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DC Circuit Switching Transients

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TITLE: DC Circuit Switching Transients.

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Overview: This course is intended to benefit engineers who design, use, inspect, or repair circuits that contain DC power sources and accompanying DC components. Application of DC circuits includes control, instrumentation, and motor excitation. Whereas both AC and DC circuits as well as transmission lines are susceptible to transient phenomena, DC components are particularly subjected to transients caused by current interruptions that routinely occur when circuits are de-energized. Simply closing and opening a switch, for example, can cause unintended radio-frequency interference and/or contact degradation. The course is intended for engineers who have knowledge of basic circuit theory and circuit components, such as resistors, capacitors, relays, contactors, and switches.

The course will cover circuit configurations and components typically encountered that become part of unintended transient phenomena. The course will include an overview of low-voltage arcing characteristics that become part of the transient response mechanism.

Specific Knowledge or Skill Attained:

1. Ability to recognize circuit configurations that harbor potential transient problems
2. Techniques for reducing or eliminating problem sources.
3. Ability to estimate available energy within transients
4. Ability to derive equivalent circuits to model first-order transient behavior

Introduction

Inductance is measure of the magnetic flux per unit of current contained in an electrical circuit or in an electrical component. If current is established then the associated magnetic field of the inductance is a form of stored energy that is often overlooked by circuit designers. Consequently, inductive energy causes unforeseen problems associated with signal noise and component degradation. The problems are particularly insidious in direct-current (DC) circuits where contacts or switches frequently open and close thereby interrupting current flow and thus causing induced voltage “spikes” or transients to generate contact arcs and high frequency interference.

While the results are not always catastrophic, transient arcing can cause progressive wear on contact surfaces that eventually fail to open (welded shut) or fail to close (material erosion). Since damage leading to failure may require many hundreds or thousands of opening-closing repetitions, product testing via a few satisfactory operating cycles does not, by any means, verify design. It is, therefore, important for engineers to recognize the potential for transient damage and to take adequate steps to eliminate or reduce transient effects in DC circuits. Alternating-current (AC) circuits are usually less prone to arcing and voltage transient problems since the very nature of AC causes the current – hence stored inductive energy – to pass through zero during each AC cycle. Relay and switch manufacturers recognize this difference and normally rate separate contact-current interruption limits for DC and AC currents, where the acceptable DC limit (Voltage &

Current) is less than that of AC. This course is designed to give the student a basic understanding of the mechanisms that cause transients, an appreciation of where to look for transient sources, and sufficient knowledge to remove or reduce transient problems in DC circuits.

Sections and Examples

1. Basic Inductive circuit
2. Switching current in an inductive circuit
3. Estimating Transient behavior
4. Transient suppression techniques
    a. Diode
    b. Voltage Regulator Devices: Metal Oxide Varistor (MOV); Transient Voltage Suppressor (TVS); Zener diode; etc….
    c. Resistors
    d. Capacitor
    e. Arc-resistant contacts
5. Distributed inductance: transient coupling & suppression between adjacent circuits
6. Real World (Non-Ideal) Components
7. Semiconductor Switches
8. Parameter Selection

1. Basic Inductive Circuit and Stored Magnetic Energy.

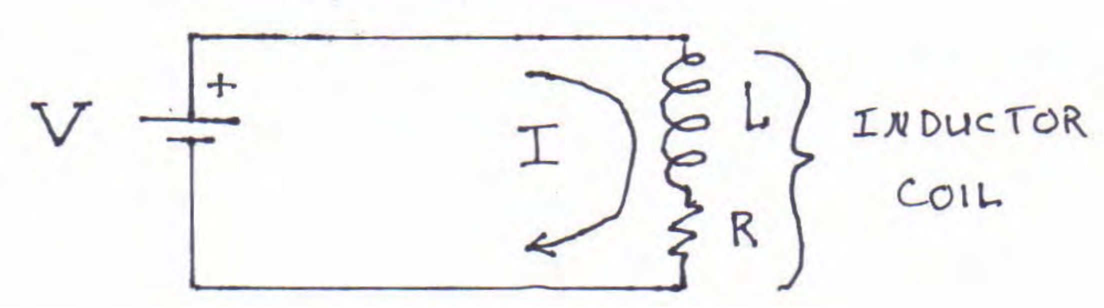

Figure 1-1
Equivalent Circuit Representation of Inductor in DC Circuit

For purposes of illustration, we first discuss a basic inductive circuit that employs a coil with an inductance L. Any device exhibiting inductance at the terminals, such as relays, contactors and DC motors are represented by the idealized inductor discussed here. As shown in Figure 1-1, a battery voltage (V) establishes a current (I) through an inductor (L) that has a winding resistance (R). As indicated in Figure 1-1, L and R represent the terminal equivalent of the coil. Steady-state current is then simply I = V/R. Since inductance is defined as "magnetic flux per unit current" (inductance = flux/current), current in the inductor creates a magnetic field that becomes a source of stored energy, where energy is proportional to inductance times current squared:

$$\text{Energy} = (1/2)*L*I^2 \qquad \text{Equ. 1-1}$$

Using the International System ("SI") of Units we have current in amperes (A), inductance in henries (H), flux in webers (Wb), and stored energy in joules (J). It is the stored inductive energy that often causes unintended consequences in DC circuits. According to Faraday's Law, a sudden circuit interruption causes stored magnetic energy to become a source of power that continues to drive current through the coil *including whatever external current path that exists at the instant of interruption*: the coil will generate enough voltage to instantaneously maintain current through the interruption path. If necessary, the coil generates sufficient voltage to create an arc across the gap of the opening circuit! Of course power supplied from the coil is limited by the initial stored energy and the current will quickly decline as the stored energy is depleted.

To appreciate the potential effects of energy dissipation when inductive current is interrupted consider the following example:

Given an inductance of 0.1 H, such as might be found in a relay coil, and a 0.2 A coil current, we have:

$$\text{Stored energy} = (1/2)*(.1)*(.2^2) = .002\ \text{J} \qquad \text{Equ 1-2}$$

To illustrate assume that stored energy is dissipated at a uniform rate over a period of, say, one millisecond, then the rate of energy transfer, or power in watts = Joules/second = .002/.001 = 2 Watts. If the same stored energy is dissipated in 1 microsecond then power = 2000 W or 2 kW!! Of course the total energy dissipated is the same in each case, but the consequences can be dramatically different since a high rate of dissipation in a concentrated area can damage material in that locale. The question we will address is "where does the energy go when the current is interrupted?" Later we will discuss several techniques for controlling the dissipation by providing alternate paths and components where energy can be absorbed without attendant damage.

2. Switching Current in an Inductive Circuit.

Now consider an inductive circuit similar to that of figure 1-1, but with a practical way of turning the circuit "ON" an "OFF": a switch connected in series with the inductor as shown in figure 2-1. In this example the switch is ideal – contact resistance zero and there is no bounce upon closing. ("Bounce" refers to a rapid closing and opening sequence that often characterizes mechanical contact closure. Later, in Section 6, we will discuss non-ideal contact behavior). Also we are using the term "switch" as a general means of opening and closing a circuit branch: clearly "switch" includes manually actuated devices as well as contacts on a control relay or contactor. In the following discussion we do not make the distinction as to how the switch is activated since the key point is that a set of contacts is provided for initiating and then interrupting current. Solid-state semiconductor switches such as Field Effect Transistors (FETs) are briefly discussed later in Section 6.

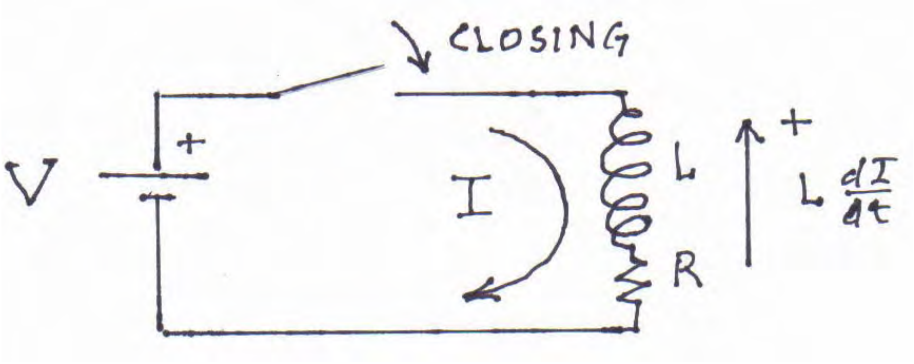

Figure 2-1
Circuit Representation of Switch Control

When the switch closes, current (initially zero) increases smoothly according to the differential equation describing voltage sums around the circuit branch:

V = I*R + L*(dI/dt) Equ 2-1

where "induced voltage" on the inductor is proportional to the rate of change of current (dI/dt). Note that polarity of the inductive voltage as defined in Figure 2-1 is positive when the rate of change of current through the coil is positive. Mathematically L*(dI/dt) > 0 when the current is increasing (dI/dt positive).

