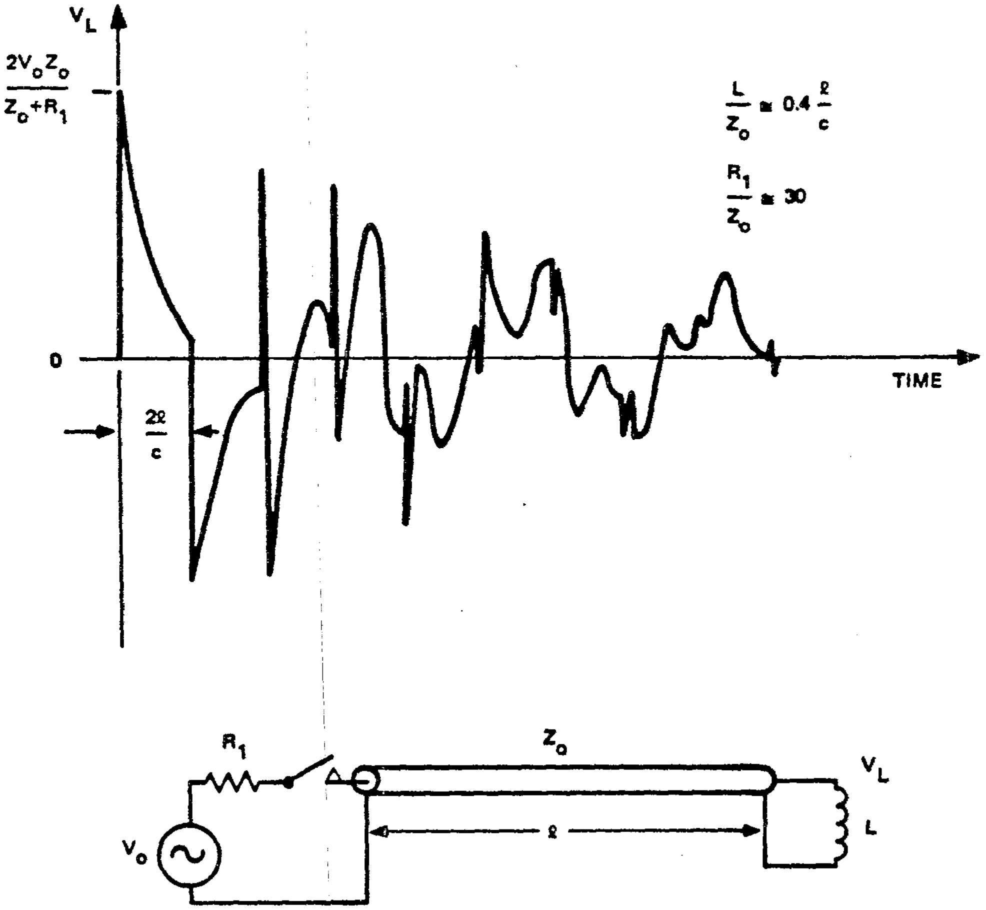


FIGURE 3 CHARGING TRANSIENTS ON SWITCHED INDUCTIVE POWER CIRCUIT

In the intermediate time region, a damped oscillation at a frequency determined by the line length and the load inductance is developed (we have again assumed a source impedance large compared to the characteristic impedance Z_o). An even more realistic waveform is obtained if the source impedance is about equal to the characteristic impedance and several additional branches of different lengths are connected to the source so that additional reflections and characteristic times occur in the response. The response then becomes very complex and contains several major frequency bands.

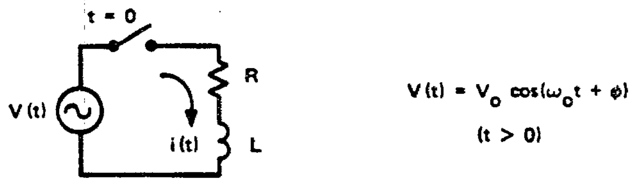
It is apparent from these examples that peak voltage changes of the order of the peak 60 Hz supply voltage can be expected from switching appliances on or off. Such transients occur in the early time regions regardless of the 60 Hz impedance of the load (they may actually occur several times because of contact bounce on switch closure). These step function transients are then modified by multiple reflections from the circuit terminations and junctions of the switched circuit and all other circuits fed from the same supply bus.

