TRANSIENTS CAUSED BY INDUCTIVE LOADS

Definition of a Transient

Webster's Dictionary defines a transient as something "passing quickly into and out of existence". This definition is applicable for momentary electromagnetic transients which are the subject of this paper. The transient suddenly appears, seemingly lasts only a moment, and then is gone. Their peak amplitudes can be very small, or can be measured in the thousands of volts. A bolt of lightning, which is a sudden static discharge, is a transient.

An electrical engineer will define transient terms as physical quantities necessary to preserve the dynamic equilibrium expressed by Kirchhoff's potential laws, during the period of transition from one mode of circuit operation to another. This is due to the fact that the current in any inductance and the potential of any capacitance cannot change instantaneously. Kirchhoff's potential laws for a circuit composed of constant series parameters are as follows:

$$e = L\frac{di}{dt} + Ri + \frac{1}{C}\int i\,dt \qquad (1)$$

or

$$e = L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{c} \qquad (2)$$

As an example, consider the simple case of a battery, perfect switch, and an inductor as shown in figure 1.

For this example, it is assumed that the inductor has a small resistance R which limits the DC current in the steady state condition while the switch is closed. It is also assumed that the inter-winding capacitance of the inductor is negligible. The instant the switch is opened, the current very rapidly decreases and a large negative di/dt is created thus a transient. This can be expressed as:

$$e = -L\frac{di}{dt} + Ri \qquad (3)$$

Actual measurements of a circuit as shown in figure 1, (using a 28 volt power supply, toggle switch, and a relay inductor with 243 ohms resistance) showed the generation of a negative transient with a peak value exceeding 1000 volts.

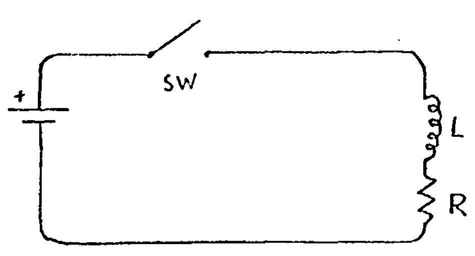


Fig. 1 TYPICAL RL CIRCUIT

Harmful Effects of Transients

If the transient were completely contained at its source, (i.e. at the relay) the harmful effects of the high voltage spike would be limited. However, the transient has many means of propagation and can be measured at remote points throughout a system.

Active solid state components can readily be damaged by unwanted transients. Diodes and transistors which have rated peak-inverse voltage ratings less than the peak value of the transient will go into the avalanche condition and/or will be burned out. Meters can be damaged after being pegged. Digital and analog systems are especially susceptible to transients since the spike may be interpreted as a digital pulse. Computers' registers have been known to shift due to the transient from the cycling of air conditioners. The many undesirable effects which result from transients, are too vast in number to be presented in this article.

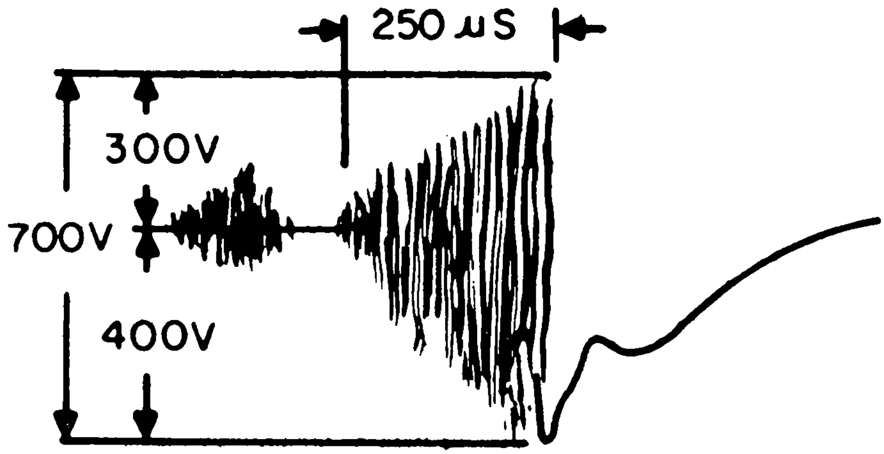
Cause of Switching Transients (Theory and Varying Parameters)

A period of time is required for the transition of a practical circuit from one mode of operation to another. This transitional period is known as the transient period. The transient period serves as a "shock absorber" to dispose gradually of the initial discrepancy between the actual values of circuit variables and the values of those variables called for by the steady state.