The solution of the differential equation is:

I = (V/R)* {1-exp [t/(L/R)]}, Equ 2-2

where the time constant (L/R) characterizes the rate of current growth.

The corresponding curve of current growth is given in figure 2-2 for V = 24 volts, L = .01 H, and R = 48 ohms. The time constant L/R equals 208 microseconds. Current reaches steady state (24 V / 48 Ohms = 0.5 A) in approximately three time constants, or 600 microseconds.

[NOTE: Curves shown in figures are generated in Excel using finite-difference approximations of circuit equations].

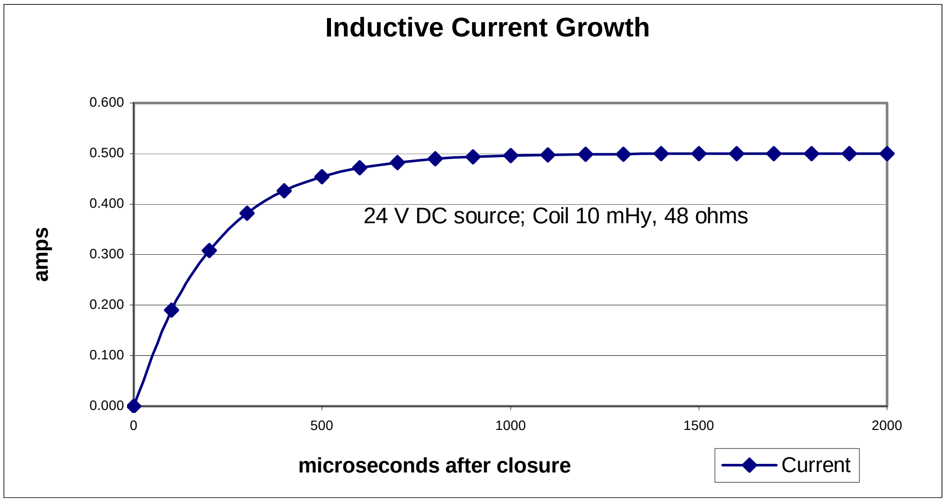

Figure 2-2
Current Growth After Switch Closing in Inductive Circuit

Now the question we are interested in answering is " what happens to the current and stored inductive energy when we open the switch?" To begin with we know from the Conservation of Energy that energy stored in the inductor cannot simply disappear, it must be dissipated by, stored in, or radiated from the connected circuit. We also know that according to Faraday's Law the induced voltage generated across the inductor, given by L*(dI/dt), reverses direction and becomes negative when the current collapses: mathematically, dI/dt becomes negative when current decreases thereby changing polarity of the induced voltage as illustrated in figure 2-3.

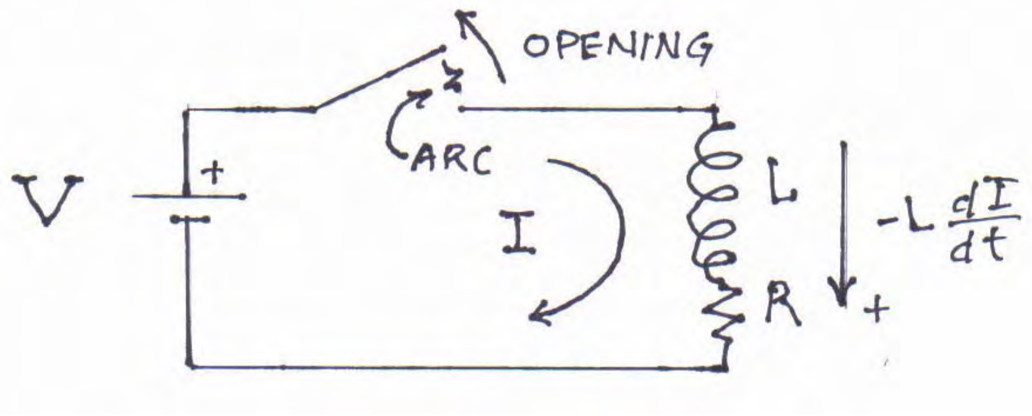

Figure 2-3
Representation of Switch Opening in Inductive Circuit

Note that a negative voltage generated across the inductor adds to the battery voltage, and we can think of the inductor as becoming a temporary (transient) voltage source that acts to maintain current through the switch opening as illustrated in figure 2-4.

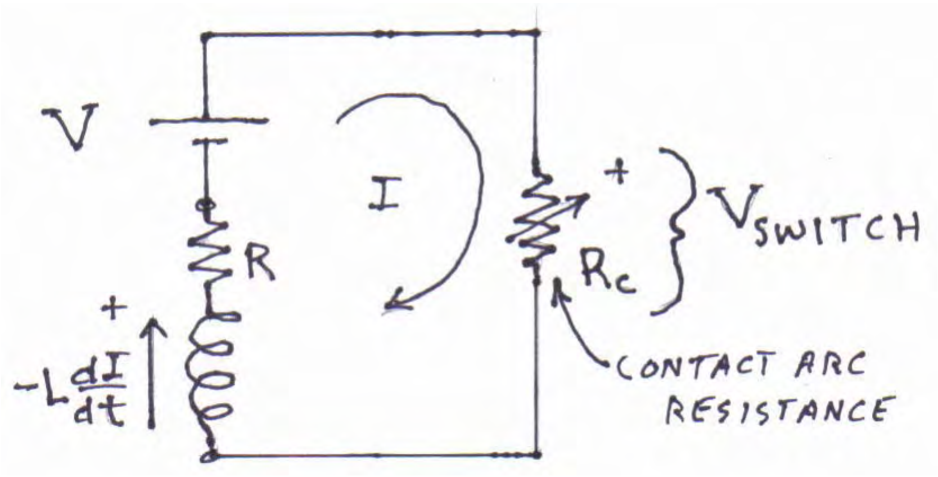

Figure 2-4
Equivalent Circuit Including Switch Arc

As described below, an arc forms between the opening contacts of the switch, thereby providing a current path for the decaying current.

3. Estimating Transient Behavior

Using the equivalent circuit shown in figure 2-4 we are now in a position to estimate the characteristics of the circuit voltages created by current collapsing within the inductor: The basic equation governing current after the switch opens is:

$$\text{Vbatt} + L*(-\,dI/dt) - I*R = \text{Vswitch} \qquad \text{Equ. 3-1}$$

Since the current is *decreasing* after the switch opens, the net effect is a *positive* inductor voltage in series with the battery as illustrated in Figure 2-4. The solution to this equation depends upon the characteristics of the switch voltage, which in turn depends upon the current. Basically we cannot solve the equation unless we know something about what is happening between the switch contacts!! So let’s take a closer look at what is happening there.

Imagine the instant at which the metal contacts are parting and the current is constrained physically to fewer and fewer contact spots as the moving surface accelerates until one tiny spot remains thru which all current must flow. Localized heating caused by current concentration in the contact resistance will vaporize metal from the surface and provide a continuous path for current to continue to flow just after the contacts have physically separated. Basically a low-voltage arc is formed when an inductive circuit is interrupted and it is this arc that causes contact degradation and leads to such diverse failures such as burned-out or welded contacts. Additionally, the transient current “spike” can generate radio frequency interference (RFI) depending upon pulse duration, circuit-wiring topology, and proximity to susceptible devices or circuits.