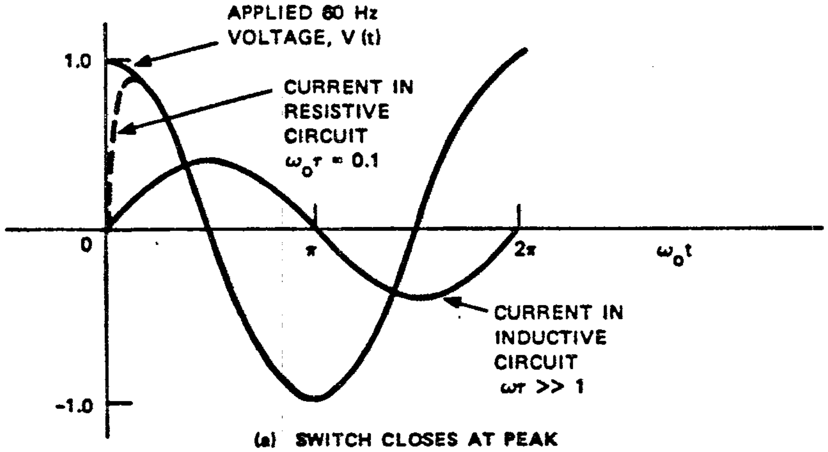
III. LATE-TIME SWITCHING TRANSIENTS

In the very late time (milliseconds) the classical 60 Hz transients may occur. At this time all of the nanosecond and microsecond transients from the early and intermediate times have usually been damped out, and all circuits appear to be electrically small. Then we can consider only lumped resistance and inductance as in Figure 4. If the switch closes when the source voltage is at its peak value, the current through the circuit will be

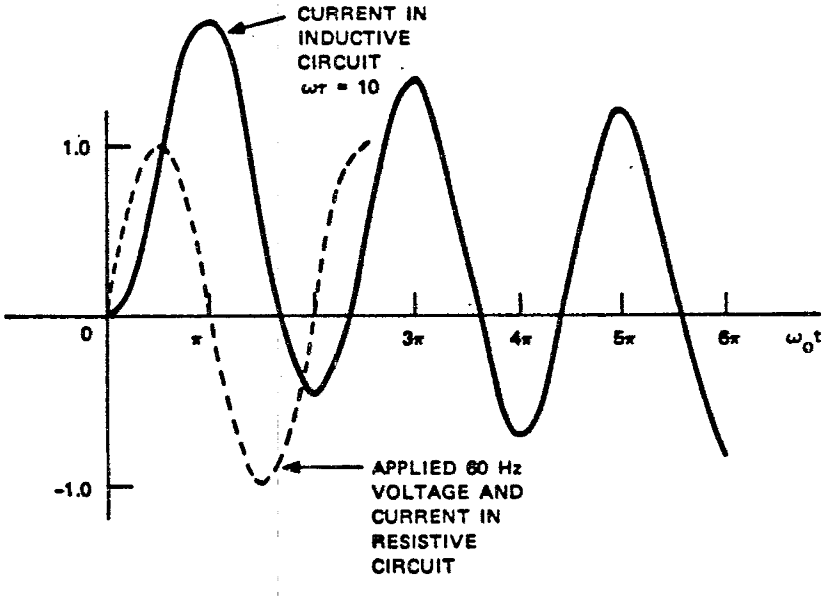
$$i(t) = \frac{V_o}{R(1 + \omega_o^2 t^2)} [\sqrt{1 + \omega_o^2 \tau^2} \cos(\omega_o t - \phi') - e^{-t/\tau}]$$

where $\phi' = \tan^{-1}(\omega_o \tau)$, $\tau = L/R$, $\omega_o = 2\pi f$, and $f = 60$ Hz. The applied voltage is $V_o \cos \omega_o t$ for $t > 0$.





(a) SWITCH CLOSES AT PEAK OF VOLTAGE WAVE ($\phi = 0$)



(b) SWITCH CLOSES AT ZERO OF VOLTAGE WAVE ($\phi = -\pi/2$)

FIGURE 4 LATE-TIME TRANSIENTS ON SWITCHED POWER CIRCUIT

For a high-Q circuit, $\omega_o L/R = \omega_o \tau \gg 1$ and

$$i(t) \simeq \frac{V_o \sin \omega_o t}{\omega_o L} \qquad (t > 0) \quad ,$$

Thus, the phase of the current lags the voltage by 90° and the magnitude of the current is the ratio of the voltage to the inductive reactance. There are no transient effects because the switch was closed when a current zero would have occurred.

For a low-Q (non-inductive) circuit, $\omega_o L/R = \omega_o \tau \ll 1$ and

$$i(t) \simeq \frac{V_o}{R} \left[\cos \omega_o t - e^{-t/\tau}\right] \qquad (t > 0) \quad ,$$

which contains an exponential transient in addition to the steady-state current. However, because of the condition $\omega_o \tau \ll 1$, $\tau \ll 1/\omega_o$, the transient vanishes during the first half-period of the 60 Hz wave as illustrated in Figure 4(a). There is no overshoot in the transient response.