The primary source of DC switching transients is the electrical characteristics of the load being switched. Switching power to a discharged capacitive load results in a high current surge for the period of time required to charge the capacitive component of the load. Interrupting power to an energized inductive load results in a high voltage surge since the inductive component of the load tends to resist any change in current. Voltage and current surges, which result due to switching of inductive or capacitive loads, are prime generators of transients and broadband electromagnetic radiation.

Complications result when an A.C. potential, which is in no way synchronized with the switching action, is applied or removed from across the load. It is possible for a mechanical or electronic switching device to switch power from an A.C. line while the voltage is at any level between zero and peak line voltage.

A secondary source of transients is the characteristic of the device which accomplishes the switching action. For instance, instead of an instantaneous opening or closing of a mechanical switching device when the load is inductive a slow opening and chattering closure is normally realized even with the most sophisticated mechanical devices. The relatively slow separation of contacts is due to their mechanical inertia which must be overcome by an actuating device. As the contacts begin to separate, they induce the formation of an electrical arc through the initially small air gap. Once the arc has been initiated it will continue to exist for larger arc lengths due to the breakdown and ionization of the air between the contacts. This arc is supported by the high -L di/dt formed by stopping the current flow through the inductive load.



(b)

Figure 2: Arcing Across a Toggle Switch

Figure 2 is a sketch of an oscilloscope display of the arcing occurring across a toggle switch while it was being opened and breaking the DC current to an inductive load.

A small amount of oscillation (ringing) can be expected when the load being switched on and off is a relay, coaxial switch, or a similar inductive device. This is due to the resonant configuration of the inductance of the coil, its distributed interwinding capacitance, and wire resistance. This can be represented in the configuration shown in figure 3.

The configuration in figure 3 can be redrawn as shown in figure 4.

Where

R_L = wire resistance

L = inductance of winding

C = interwinding capacitance

R_C = capacitive resistance (very small)

Parallel Impedance = $Z = \left[\dfrac{R^2 + w^2L^2}{(1-wLC) - wCR}\right]^{\frac{1}{2}}$ (4)

Parallel Resonance = $f_{p.r.} = \frac{1}{2}\pi\sqrt{LC}\sqrt{1 - \frac{C}{L}R_c^2}$ (5)

The circuit Q = $\dfrac{wL}{R_L}$ where $w = 2\pi f$ (6)