While the exact nature of the arc is difficult to model, we can use several approximations to help us understand the phenomena that occur as the switch opens, and it is helpful to realize that the voltage necessary to maintain an arc tends to increase as the contacts separate and the arc stretches between the contact surfaces. Since the arc voltage is powered by collapsing inductive energy, the rate of collapse is accelerated as the contacts move apart and the voltage demands of the arc continue to increase. In addition to contact separation rate, arc characteristics generally depend upon several parameters, including:

a.) Magnitude of parting current
b.) Inductance (hence stored magnetic energy feeding the arc current)
c.) Contact material – specific metals and metallic alloys exhibit unique arc characteristics
d.) Contact environment such as surrounding gases, contamination, humidity, temperature, ect.

Since our goal is to control transient currents created within inductive switching circuits, it is not necessary to create accurate models of arcing in order to gain an appreciation for and an understanding of the underlying mechanisms of inductive energy collapse. Several examples described below illustrate the nature of the transient characteristics that we are dealing with. In each of these examples we have idealized the contact phenomena to a simple “initial” voltage establishing the arc along with a variable resistance characteristic representing arc extension as the contacts separate. Again, for our purposes, the details of the characteristics are not important; what is important is the *transfer of stored magnetic energy from the inductor to the circuit – including the interruption switch - in which the current had been established prior to the switch opening*.

Example I: Opening contact resistance results in a 30 V initial arc voltage; arc resistance increases at 1,000 ohms per millisecond as contacts continue to open. As shown in figure 3-1 the contact voltage peaks at 47 V and the inductance current decays to zero in approximately 180 microseconds. Arc power (see figure 3-2) peaks at 17 W about 25 microseconds after contacts part. Note from figure 3-3 how instantaneous values of (dI/dt) adjust to match circuit conditions. For example if we account for voltage drops around the circuit at the instant of switch opening we observe in figure 3-3:

> $dI/dt = -30000$ A/s at $t = 0$
> and therefore the induced voltage = $L*(dI/dt) = .01*(3000) = 30$ volts, which exactly matches the initial arc voltage assumed for this arc model.

The key point is that no matter what value of initial arc voltage we assume, the instantaneous inductive voltage will match it – a requirement that guarantees continuous current through the inductor, which is a fundamental point demonstrated by this example and by the second example where we illustrate by assuming different arc parameters.

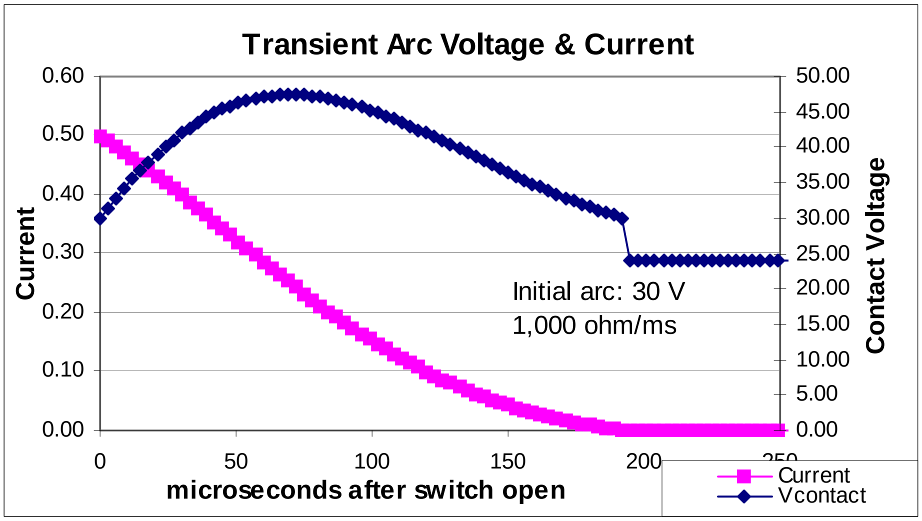

Figure 3-1
Current Decay and Corresponding Arc Voltage

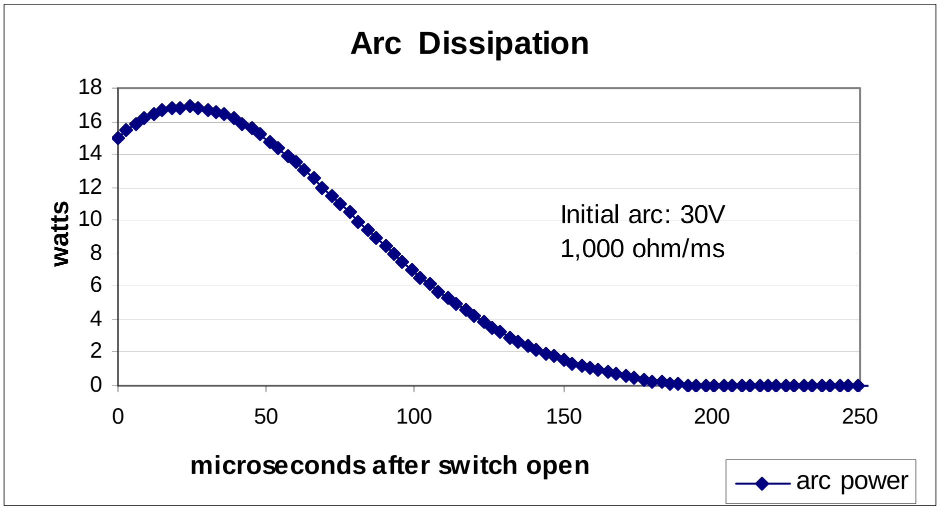

Figure 3-2
Power Consumed by Arc During Current Decay: Peak ~ 17 W

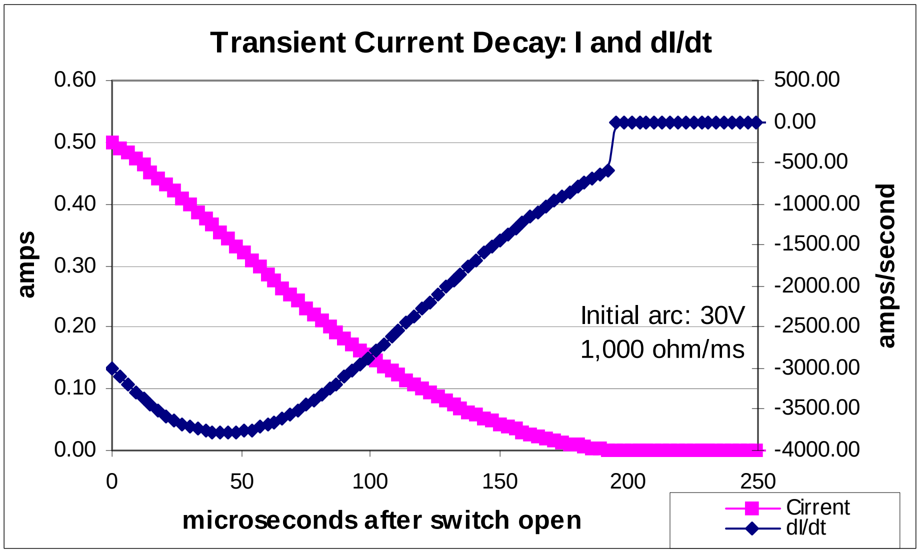

Figure 3-3
High Rate-of-Change of Current During Decay Period

Example II: Opening contact resistance results in a 10 V initial arc voltage; arc resistance increases at 10,000 ohms per millisecond as contacts continue to open. As shown in figure 3-4 the contact voltage peaks at 105 V and the inductor current decays to zero in approximately 90 microseconds. Arc power (figure 3-5) peaks at 38 W about 20 microseconds after contacts part.