If the switch closes when the 60 Hz voltage is zero, the current in the load is

$$i(t) = \frac{V_o}{R(1 + \omega_o^2 t^2)} \left[\omega_o \tau e^{-t/\tau} + \sqrt{1 + \omega_o^2 \tau^2} \cos(\omega_o t + \pi + \phi'')\right] \qquad (t > 0),$$

where $\phi'' = \tan^{-1}(1/\omega_o \tau)$. For a low-Q load impedance ($\omega_o \tau = Q = \omega_o L/R \ll 1$),

$$i(t) \simeq \frac{V_o \sin(\omega_o t)}{R} \qquad (t > 0)$$

and no transient is produced because the voltage and current are in phase for a resistive load. For an inductive load impedance, however, the current has a significant transient represented by the exponential term in

$$i(t) = \frac{V_o}{\omega_o L} [e^{-t/\tau} - \cos \omega_o t] \qquad (t > 0) \quad .$$

Since $\omega_o \tau \gg 1$ for this case, the time constant τ may be many periods of the 60 Hz wave. As illustrated in Figure 4(b) for $\omega_o \tau = 10$, the current in the inductive load displays a large overshoot (~75% for $\omega_o \tau = 10$) and has not subsided after three periods of the 60 Hz wave. For very inductive circuits, the transient peak current can approach twice the steady-state peak current and the transient can last for many periods.

The current spectra for each of the switch closing points and for several time constants are shown in Figures 5 and 6. In either case the current magnitude decreases very rapidly above the line frequency (e.g., 60 Hz).

IV. INDUCTIVE LOADS

Many appliances and devices that have primarily inductive impedances are found within typical facilities. Some examples are motors, relays, and solenoid-actuated devices (valves, time-clocks, vending machines, etc.). When such devices are energized, the current behaves as described in the preceding sections. When the switch is opened, however, the intermediate and late-time transients may be quite different from the switch-closing transients.

When the switch opens the circuit containing the inductive load, there is a voltage Ldi/dt developed across the inductive device by the collapse of the current (di/dt). This "inductive kick", as it is sometimes called, can be quite large if the inductance is large and the switch opening-time is short. While the transient voltage produced by

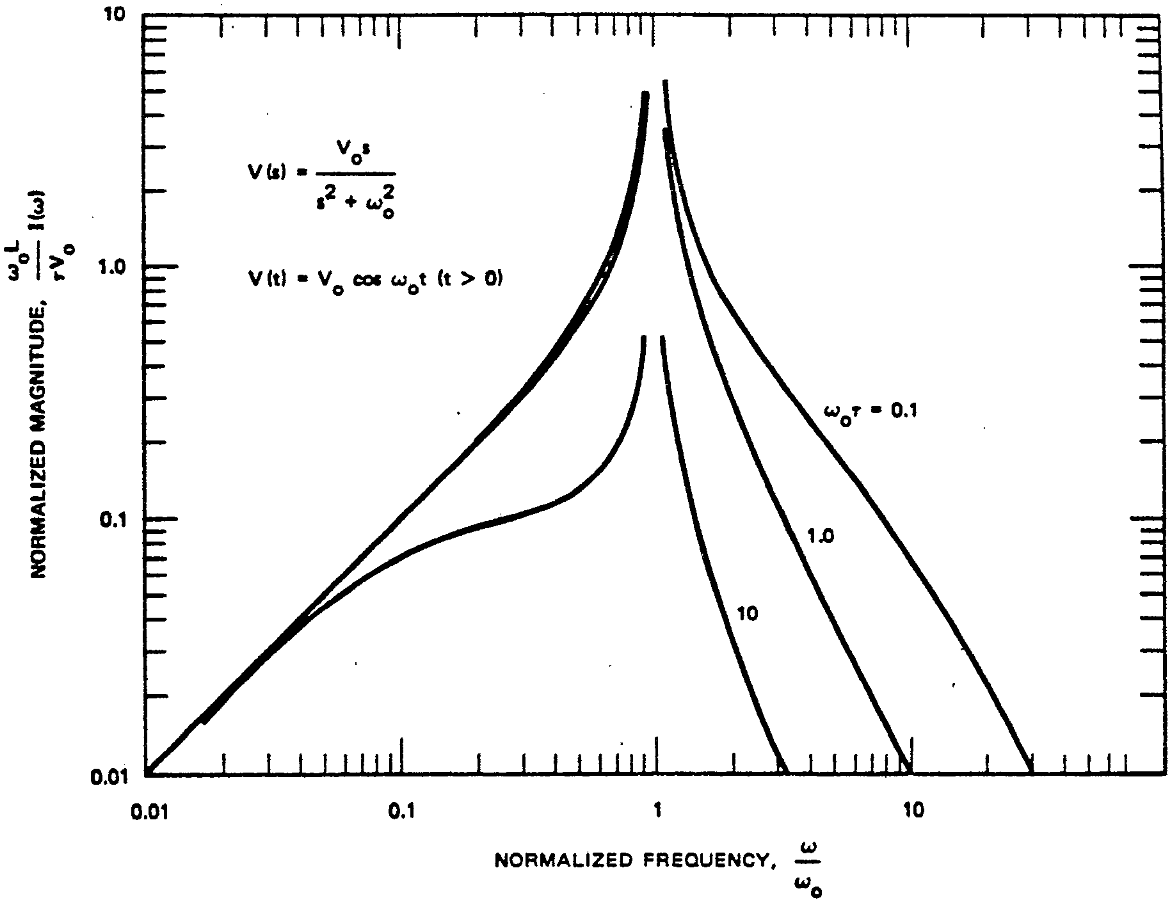


FIGURE 5 SPECTRUM OF LATE-TIME TRANSIENTS WHEN VOLTAGE IS SWITCHED AT PEAK

closing a switch seldom exceeds the supply voltage (unless there is sufficient capacitance to cause resonances), opening the switch in a relay or solenoid circuit can produce voltages many times the size of the supply voltage.