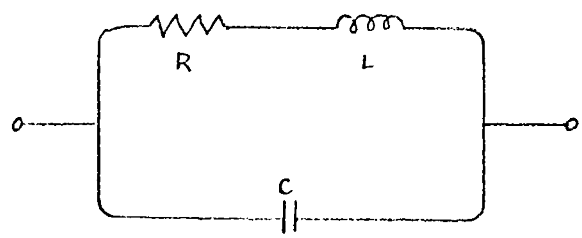


Fig. 4 Simplified Equivalent Circuit of a Coil

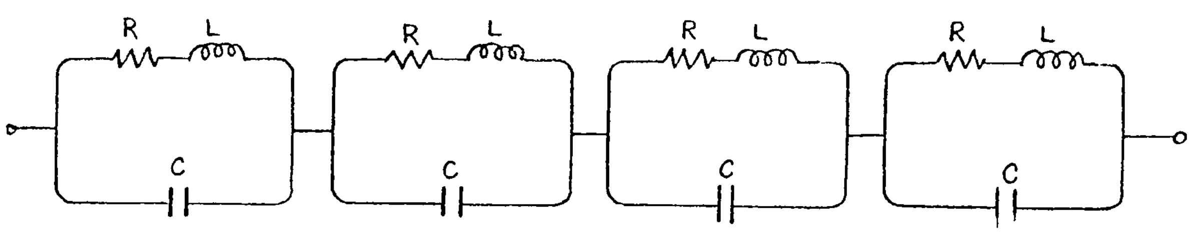


Figure 3: Equivalent Circuit of a Coil

Under steady state conditions with the DC voltage applied to the equivalent circuit of the relay, the capacitance is charged and represents an open circuit, the inductance has established a magnetic field and represents a short, and the resistance provides the load and path for the steady state current flow. When the voltage is removed, we have a charged series R-L-C circuit (neglecting R_C) and the condition for dynamic equilibrium is found to be:

$$E = L\frac{di}{dt} + Ri + \frac{1}{c}\int idt \qquad (7)$$

Differentiating we have

$$0 = L\frac{d^2i}{di} + R\frac{di}{dt} + \frac{i}{c} \qquad (8)$$

Equation 8 is a second order differential equation. The auxiliary equation is

$$m^2 + \frac{R}{L}m + \frac{1}{LC} = 0 \qquad (9)$$

The solution of this quadratic equation is

$$m = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \qquad (10)$$

Following the straightforward application of differential equations, the general expression for current flow in the RLC circuit in which a direct voltage has suddenly been removed, neglecting the steady state current, is

$$i = \frac{q_o}{\sqrt{R^2C^2 - 4LC}}\left[e^{(-a+b)t} - e^{(-a-b)t}\right]$$

$$\text{where } a = \frac{R}{2L}$$

$$b = \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

q = charge of the capacitance

The interwinding capacitance of a relay is very small compared to the resistance and inductance ($R^2/4L^2 \quad 1/LC$) and therefore the circuit is in an underdamped (oscillator) condition. Thus, the ringing occurs when the capacitance is being discharged through the series R-L parameters.

Measuring Transients

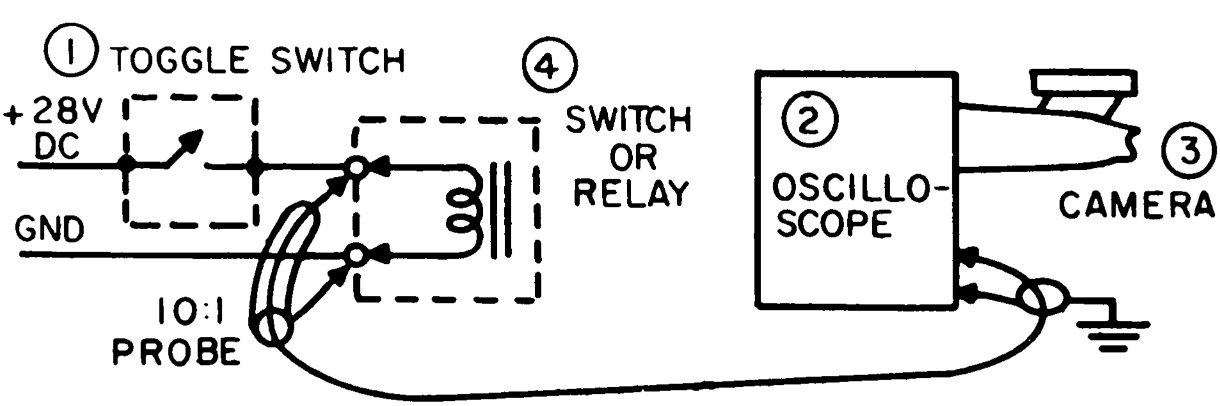
One of the simplest methods of measuring transients is with an oscilloscope. A simple test set-up used to make the photographs is shown in figure 5. There are many other techniques which can be employed. For instance, when making transient measurements in accordance with current Government interference control specifications, a tunable superhetrodyne receiver is used. The audio output from the receiver is monitored with a headset and the audio (slide-back) gain control adjusted until the occurrence of the transient is just audible. Then broadband noise from a calibrated impulse generator is fed into the receiver until the same level is obtained. The amplitude of the transient at the tuned frequency is thus measured in terms of db above one microvolt per megacycle band-width (dbmc) by reading the level from the impulse generator. The transient level is then plotted versus frequency on a semi-log graph as broadband noise.