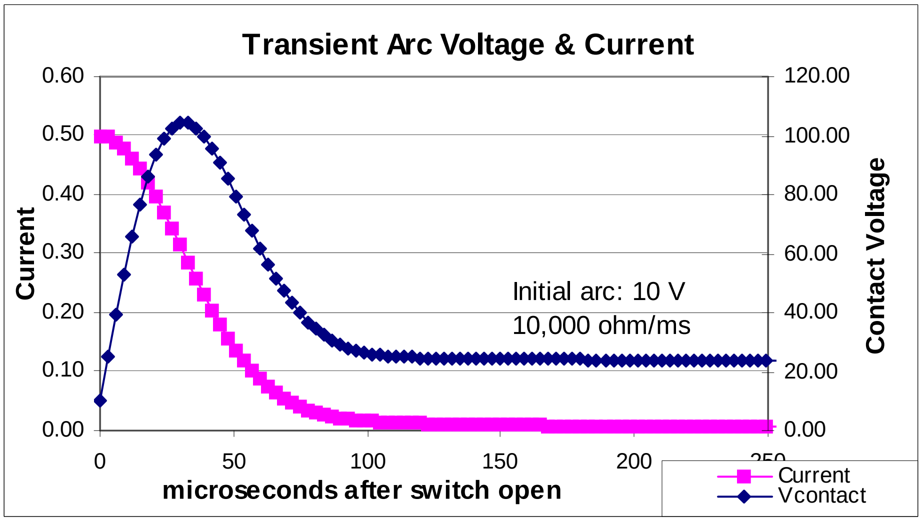

Figure 3-4
Current Decay and Corresponding Arc Voltage

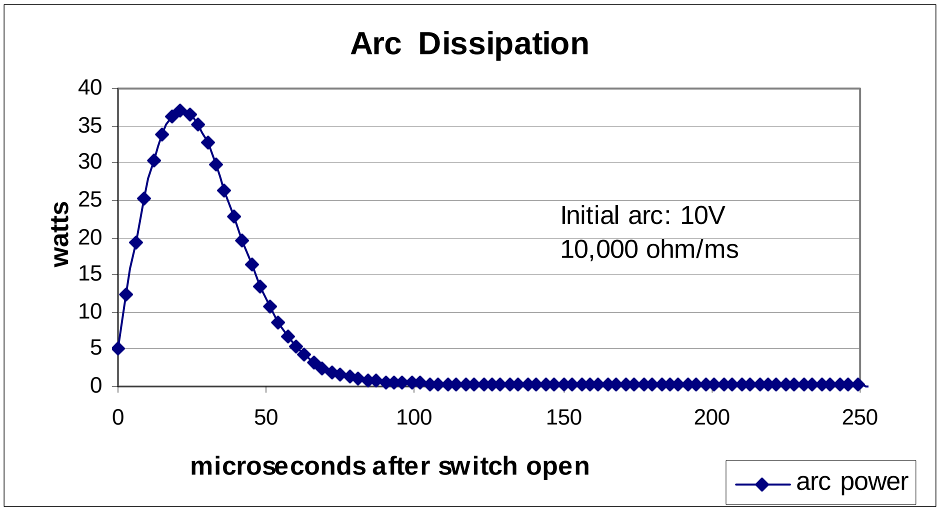

Figure 3-5
Power Consumed by Arc During Current Decay: Peak ~ 37W

Examples I and II serve as a basis to illustrate several fundamental points regarding inductive current interruption:

a) Arcing between contact surfaces creates a current path within an opening switch

b) Current decays smoothly to zero, even under variable arc conditions.

c) Induced voltage created by collapsing inductor current adjusts to satisfy circuit parameters such as instantaneous arc resistance.

d) As the stored magnetic field of the inductor collapses, the inductor functions as a temporary power source providing transient energy to the interrupting circuit; if the circuit includes capacitors, a portion of the energy may be stored there; otherwise power dissipates in resistors and contact arcs.

e) The distribution of power throughout the interrupting circuit depends upon circuit elements – some power is consumed by the inductors coil's resistance (or any other resistance in the circuit), some in the "effective resistance" of the arc. The exact nature of the distribution depends upon relative magnitudes of the various instantaneous circuit resistances.

f) Rapidly changing current may couple magnetically induced voltages into adjacent circuits and therefore "electrical noise" is often associated with current interruption in an inductive circuit, in which case mutual or "transformer" coupling transfers energy between local circuits in close proximity.

g) Radiated noise or Radio Frequency Interference (RFI) can be generated by rapidly changing current, and therefore inductive circuit interruption can be a source of RFI, depending upon circuit parameters that determine current decay time as well as the effective antenna characteristics created by circuit wiring. RFI is by definition not confined to local circuits and propagates as a radiated energy spectrum over a band of frequencies.

4. Transient Suppression Techniques.

In order to control transients created in DC circuits it is important to accommodate stored energy during the interruption process:

a.) Inductor currents create stored magnetic energy

b.) Transient voltages generated during current decay maintain instantaneous current flow, regardless of circuit conditions: if the external circuit requires a high voltage to maintain continuous current then the collapsing magnetic field will create that voltage.

c) The greater the required terminal voltage from the inductor, the faster power is extracted from stored magnetic energy; hence low-voltages tend to stretch out decay time; high voltages compress decay time.

The basic idea then is to control current decay by:

1) Providing a suitable circuit path to minimize or eliminate contact arcing.

2) Controlling the rate of current decay to minimize or eliminate high frequency transients that cause RFI, and/or induced “noise” in adjacent circuits.

There are two approaches that are used to provide a continuous current path for the switching transient phenomenon: One is to provide a path at or near the inductive source; the other is to provide a path around the opening contacts. Both approaches are effective and each as advantages and disadvantages as discussed below, and terms used to describe these techniques include “snubbing” and “fly-back”. (Note that in this section we are discussing inductance of a coil or relay – in circuit terminology a “lumped” parameter. Later, in Section 5 we address “distributed” inductance and associated transient suppression.).

4.1) One of the simplest transient-suppression techniques is to add a “fly-back” or “snubber” diode across the inductor coil as shown in Figure 4.1-1.

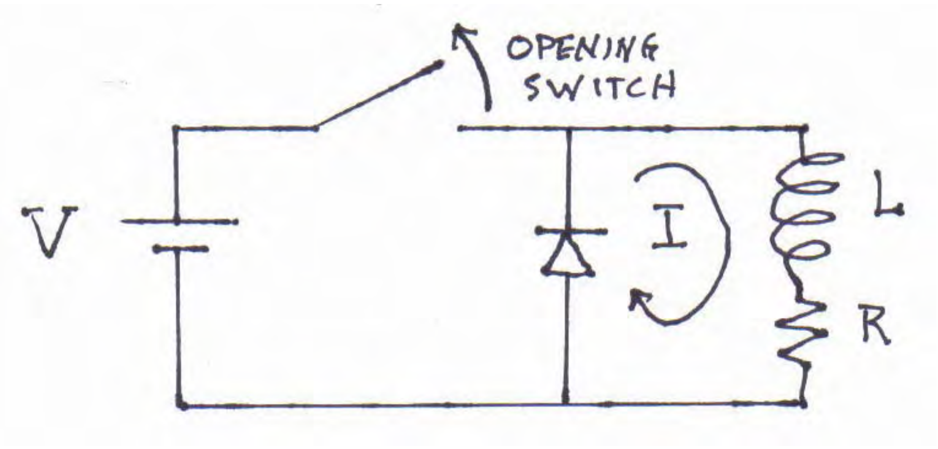

Figure 4.1-1
Transient Suppression Using “Snubber” or “Fly-Back” Diode

In this case the reverse terminal voltage of the inductor equals the forward drop of the conducting diode (approximately 1.5 volts). Using the same supply voltage, inductance and coil resistance as in previous examples, the current decay is shown in figure 4.1-2. Since the reverse diode configuration provides a low-voltage current path, it effectively eliminates arcing between the opening-switch contacts; however, if the inductor is a relay coil, then the relay will remain activated until the current falls below the “drop out” value, and circuit designers need to be aware of delay consequences when a low-voltage current path is used to control transient currents.