The analysis of the switch opening is much less exact than that of the switch closing because the phenomena that determine di/dt during the switch arcing and arc extinguishing are nonlinear and not thoroughly understood. Nevertheless, an important difference between contact closing and opening can be identified. During closing, the maximum voltage between the contacts is the line voltage, and this voltage is not sufficient to ionize the air between the contacts until immediately before physical contact is made. The current build up and the Ldi/dt

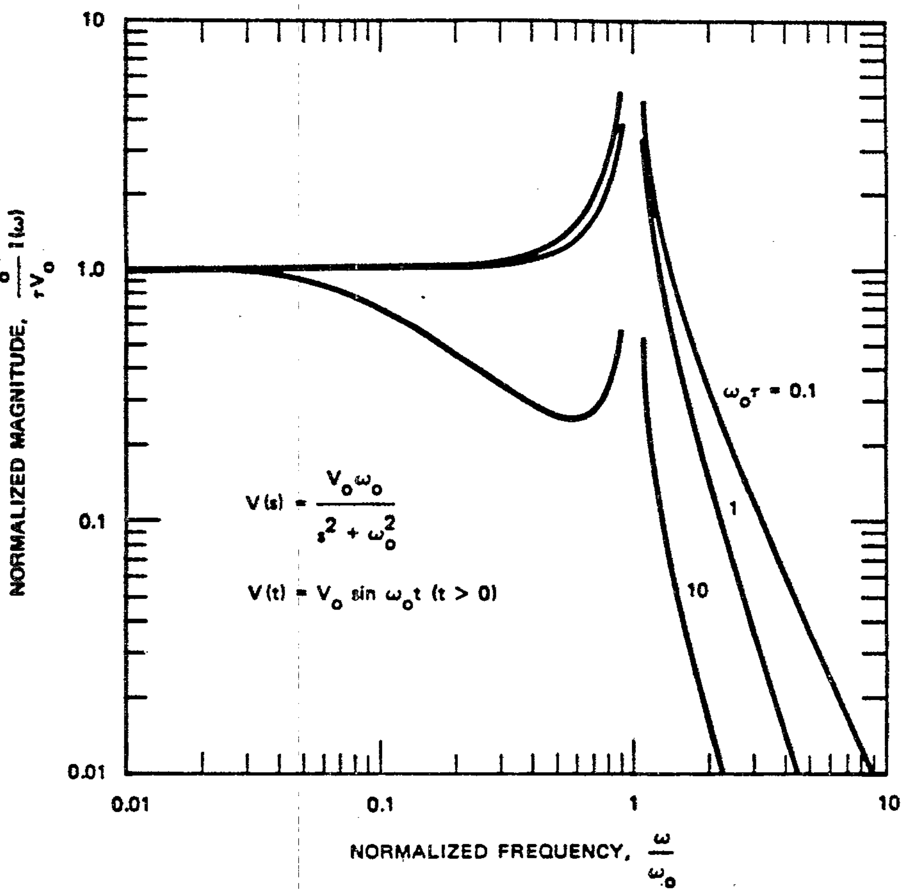


FIGURE 6 SPECTRUM OF LATE-TIME TRANSIENTS WHEN VOLTAGE IS SWITCHED AT ZERO

voltages are determined mostly by the linear circuit resistance and inductance, as has been assumed in the intermediate- and late-time analyses.

During contact opening, however, the current tends towards zero when physical contact breaks, but this produces an Ldi/dt voltage across the contacts which ionizes the space between the contacts and allows current to continue through the arc. As the contacts separate the arc length increases and its resistance increases somewhat (but not in proportion to its length). The arc is sustained by the Ldi/dt voltage (part of which is dropped across the circuit resistance). This voltage is sufficient to sustain the arc only as long as the current is decreasing ($di/dt \neq 0$). Eventually the current goes to zero and the arc extinguishes completely. This sequence of events[1] is illustrated in Figure 7. Thus, the effective switch opening time is not zero, but it may be much shorter than the time constant L/R of the circuit because of the addition of the nonlinear resistance of the arc.

