Magnetic Energy, Inductance, Back Voltage, Resonant Circuits and Superconducting Electromagnets

We have seen that there is a magnetic field around a wire when current is flowing through it. Some energy was required to grow that magnetic field, but once it exists and no longer growing no additional energy is required. When the current is shut down, that energy is returned to the wire.

Power is energy transfer per unit time. Electrical power is voltage multiplied by current so the energy to create the magnetic field comes from an additional voltage necessary to produce the current. When the magnetic field is no longer growing, that extra voltage disappears. When the current is shut down, however, an opposite extra voltage appears as the decreasing magnetic field energy is returned to the source of the current. This extra voltage associated with the changing magnetic energy is called the back voltage and always opposes the change in voltage across the wire.

There is a similar effect in capacitors where electrical energy is stored in the capacitor when it is being charged, held there when the charge remains constant, and returned when the capacitor charge is drained off. This effect is described by the **capacitance** of the **capacitor**. The comparable effect of magnetic field energy storage is described by a quantity called the **inductance** of the wire carrying the current. When the wire is wound into a solenoid, the effect is much greater. A wire arranged in a coil has a particularly large inductance and such a device is called an **inductor**. The inductance of a straight wire is generally too small to be important.

For capacitors, it is easy to demonstrate this energy storage process because the time for the charging and discharging of capacitors can arranged to be easily observed on a human time scale. The corresponding time for the generation and collapse of magnetic fields is too short to be easily observed except when working with inductors made of superconducting wire.

A capacitor and an inductor can be connected in series or parallel to produce what is called a resonant circuit with a characteristic frequency called its resonant frequency. This is analogous to the special frequency of a pendulum where gravitational energy and kinetic energy are exchanged back and forth as it swings. The magnetic and electric energy in a inductor-capacitor circuit also swish back and forth at the resonant frequency of the circuit. Such circuits have traditionally been used to sort out the different stations in a radio or television although modern radios do use different types of resonators.

We saw this back voltage cause the impressive arc when the battery was disconnected from the solenoid. Back voltages are present when powering motors and transformers. In our levitation demonstration, the resistance of the large solenoid is only about 0.7 Ω. If we were to use Ohm's Law V=IR to calculate the current that would flow when this is connected to the 120 V power outlet, we would obtain I=120 V/0.7 Ω = 171 A, far greater than the 15 A limit set by the outlet circuit breaker. That would be true if the 120 V were direct current like that supplied by a large battery. In fact the 120 V from the outlet is constantly reversing direction with a frequency of 60 Hz. The changing voltage causes a changing current which in turn causes a back voltage the nearly cancels the applied 120 V so that the actual current is only about 10 A.

A more impressive example is when energizing a solenoid made of superconducting wire which completely lacks any resistance to current flow. In that case, forcing a voltage across the superconductor causes a constantly increasing current which will destroy the superconductivity of its wire if it exceeds a critical value determined by the material and design of the superconducting solenoid. As the current nears that limit, the voltage must be forced to zero and a "persistent current" switch activated before the voltage source is disconnected. Magnetic resonance imagining (MRI) devices in hospitals use superconducting solenoids maintained at a temperature near 4 K (-269 ^{o}C).