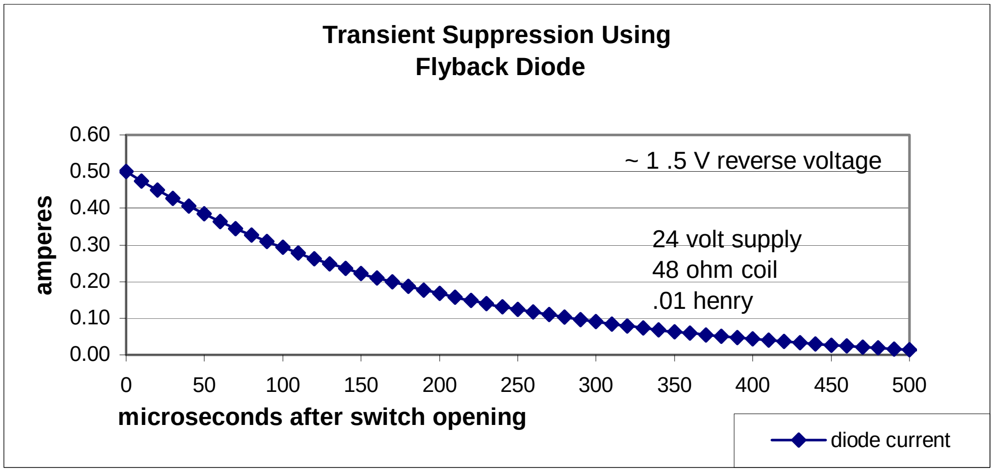

Figure 4.1-2
Extended Decay Time Characteristic Using Fly-Back Diode

Fly-back diode	
Advantages:	Simple, yet effective Reverse terminal voltage approximately 1 volt
Disadvantages:	Decay time determined by coil resistance – the L/R time constant could result in unacceptably long relay hold-times

4.2) Adding resistance in series with the fly-back diode, as illustrated in Figure 4.2-1, increases reverse voltage while reducing current decay time: by simply adding a resistor (R_d in figure 4.2-1) to the fly-back connection we force the reverse voltage to be greater than that of the diode alone, thereby causing an increase in the instantaneous power extracted from the inductor, which, in turn, reduces decay time as the coil energy collapses. Of course there is a trade-off: if the resistance is too high, a contact arc becomes the preferred current path. A rational for selecting resistance values is discussed in Section 8.

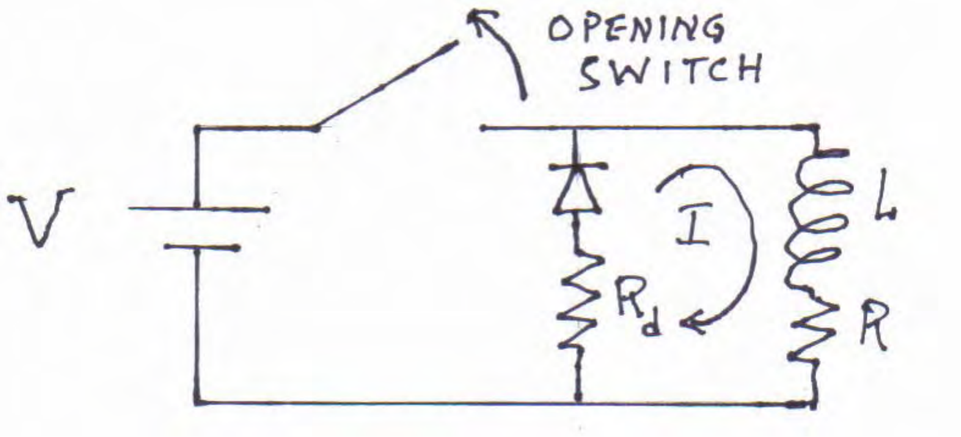

Figure 4.2-1
Transient Suppression Using "Fly-Back" Diode and Resistor

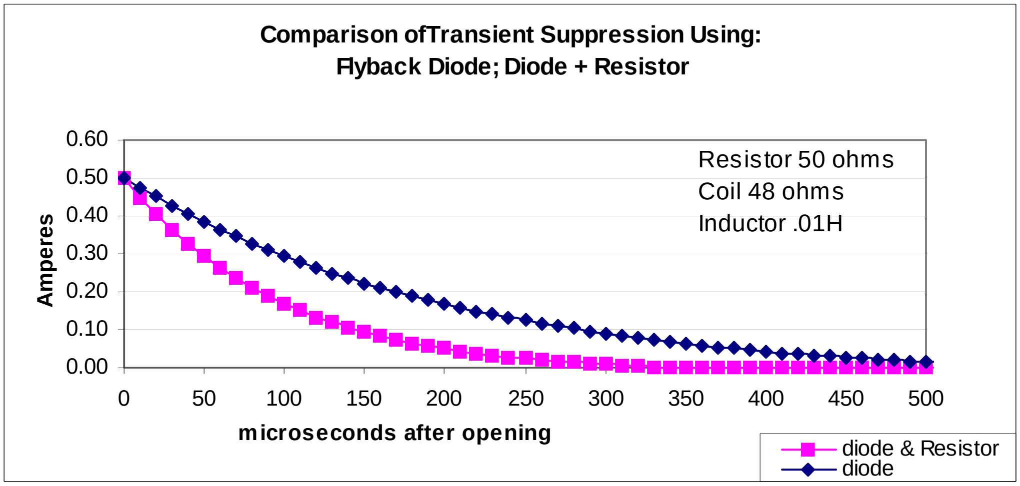

Figure 4.2-2
Faster Decay Time Characteristic of Fly-Back Diode Plus Resistor

4.3) Transorb or Zener diode across coil

As indicated in figure 4.3-1 a voltage-regulation (VR) device is connected in series with the fly-back diode thereby forcing the reverse inductor terminal voltage equal to VR + diode forward drop. Since power = voltage x current, the inductor's stored magnetic energy is depleted more rapidly than a diode alone: an example comparison between current decay of diode and diode plus VR device is shown in figure 4.3-2. Again, the same precaution discussed in Section 4.2: the preferred current path will remain through the contacts if the VR voltage is too high.

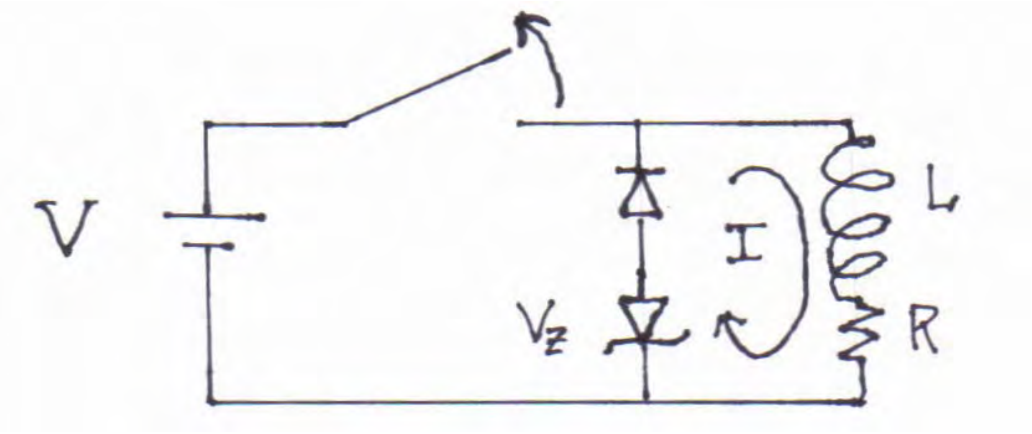

Figure 4.3-1
Transient Suppression Using "Fly-Back" Diode and Voltage Regulator

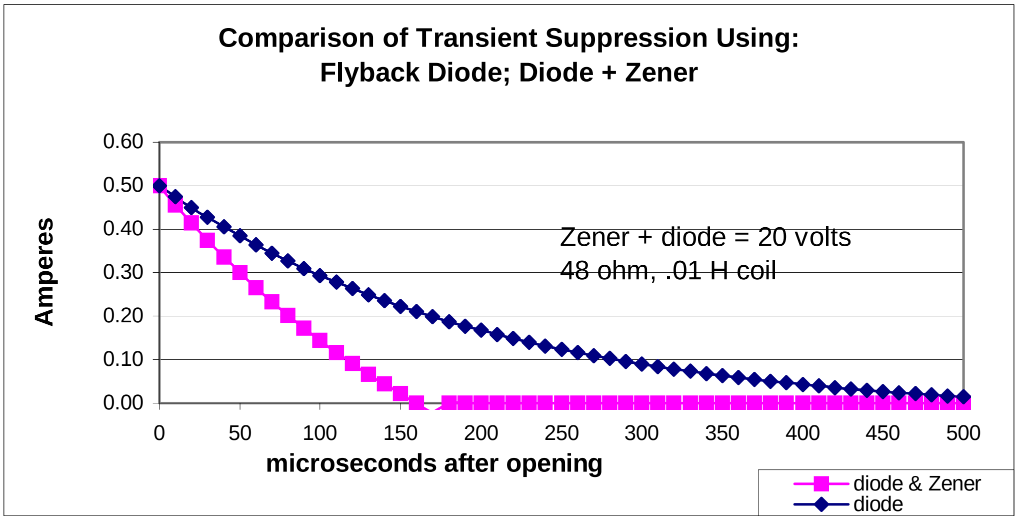

Figure 4.3-2
Faster Decay Time Characteristic Using Voltage Regulator Device

4.4) Capacitor bypass across contacts

In this case a capacitor is connected in parallel with the switch terminals. As the contacts separate, the capacitor provides a current shunt path as indicated in figure 4.4–1