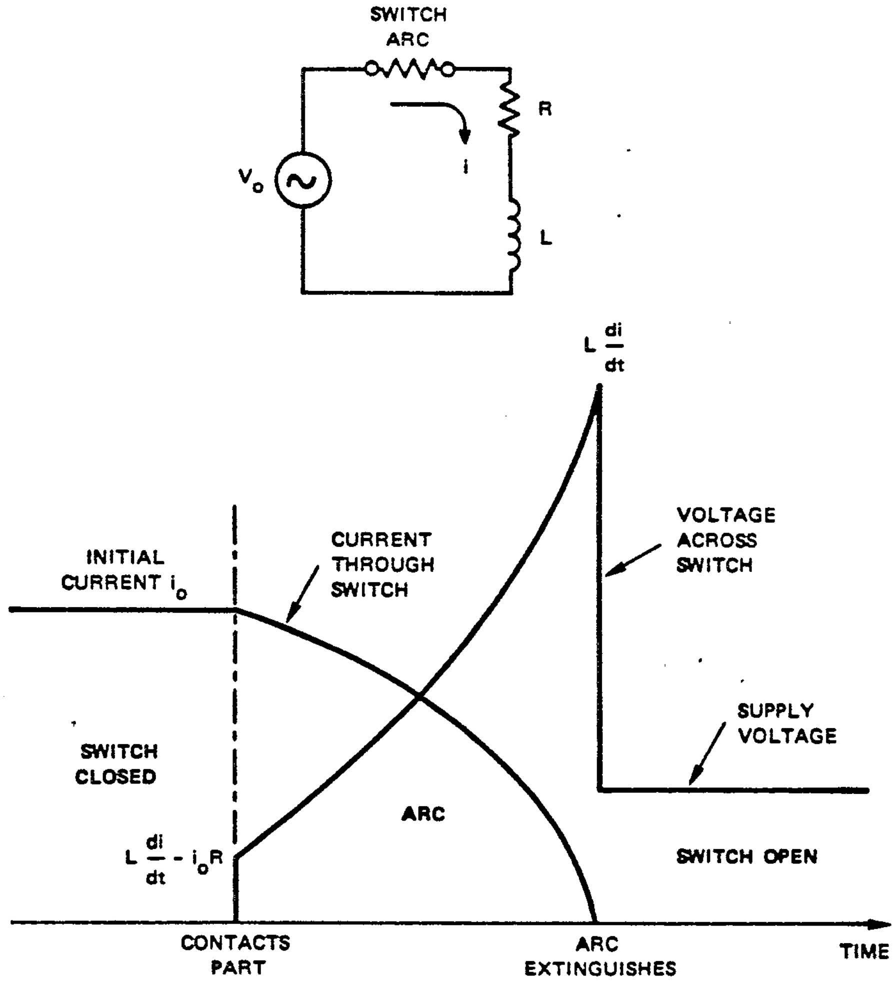


FIGURE 7 TRANSIENT PRODUCED BY OPENING AN INDUCTIVE CIRCUIT

From such inductive devices, transient voltages of several hundred to a few thousand volts can be induced on 120 V power conductors. In principle, these transients are generated on the circuits being disconnected and are not delivered to the remainder of the power distribution system. However, because the switched circuit wiring may share the same conduits and gutters with other circuits, the transient frequently finds its way to other parts of the facility.

V. LIGHTING LOADS

Incandescent lamps with tungsten filaments draw much larger initial currents than their equilibrium operating currents. The operating temperature for tungsten filaments is usually 2500 °C or greater and at this temperature the resistance of the filament is 10 to 15 times its resistance at room temperature. The time required to reach 90% of the steady-state operating temperature is tens to hundreds of milliseconds -- a few to several periods of the 60 Hz wave. Filament resistance, temperature, and current calculated for 120 Vdc applied across the filament (assuming no heat losses) are shown in Figure 8.

Although the current rise time is assumed to be zero in Figure 8, the early-time phenomena discussed above will occur during the nanosecond region, and the series inductance of typical wiring may cause the current rise time to be a few microseconds or longer. The peak current observed in a typical installation may therefore be somewhat smaller than that shown for zero rise time.

Fluorescent lights, which are low-pressure mercury arc tubes, produce distortion of the current during normal operation. Because the low-pressure arc tube is a nonlinear device that virtually extinguishes and restrikes each half-period of the power frequency, the current through the tube resembles the current through a gas tube full-wave rectier. Crude RFI suppression is provided in some fluorescent light ballasts with capacitors across the tube. The interference produced by operation of the fluorescent lamps is rich in the harmonics of the ac power supply frequency. Starting fluorescent lamps causes transients in the voltage across the tube, but the starting currents are modest.

