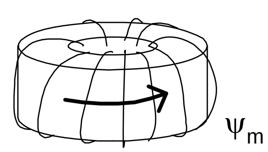
Lecture 4: RL Circuits. Inductive Kick. Diode Snubbers.

Inductors are the third basic discrete component listed in Lecture 2. Uses for inductors in the NorCal 40A include filters and RF "chokes." The latter provides essentially a short circuit at DC and nearly an open circuit at RF frequencies. (Essentially the opposite function of a DC blocking capacitor!)

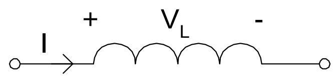
You will wind some of your own inductors for the NorCal 40A. (The others are axial-lead inductors. They look like resistors, but are green with colored bands indicating L in units of μH. These band colors are sometimes difficult to distinguish, so be sure to measure them with the LCR meter in the lab before using.)

The inductors you wind will be wound on a toroidal-shaped ferrite core. Toroid inductors are essentially "self shielding" at RF frequencies since most magnetic flux ψ_m is contained in the core.



Consequently, these inductors can be placed close to each other on a PCB without too much mutual (and undesirable) interaction. However, be careful in your own designs. (For example, keep air-core inductors perpendicular to each other.)

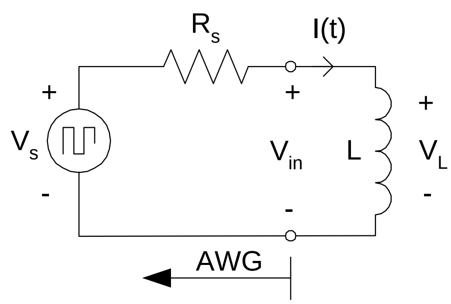
Inductors store energy in a magnetic field. They also oppose a change in the current through them.



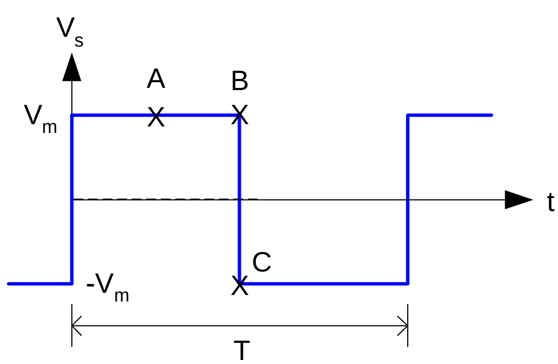
$$V_L = L\frac{dI}{dt}$$

This opposition can cause the inductor voltage to become enormous if there is a big change in the current. This effect is called "inductive kick."

To see this explicitly, consider this simple circuit (an inductor connected directly to an AWG, for example)



The open circuit source voltage is



We will carefully analyze this circuit to predict the input voltage V_{in}. In the following analysis we'll assume that $\tau = L/R \ll T/2$.

1. At "A" V_s has reached steady state so that $I(t)$ is nearly constant and approximately equal to $V_m/(R_s + R_L)$, where R_L is the resistance of the inductor.

The work done by the source against the magnetic force produces energy stored in the magnetic field

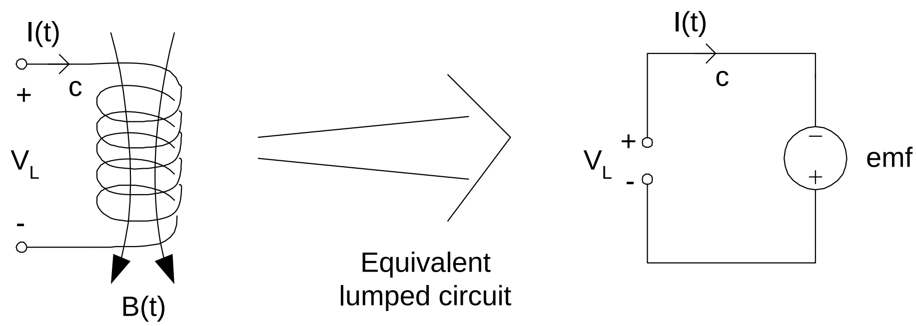
$$W_L = \frac{1}{2} L I^2 \quad \text{[J]}$$

2. From "B" to "C" the source V_s is switching from V_m to $-V_m$ volts. Since $V_L = L\, dI/dt$, I cannot change instantly, but it can change rapidly.

3. From Faraday's Law of Induction

$$\text{emf} = -\frac{d\psi_m}{dt} \quad \text{[V]} \qquad \text{or} \qquad \oint_{c(s)} \bar{E} \cdot d\bar{l} = -\frac{d}{dt} \int_{s(c)} \bar{B} \cdot d\bar{s}$$

where $\psi_m = \text{magnetic flux} = B(t) \cdot N \cdot A$, where N = number of identical turns of wire and A is the cross-sectional area.



Recall that as V_s goes from V_m to $-V_m$, there will be a rapid decrease in $I(t)$. It's not an instantaneous change from $V_m/(R_s+R_L)$ to $-V_m/(R_s+R_L)$ because of L, but a rapid change.

However, $B(t) \propto I(t)$ which implies there will be a rapid decrease in $B(t)$ and, hence, $\psi_m(t)$.

4. Therefore, the $\text{emf} = -d\psi_m/dt$ will be large and positive. This emf (a net "push" on the charges) keeps current moving in the same direction (from top to bottom in the figure) and thus opposing the **change** in the magnetic flux linking the coil.