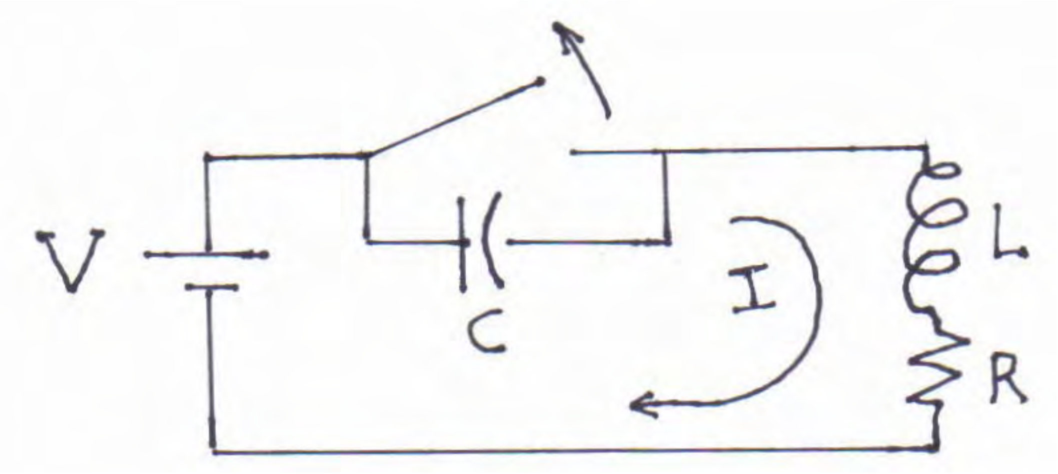

Figure 4.4-1
Transient Suppression Using Capacitor By-Pass of Contacts

Calculated waveforms of current and voltage during the open-switch transient period are shown figure 4.4-2. Here we have chosen 1 microF for C along with 0.01 H and 48 ohms for L and R, respectively, in which case the waveforms are under-damped. As energy transfers into the capacitor the current falls to zero at ~ 200 microseconds (note the capacitor voltage reaches a peak of ~60 V at the same time); then the energy oscillates back into the inductor, loosing energy through resistive losses in R, and therefore successive peaks diminish as the transient settles to a steady state value, which in this case is eventually 24 volts.

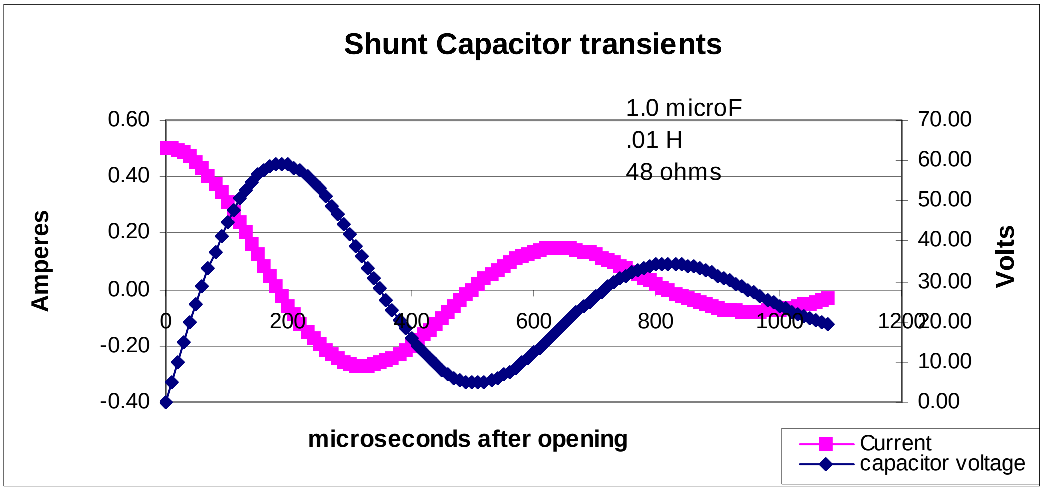

Figure 4.4-2
Oscillation Characteristic of Under-Damped Capacitor-Inductor Circuit

If we choose a smaller capacitor, say, 0.5 microF, both the capacitor voltage peak and the oscillation frequency increase while simultaneously reducing the time to the first current zero as shown in figure 4.4-3. In that figure the first current zero is at ~ 125 micrseconds while the capacitor voltage peaks at ~ 80V. Again, we see the basic induced-voltage principle where the current decays more quickly as the inductor voltage generated by collapsing current increases.

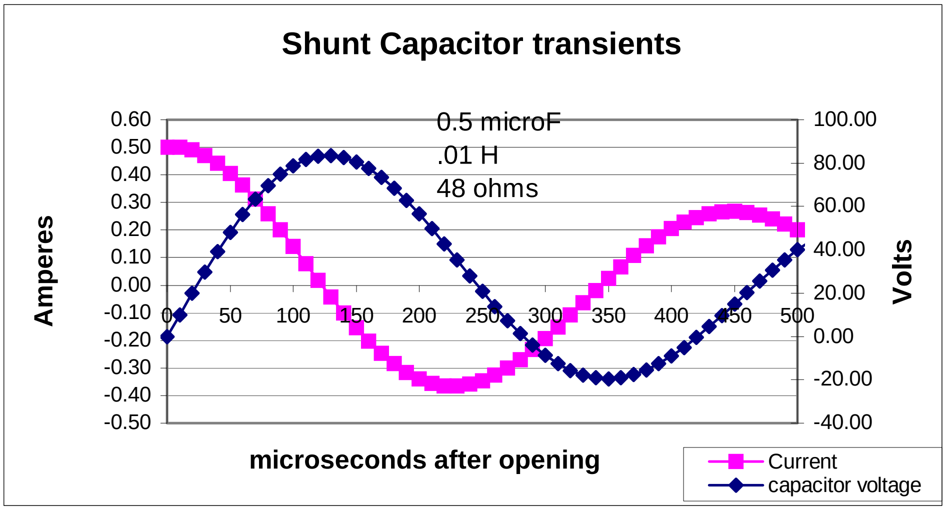

Figure 4.4-3
Oscillation Characteristic of Under-Damped Capacitor-Inductor Circuit

Choosing a larger capacitor (5 microF) we obtain waveforms nearly "critically" damped were the "settling" time has been stretched (first current zero at ~ 550 microseconds) and the peak capacitor voltage reduced to ~30 V. Note that in all cases the capacitor voltage settles out to equal the 24 V supply voltage (as evident in Figure 4.4-4).

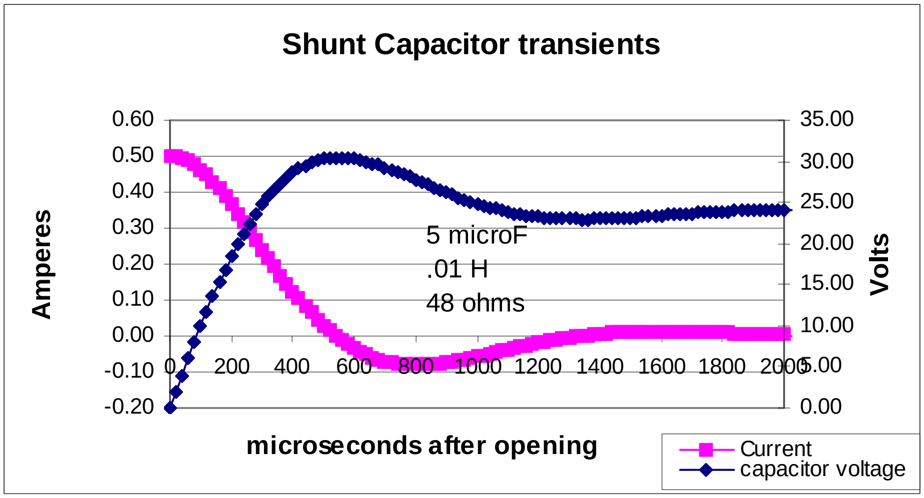

Figure 4.4-4
Oscillation Characteristic of Critially-Damped Capacitor-Inductor Circuit

In some cases a damped oscillatory response ("ringing") may be unacceptable and the stored charge remaining on the contact capacitor after the switch is open may also present a problem: discharge through the contacts when the switch is closed can result in excessive contact damage from the shorted-capacitor current. Switch “bounce” – where mechanical contacts make and break the circuit multiple times before settling to a final resting state – can exacerbate the problem. Low-voltage arcing created during the bounce period can erode and damage contacts: severity of damage depends upon current magnitude and duration (see Section 6 for additional discussion of “bounce”). It is, therefore, good practice to include some means of discharging the capacitor. One example is shown in figure 4.4-5 where a diode blocks capacitor discharge back into the contacts and a parallel “bleed” resistor removes capacitor charge. In figure 4.4-6 the resulting waveforms are displayed for the same values used to compute figure 4.4-2. Note that once the current drops to zero it remains there since the diode blocks reverse current through the inductor circuit. With a parallel “bleed” resistor of 1000 ohms the discharge time constant is 1000 microseconds; the capacitor peaks at ~50 V and then discharges down to equal the 24 V supply voltage within several hundred microseconds. Upon the next switch closing the capacitor discharges to zero through Rc and the voltage remains at zero until the switch opens again.