VI. RECTIFIERS

Facilities requiring large quantities of dc power and facilities using "uninterruptible power systems" contain polyphase rectifiers that frequently produce interference rich in the harmonics of the ac supply

TUNGSTEN FILAMENT

Resistivity at 20°C:	$5.6 \times 10^{-6}\ \Omega$ cm
Temperature coefficient of resistivity:	$0.0045\ (^\circ C)^{-1}$
Specific heat:	0.035 cal/g°C
Specific gravity:	19
Length:	5 cm

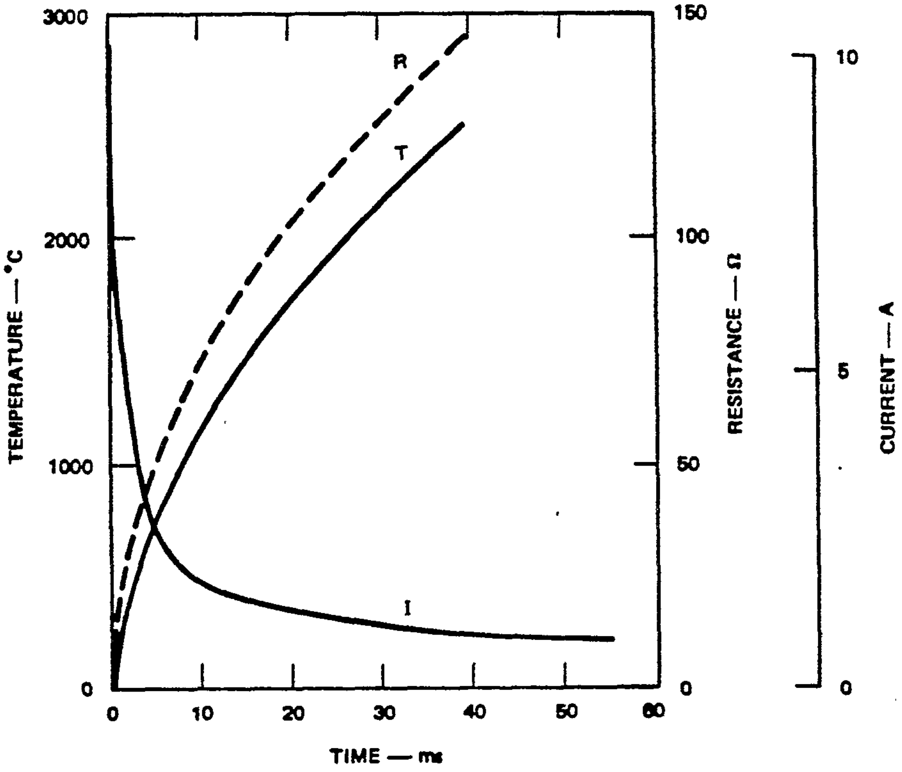


FIGURE 8 APPROXIMATE FILAMENT RESISTANCE R, TEMPERATURE T, AND CURRENT I WHEN A 100 W INCANDESCENT LAMP IS TURNED ON

frequency. As with fluorescent lights, this noise is continuously present.

The dc output of the rectifier is often filtered so that it is not a source of interference to the dc equipment. However, the rectifier also produces interference on the ac supply because of the nonlinear behavior of the rectifier. The ac supply lines may also be filtered if the rectifier causes malfunctions in other equipment. Frequently, however, the rectifier transformer provides sufficient isolation so that malfunctions in associated equipment are avoided. In spite of this, the ambient noise delivered to the power mains may be quite large.

VII. MISCELLANEOUS SOURCES OF INTERFERENCE

There are, of course, many other sources of interference inside a facility. Doorbells, buzzers, copying machines, electrostatic discharges, welders, etc. all contribute to the noise environment inside a facility. In the hospital environment, diathermy machines are notorious sources of interference. In communication facilities, high power transmitters and modulators are often the source of large interference signals. In areas where moving belts, dust, or aerosols can produce charge separaton, large electrostatic discharges can occur. Vehicle ignition systems produce similar high-voltage, moderate energy discharges that interfere with electronic circuits.

Aside from the electrostatic discharges, which are often unpredictable, and the high power RF sources, which are usually known and may even be shielded, these sources are usually smaller in peak value than the switching transients described above. Therefore, the peak voltages and currents normally encountered in a facility will be determined by these switching transients and will normally be proportional to the supply voltage. That is, the switching transients in a 240 V system will be roughly twice as large as those in a 120 V system.

The fluorescent lights, rectifiers, and the multitude of miscellaneous sources contribute to the ambient broadband noise that exists long after transients from the energizing of individual circuits or the de-energizing of solenoids have disappeared. This background noise is not ordinarily capable of damaging equipment, but because it is a factor in determining the signal-to-noise ratio on equipment signal lines, it may affect the performance of the equipment.

VIII. DISTRIBUTION OF TRANSIENTS

The transients associated with switching ac or dc power are generated on the power wiring and can propagate throughout the power system to all equipment supplied from the switched power system. That is, transients of the type illustrated in Figures 1 through 4, modified by the transmission properties of the wiring, may be seen at the power terminals of any equipment in the facility. Experienced equipment designers are aware of this and routinely install filters on the incoming power leads. Thus, transients do not usually affect commercial equipment, but occasionally equipment designed by the inexperienced is found to malfunction.