5. Using the equivalent lumped circuit above, we see that

$$V_L = -\text{emf} = \frac{d\psi_m}{dt}$$

Notice the negative sign! With $\psi_m = LI$, then

$$V_L = \frac{d}{dt}(LI) = L\frac{dI}{dt} + I\,\cancelto{0}{\frac{dL}{dt}}$$

or

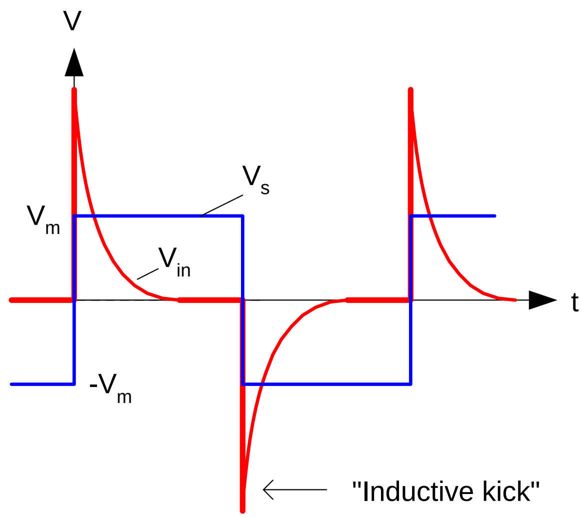
$$\boxed{V_L = L\frac{dI}{dt} \quad [\text{V}]} \tag{1}$$

which is what we originally stated on page 2.

Now, we'll use (1) to predict the voltage $V_{\text{in}} = V_L$ shown in the circuit on page 2.

V_s	$I(t)$	$V_{\text{in}} \propto \dfrac{dI}{dt}$
As V_s goes from $V_m \to -V_m$.	$I(t)$ is changing rapidly from $\dfrac{V_m}{R_L+R_s} \to -\dfrac{V_m}{R_L+R_s}$.	Negative spike in voltage.
As V_s goes from $-V_m \to V_m$.	$I(t)$ is changing rapidly from $-\dfrac{V_m}{R_L+R_s} \to \dfrac{V_m}{R_L+R_s}$.	Positive spike in voltage.

In graphical form:

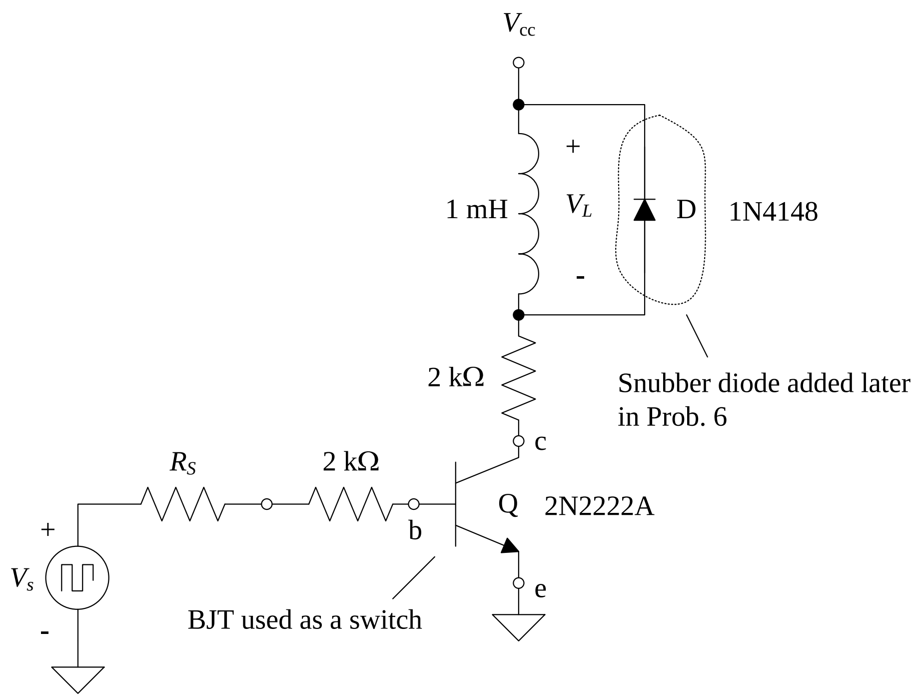


This rapidly changing current in an inductor can produce enormous V_{in} (= V_L). Sometimes this is useful, as in an automobile spark ignition (see Fig. 2.19).

Similarly, this "inductive kick" can produce arcing in switches when they turn off electric motors. (I had a switch in a vacuum cleaner burn a hole through beryllium-copper sliding contacts due to this source of arcing.)

In sensitive electronic circuits, such inductive kick can be catastrophic and burn out transistors, for example.

You will study this phenomenon in Probs. 5 and 6. From Fig. 2.32(b) in Prob. 5:



If Q was initially "on" and then turned "off," there would be a very large and <u>negative</u> voltage V_L if D were not present. This large voltage appears across c and e of Q. If this voltage is too large, then Q could be damaged. (Think of L as an equivalent inductance of an electric motor, for example.)

With the snubber diode D, this reverse voltage on L is limited to the forward voltage drop of D! (Note that D must be able to withstand all of the current that initially exists in L just before D begins to conduct.)

We'll see the snubber diode again in Prob. 20 inside the Magnecraft W171DIP-7 reed relay.