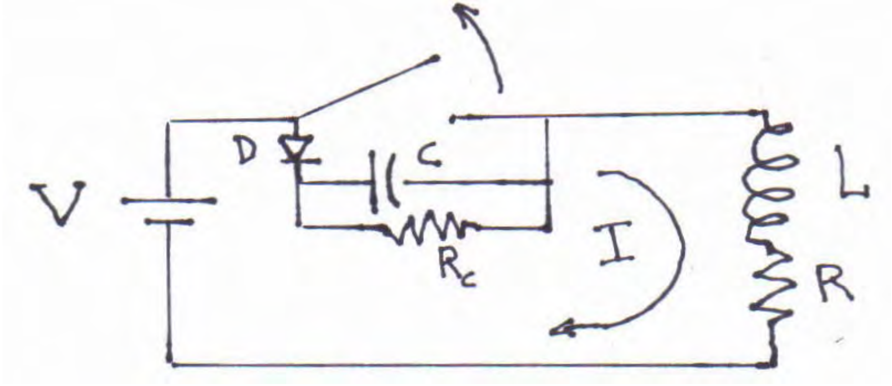

Figure 4.4-5
Transient Suppression Using Capacitor By-Pass Circuit That Inhibits Oscillation: Diode, Capacitor and Parallel Discharge Resistor, Rc

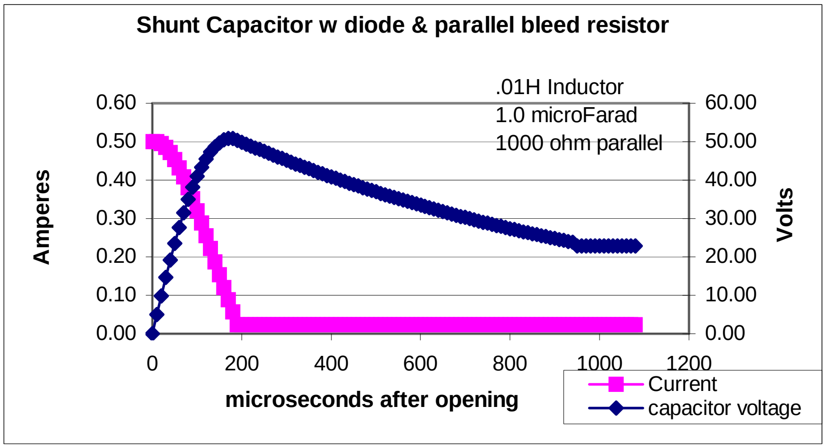

Figure 4.4-6
Shunt Capacitor Voltage Rises to Peak as Current Drops to Zero

Finally, since the capacitor creates an AC shunt that permits high-frequency signals to bypass the switch when it is open, designers need to be aware of the consequences of not having AC isolation between source and load when the switch is open – in some applications AC coupling will not be acceptable.

For additional discussion of capacitive arc suppression (i.e. "snubbing") in a DC motor-control circuit see US Patent #6,885,535 "Non-linear Snubber Circuit", Hummert, et al., April, 2005.

4.5) Arc-resistance contact material

Contact materials such as silver/molybdenum alloys are capable of withstanding high-temperature current concentrations with relatively minor surface damage and, therefore exhibit excellent contact wear compared to copper, brass or tin alloys. Often switch manufacturers provide an "interrupt rated life" in terms of rated number of operations at a specified DC current. While arc-resistant contacts may not physically suppress transient arcing, the durability of such contacts often results in an acceptable lifetime. Rugged contact materials alone, however, do not suppress transient noise –such as RFI - created by rapidly decaying current through contact arcs, and some form of transient suppression may be necessary to attenuate high-frequency noise even when contacts are capable of withstanding interruption arcs. In addition, circuits without transient suppression are subjected to high-voltage pulses each time contacts open (and the inductive power reacts to the instantaneous arc resistance). These high voltage "spikes" can cause degradation of insulation on components within the circuit. Again the designer must use judgment as to how frequently such pulses occur and what components are present.

4.6 Summary of Suppression Techniques

Suppression Technique	**Advantages**	**Disadvantages**
Fly-back Diode	Simple, easy to implement; stretched decay reduces high frequency components & RFI	Long decay time determined by coil resistance;
Diode + Resistor	Fast decay time	High reverse voltage; faster decay ➔ higher frequency components than diode alone
Diode + Voltage Regulator	Fast decay time	High reverse voltage; faster decay ➔ higher frequency components than diode alone
Capacitive Shunt	Effective shunt path eliminates contact damage	Diode & Resistor may be necessary for discharge; AC bypass of open switch
Arc-Resistant Contacts	Simple, easy to implement	More costly contacts; high frequency components; RFI

5. Distributed Inductance

Thus far we have been addressing transient effects attributed to a "lumped" inductance such as that formed by the winding of a relay coil, where the magnetic field and stored energy are confined to the coil winding. Circuit wiring, however, creates another source of stored magnetic energy, where spaces between current-carrying wires form inductive loops, as illustrated in figure 5 –1, and magnetic coupling between loops within the same circuit or to other nearby circuits can lead to transient interference during current interruption. Since inductance is created by the magnetic flux contained within a current-carrying region and is proportional to the physical area between wires, large loops are potential sources of transient energy during current interruption.

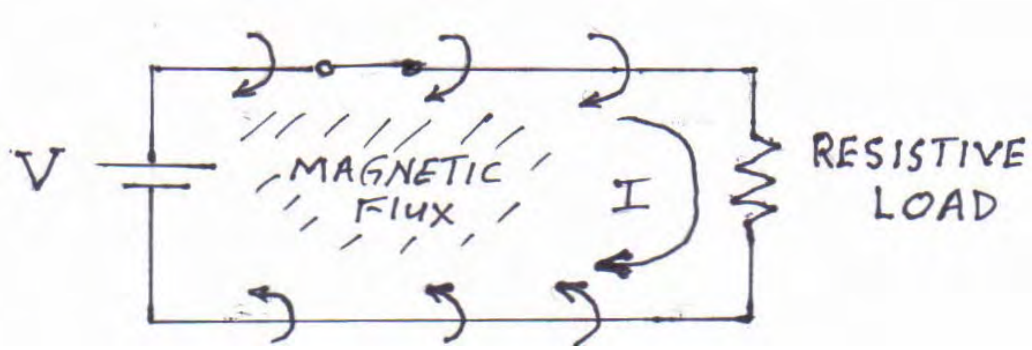

Figure 5-1
Representation of Circuit Self-Inductance Created By Wiring Loop

As illustrated in figure 5-2, a simple, yet effective technique for minimizing DC transients is to close the loop by keeping circuit wires carrying opposing current in close proximity.