Suppression Devices

There are two basic methods of protecting equipment and systems from the harmful effects of transients. One method is to protect the equipment and circuits which are susceptible, and the other is to prevent the transient from occurring or to contain it. Suppression devices are available for both purposes.

Conventional Filtering Techniques

A filter is an electrical circuit designed to have specific characteristics with respect to the transmission or attenuation of various frequencies that may be applied to it. Power and control lines normally require low-pass filters which will permit all frequencies below a specific frequency to be transmitted with little or no loss. In this manner low frequency control signals (DC to 400 cps) may be passed through the filter, while transients generated by the switching device will be eliminated since they are made of high harmonic frequency components.



1. CUTLER-HAMMER ST42A
2 FAIRCHILD 776H
3. H.P. 196A CAMERA
4. ITEM UNDER TEST

Fig. 5 Test Set-up used to Measure Coil Transients

Diodes Suppression

Diodes are most commonly used when transients generated by DC relays, switches, motors, etc., are to be suppressed. They are applied in the reverse polarity direction directly across the inductive winding terminals as shown in figure 6.

This technique is very effective in reducing the transient voltage

$$e = -L \frac{di}{dt}$$

since the negative voltage is shorted out by the diode. Not just any diode can be used in this application. The diode selected must have an adequate current rating, transient peak reverse voltage rating, fusing rating (i2t) etc.

For AC applications, back-to-back diodes are often used. They are rated conservatively above the peak line voltage. When a transient or voltage spike occurs which exceeds the reverse breakdown voltage of one of the diodes, the diode conducts. The second diode would then be biased in the forward direction thus providing a short across the inductive winding. The diodes continue to conduct until the voltage returns to a below the breakdown voltage. This method does not completely eliminate the transient, but does reduce its harmful amplitude.

Capacitor and RC Suppression

Capacitors can be placed across the inductive windings of a transient causing device to eliminate the transient. A resistor can also be added in series with the capacitor in order to damp the oscillations which may occur from a parallel tuned circuit. The use of a capacitor or RC combination is not very effective, since the capacitance must be large to pass the lower harmonic content of the transient. The large capacitance delays the switching action as well as draws a large amount of reactive current in AC applications.

Bifilar Windings

The use of a bifilar winding on a relay, for instance, is most effective in suppressing a transient. Bifilar winding, a type of shunt suppression, is accomplished by winding the coil bifilarly as defined in transformer terminology. Two wires are wound together, side by side, continuously throughout the coil thus forming two closely coupled coils of the same number of turns on one bobbin. The two ends of one of these coils are then connected, forming an effective shorted secondary transformer winding. The other coil then actuates the relay.

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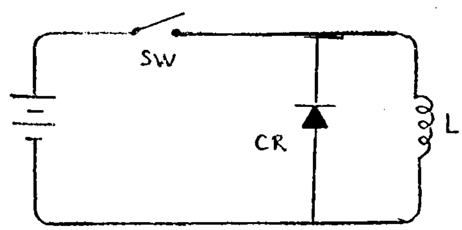

Fig. 6 Diode Suppression

TABLE 1

	RF Inductive Switch 240 ma	Electronic Switch 200 ma	Six Pole Relay 140 ma	Four Pole Relay 115 ma
ENERGIZE CYCLE				
Max Pk-Pk Transient	200v	200v	200v	200v
Frequency of Ringing	150KC	150KC	87KC	87KC
Switch Bounces	6	4	6	5
Time to Steady State	750μs	700μs	700μs	725μs
DE-ENERGIZE CYCLE				
Max Pk-Pk Transient	400v	450v	550v	600v
Frequency of Ringing	150KC	150KC	87KC	150KC
Duration of Transient	300μs	350μs	900μs	700μs
Time to Steady State	700μs	700μs	1000μs	850μs