



DC Circuit Switching Transients

An Online Continuing Education Course for Engineers

Course Number: E-3020

Credit: 3 Hours / 3 PDH / 3 CPD

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.

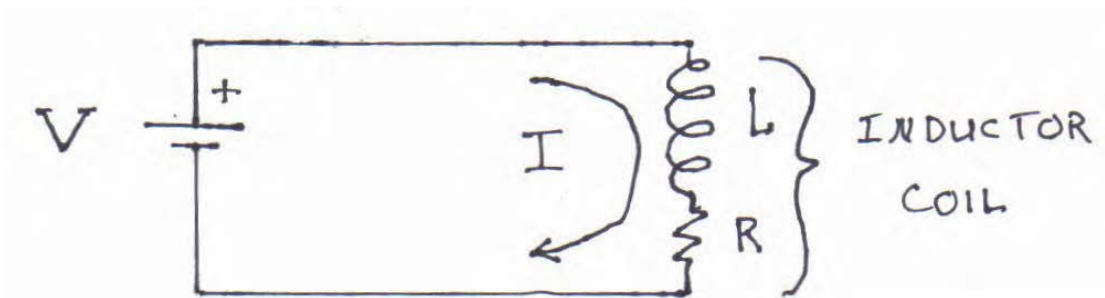


Figure 1-1
Equivalent Circuit Representation of Inductor in DC Circuit

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:

$$\text{Stored energy} = (1/2)*(0.1)*(0.2^2) = .002 \text{ J} \qquad \text{Equ 1-2}$$

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.

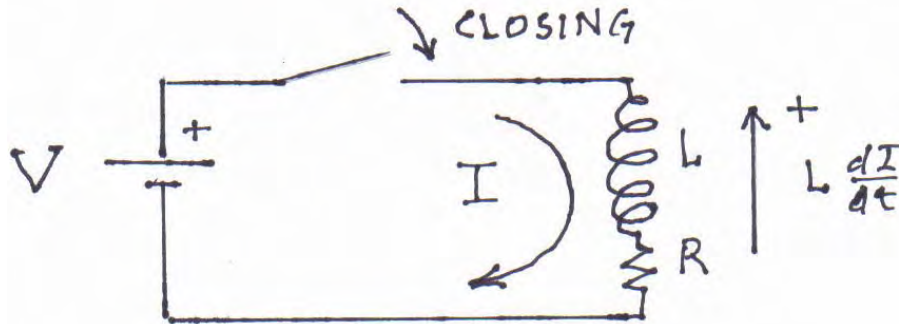


Figure 2-1
Circuit Representation of Switch Control

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

$$V = I \cdot R + L \cdot \left(\frac{dI}{dt}\right) \quad \text{Equ 2-1}$$

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 $L \cdot (dI/dt) > 0$ when the current is increasing (dI/dt positive).

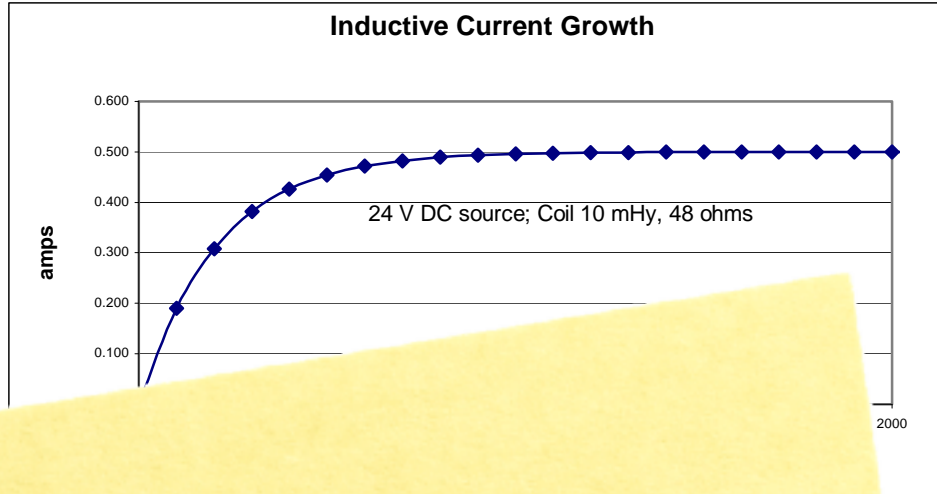
The solution of the differential equation is:

$$I = (V/R) \cdot \{1 - \exp [t/(L/R)]\}, \quad \text{Equ 2-2}$$

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

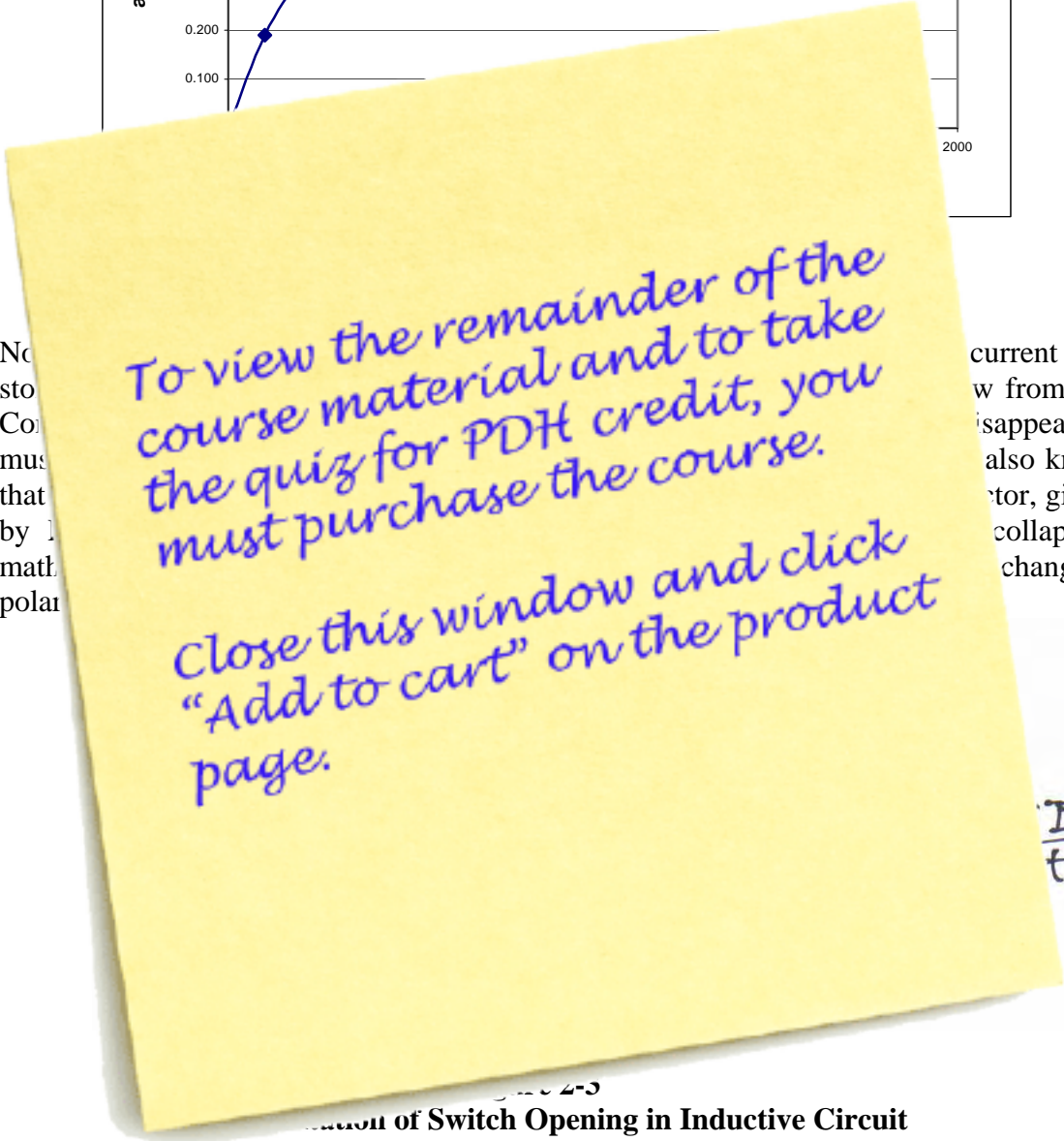
The corresponding curve of current growth is given in figure 2-2 for $V = 24$ volts, $L = .01$ H, and $R = 48$ ohms. The time constant L/R equals 208 microseconds. Current reaches steady state ($24 \text{ V} / 48 \text{ Ohms} = 0.5 \text{ A}$) in approximately three time constants, or 600 microseconds.

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



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Figure 2-3
Induction 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.