A more subtle and insidious path for these transients to enter the equipment is on the signal and control wiring. Because the transient currents and voltages induced on the power wiring possess large derivatives, they are easily coupled to nearby signal and control wiring through mutual capacitance (Cdv/dt) and mutual inductance (Mdi/dt), as illustrated in Figure 9. Thus, signal wiring routed in the same cable tray or in the same bundle as the power wiring will be exposed to this derivative coupling. Note that since the time domain operators d/dt transform to jω in the frequency domain, the high-frequency interference spectrum is emphasized by the mutual coupling process -- regardless of the equipment operating frequencies.

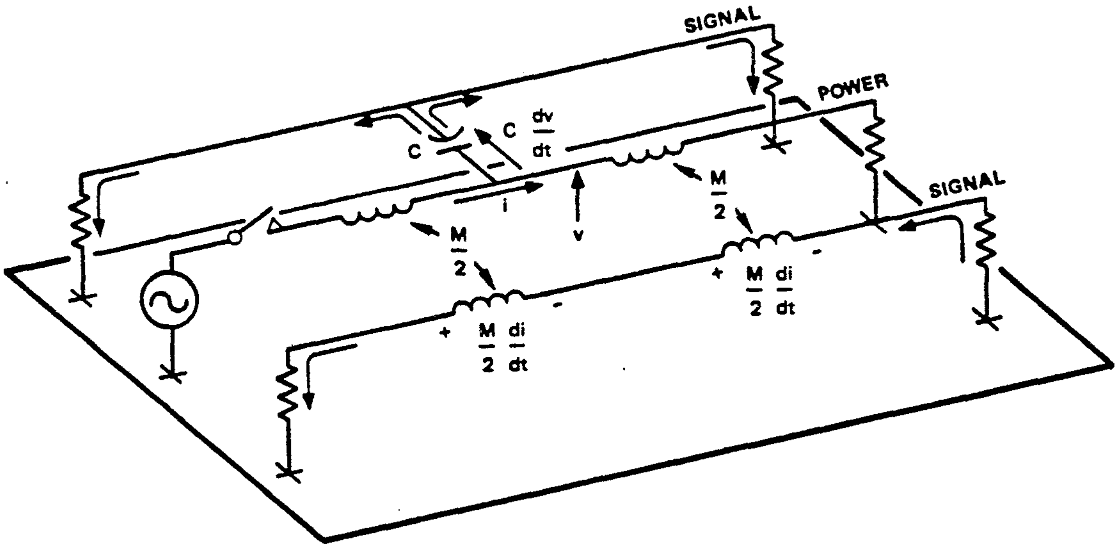


FIGURE 9 MUTUAL COUPLING BETWEEN POWER WIRING AND ADJACENT SIGNAL WIRING

The mutual coupling can be reduced by keeping power wiring separate from signal wiring, by shielding the signal wiring (but only with closed shields), and by using balanced twisted pairs and common-mode rejection for signal wiring and/or power wiring as well as traditional filtering and other after-coupling treatments. Experienced designers use these techniques generously to control "crosstalk" between the power and signal circuits.

Another subtle path by which the interference may enter the electronic circuits is through an ill-conceived grounding system. This mechanism is illustrated in Figure 10, where a commonly-used perversion of the single-point grounding system serves as an interference distribution system. The transient produced by switching the circuit on the left of Figure 10 propagates in the transmission line mode between the black and white wires. As indicated by the arrows and dotted lines, a portion of the transient propagates onto the "signal reference" conductor which has been (unnecessarily) installed to "ground" the electronic circuits in the equipment on the right. Although the conductor serves no useful purpose, it does provide a path for interference to propagate virtually unattenuated from the ground point G into the electronic circuit inside the equipment cabinet[2] W This grounding conductor violates the closed barrier topology; it must be eliminated or treated in some manner so that the barrier is preserved. (However, since this grounding conductor serves no useful purpose, installing it, then treating it to make it acceptable, adds cost but no benefit).

These three modes of distribution -- propagation on power conductors, propagation on grounding conductors, and mutual coupling to signal conductors -- usually dominate internal interference distribution processes. Other processes that are usually much weaker than these also occur and in special cases may be significant. Thus, for example, the interference current propagating on the green wire or on power wires that are treated at the equipment entry flows onto the equipment case and through its mounting hardware to structural metal. Such