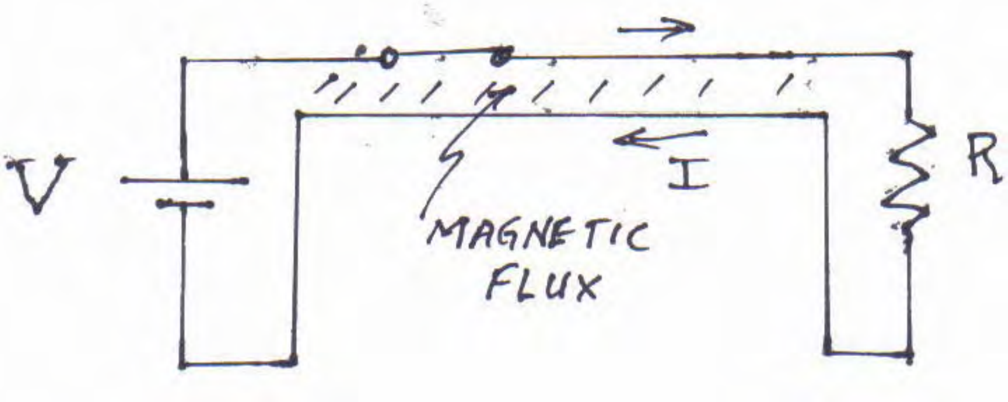

Figure 5-2
Reduction of Self-Inductance By Reduction of Loop Area

Better yet, twisting wires together (see figure 5-3) creates alternating magnetic field polarities that tend to cancel each other out. Generally it is good practice to use twisted, shielded cable (grounded shield) rather than individual wires in sensitive circuits. If wiring topology is not an option, then lumped techniques discussed earlier can be used to provide alternate transient-current paths to minimize contact wear and to slow down transient decay – thereby reducing induced voltages in adjacent circuits.

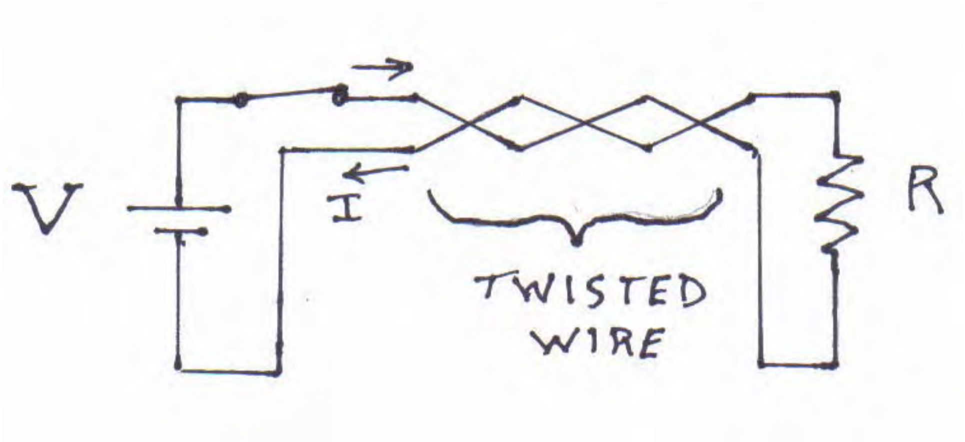

Figure 5-3
Reduction of Self-Inductance Using Twisted Wires

6. Real World (Non –Ideal) Components

6.1 Switches

Earlier, in Section 2 where basic growth of current in an inductive circuit was described, we used an ideal switch with no contact bounce to close the circuit and initiate current through the inductor. Mechanical switches, however, can exhibit "bounce" where the contact surfaces actually make and break physical contact several times before settling to a final closed position. Rapid opening and closing –i.e. "bounce" – may or may not cause contact degradation and RFI, depending upon the R/L time constant: if the bounce occurs, say, in a few microseconds and the time constant is a millisecond, then the growth of current between successive contact closures would likely be negligible compared to the final steady-state current. However, if the bounce frequency is of the same order as the time constant, then each contact separation may cause significant transient pulses as described earlier. Designers need to be aware of the possible consequences of contact bounce and make appropriate design decisions regarding arc suppression or in choosing a switch with negligible bounce – either bounce oscillations much faster than the L/R time constant or a sliding contact closure exhibiting no bounce.

6.2 Inductors

The inductor model used earlier invoked a simplified equivalent circuit consisting of inductance in series with resistance representing a magnetic coil composed of wire windings and winding resistance. A more detailed and accurate model would include a parallel capacitor or capacitive network representing inter-winding parasitic capacitance: without transient suppression on the coil, a voltage spike generated by collapsing current creates a high-frequency current path through the coil's equivalent winding capacitance. The net result (depending upon contact arcs and other circuit parameters) can be a "ringing" voltage waveform on an inductor that does not have adequate transient protection during current interruption. Coil ringing can cause several problems:

a) High voltage stress of coil winding insulation (and of other circuit components)
b) RFI interference
c) Induced “noise” voltages

In some applications, ringing may be tolerable; but again, designers should be aware of causes and if necessary take appropriate steps to provide transient current paths as discussed earlier.

Since an electromechanical relay (or contactor) contains a moving ferromagnetic element (plunger) that alters magnetic flux as it moves from OPEN to CLOSED, the terminal inductance varies as the plunger moves under influence of the field. Therefore, one average or “ballpark” value of inductance, L, although an approximation, is still useful in most cases for estimating time constants.

7. Semiconductor Switches

Solid-state devices are an important class of current control devices excitation. Field effect transistors (FET) are effective OPEN CLOSED devices that exhibit a fast transition from high OPEN to low CLOSED resistance and visa versa. Although internal semiconductor junctions of FETs exhibit parasitic capacitance that can help shunt transient current around internal junctions - thereby providing some inherent protection to high voltage spikes generated as the FET is gated OFF – in general appropriate transient-suppression must be invoked to prevent FET damage when switching inductive circuits: either by alternate current paths through fly-back diodes and / or some form of a capacitive-shunting network at the FET terminals. There are many guidelines provided by component suppliers that are readily available on their websites. See for example “Snubber Circuits; theory, Design, and Application”, Philip Todd (Unitrode, Corp) http://focus.ti.com/lit/an/slup100/slup100.pdf

8 Parameter Selections

At this point the reader may be wondering how to choose the value of components employed in any of the suppression schemes discussed above. The most accurate and efficient technique is to simply to monitor switch voltage and current with an oscilloscope. Then observe voltage and current both with and without transient suppression, using trial and error to select various components. A peak-hold voltmeter is helpful if an oscilloscope is not available. Of course if the values of inductance and coil resistance along with approximate arc characteristics are known, we can analytically solve for appropriate suppression parameters. If the inductance is not known, we have several options:

1. Assume the circuit inductance is that of a relay or contactor coil. We begin by simply adding a fly-back diode, where the non-repetitive peak current rating is sufficient to absorb the interrupt current. Then, if the hold time has not been extended too long, we are most likely finished – the transient pulse is controlled by a single component addition!!
2. If the hold time is not acceptable and must be reduced, we proceed to add resistance in series with the diode using the coil resistance as a starting point: the

L/R decay time constant needs to be reduced; since we can easily measure the coil's resistance, R we know that adding a resistor of value R in series with the diode will roughly halve the original decay time constant. If that is not enough, then we continue the same line of reasoning to find an appropriate damping value for the diode resistor.

3. To select a shunt capacitor across switch contacts, we begin by assuming a transient period of say, 1 millisecond and that the interrupted current flows into the capacitor for that period during the switch opening. Then we choose a desirable voltage rise on the capacitor as the switch opens and use this as a starting point. For instance assume the DC supply is 24 V and we choose 100 V for desired capacitor peak voltage, and that the interrupted current is .5 A; then

   Vcap ~ I* (deltaT)/C or C ~ .5*(.001)/100 = 5 microF

   This gives us a starting point and if we observe switch voltages and current with an oscilloscope we will quickly see how accurate our estimates were. Without an oscilloscope, we can measure the peak capacitor voltage and make several observations with various values of capacitance.

4. Although crude, another technique that can be useful for any of the above suppression techniques is to interrupt the circuit with an observable "knife blade" type of switch and observe sparking in the dark, both with and without arc suppression. If arcing is a problem, the results will be clearly evident when suppression is added!!

Summary

Inductive circuits inherently store magnetic energy that can cause harmful transients during switching. Understanding the basic characteristics of these transients enables circuit designers to include appropriate remedial steps to minimize or eliminate sources of transient behavior. There are several techniques that are described, including alternate current paths around inductive elements; capacitive bypass of switch contacts; and circuit wiring precautions to minimize loop inductance. Practical techniques for selecting component values are suggested.