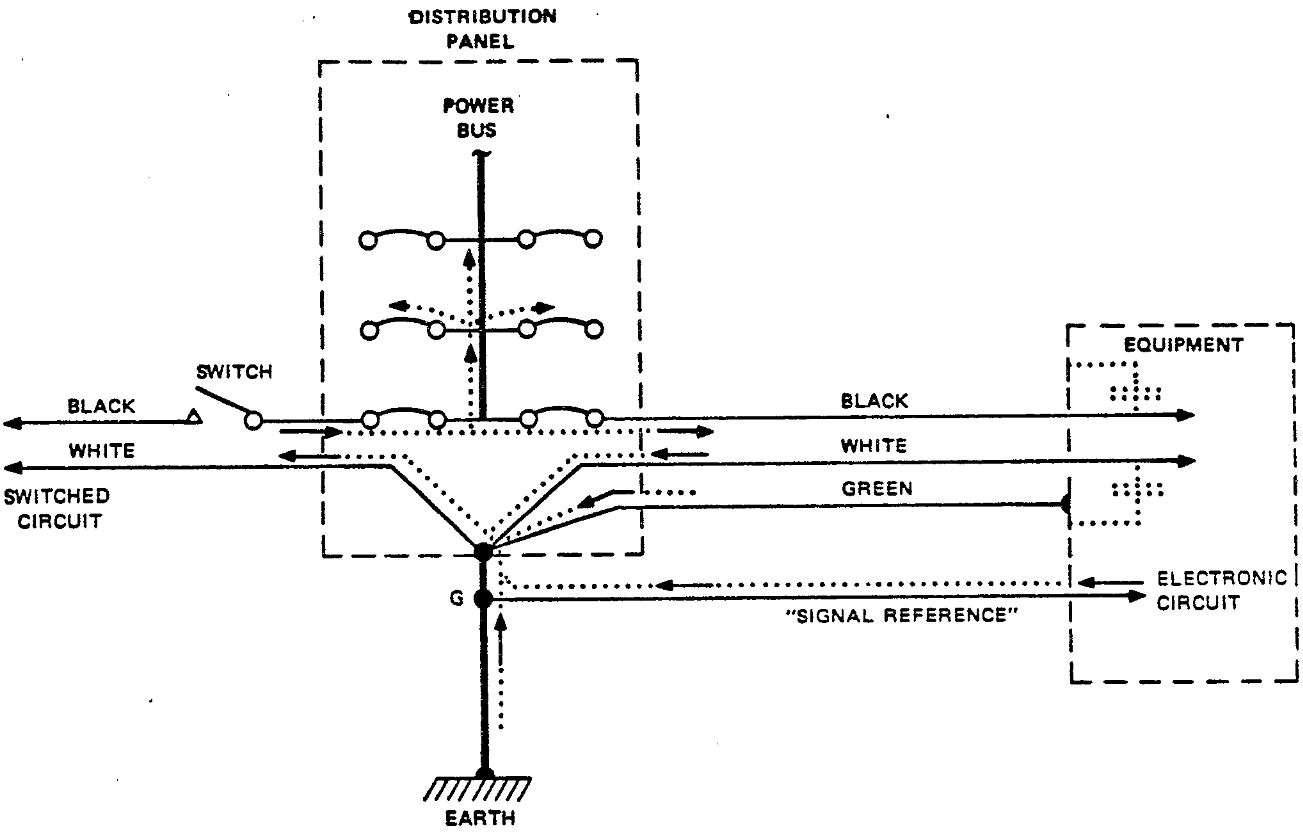


FIGURE 10 INTERFERENCE DISTRIBUTION THROUGH AN ILL-CONCEIVED GROUNDING SYSTEM

currents may interact with internal circuits through apertures in the equipment shield.

In addition, although most of the transient energy inside a facility is propagated along the conductors, some will be radiated from the source. This radiated transient energy propagates from the source and is reflected from the walls and other equipment; it can be received by any conductor exposed to the radiated field. While this mechanism is often credited with being an important interaction mechanism ß it is doubtful that it is comparable to propagation along conductors--directly or after inductive coupling through mutual capacitance and inductance--except perhaps at microwave frequencies.

IX. CONCLUSIONS

Transient voltages having peak values comparable to the peak ac supply voltage will occur routinely inside a facility as a result of electric circuit switching and cyclic equipment regulation (air conditioners, water heater, etc.). Much larger transients, perhaps up to 10 times the peak supply voltage, may occur if untreated relays, solenoids, or other inductive loads, in the facility are switched. Transient peak currents 1 to 10 times the steady-state load currents of the facility appliances may occur from routine operation of these appliances.

These currents and voltages are characterized by very fast rise times; hence, they contain energy throughout the 0 to 100 MHz spectrum in which interference propagation along wires and cables is efficient. In the high-frequency portion of this spectrum, inductive coupling between power wiring and signal and control wiring is also efficient. Therefore, it is believed that this interference will be manifested primarily as currents and voltages on cabling inside the first-level barrier.

In addition to these transients that occur at least several times per day, there are lower-level, but more or less continuous, sources of interference such as fluorescent lights and rectifiers. Interference from these sources affects the signal-to-noise ratio on the signal conductors, but it is not usually a factor in determining the barrier effectiveness required to control externally produced transients such as the EMP and lightning.

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3. H. W. Ott, Noise Reduction Techniques for Electronic Systems, (John Wiley and Sons, New York, 1976).