Basic Definitions and Terms

Before we begin our analysis of electric circuits, we must define terms that we will employ. We will simply refer to an *electric circuit* as an interconnection of electrical components, each of which we will describe with a mathematical model. The most elementary quantity in an analysis of electric circuits is the electric *charge*. Our interest in electric charge is centered around its motion, since charge in motion results in energy transfer. An electric circuit is essentially a pipeline that facilitates the transfer of charge from one point to another. The time rate of change of charge constitutes an electric *current*. The basic unit of current is the ampere (A), and 1 ampere is 1 coulomb per second. Although we know that current flow in metallic conductors results from electron motion, the conventional current flow, which is universally adopted, represents the movement of positive charges. It is important that the reader thinks of current flow as the movement of positive charge regardless of the physical phenomena that take place. Therefore, it is important to specify not only the magnitude of the variable representing the current but also its direction.

The term *direct current* or DC is used to describe current that flows in only one direction. Direct current moves only one way, from positive to negative. A battery is a common direct-current device. A DC source will always try to move current in the same direction. One thing to note is that the current coming out of the source always needs to get back to the source somehow. The ground connection on the schematic should be thought of as a label that connects the signal back to the source. If the signal does not get back to the source, then there is no current flow. AC or *alternating current* came about as the interaction of magnets and electricity were discovered. This type of current most commonly comes from big AC generators at your local hydroelectric dam. When you move a coil of wire past a magnet, the current first climbs as the strength of the field increases, then as the field decreases and switches polarity, the current also decreases and switches polarity. The voltage and current change in a sinusoidal fashion naturally as the coil passes by the magnets. As long as you keep moving the coil, AC power will continue to be generated.

We have indicated that charges in motion yield energy transfer. Now we define the *voltage* (also called the *electromotive force*, or *potential*) between two points in a circuit as the difference in energy level of a unit charge located at each of the two points. Charges in motion represent a current. The motion of charges in an electric circuit will be resisted as well. We will introduce the concept of resistance later to describe this effect. Energy is measured in joules (J). Hence, voltage is measured in volts (V) and 1 volt is 1 joule per coulomb. If a unit positive charge is moved between two points, the energy required to move it is the difference in energy level between the two points and is defined voltage.

Energy is yet another important term of basic significance. Let's investigate the voltage–current relationships for energy transfer using the flashlight. The basic elements of a flashlight are a battery, a switch, a light bulb, and connecting wires. Assuming a good battery, we all know that the light bulb will glow when the switch is closed. A current now flows in this closed circuit as charges flow out of the positive terminal of the battery through the switch and light bulb and back into the negative terminal of the battery. The current heats up the filament in the bulb, causing it to glow and emit light. An energy conversion process occurs in the flashlight as the chemical energy in the battery is converted to electrical energy, it is converted to thermal energy in the light bulb.

Ohm's law is named for the German physicist Georg Simon Ohm, who is credited with establishing the voltage–current relationship for resistance. As a result of his pioneering work, the unit of resistance bears his name. *Ohm's law states that the voltage across a resistance is directly proportional to the current flowing through it*. Some important parameters that are used to specify resistors are the resistor's value, tolerance, and power rating. The tolerance specifications for resistors are typically 5% and 10%. The power rating for a resistor specifies the maximum power that can be dissipated by the resistor. Some typical power ratings for resistors are 0.25 W, 0.5 W, 1 W, and 2 W and so forth, up to very high values for high-power applications. Thus, in selecting a resistor for some application, one important selection criterion is the expected power dissipation.

We now need to consider Kirchhoff's laws, named after German scientist Gustav Robert Kirchhoff. These two laws are quite simple but extremely important. The first law is Kirchhoff's current law (KCL), which states that *the algebraic sum of the currents entering any node is zero*. There are alternative forms of Kirchhoff's current law that *the algebraic sum of the currents leaving a node is zero*, or that *the sum of the currents entering a node is equal to the sum of the currents leaving the node*. Kirchhoff's second law, called *Kirchhoff's voltage law* (KVL), states that *the algebraic sum of the voltages around any loop is zero*.

Thevenin's Theorem (Unit 5 in Basic Engineering Circuit Analysis 10th Edition)

Thevenizing is based on the idea of using superposition to analyze a circuit. When you have two different variables affecting an equation, making it difficult to analyze, you can use the technique of superposition to solve the equation, provided that you are dealing with linear equations. The idea of superposition is simple: When you have multiple inputs affecting an output, you can analyze the effects of each input independently and add them together when you are all done. Using Thevenin's theorem allows you to reduce basically any circuit into a voltage divider. There is a sister theorem called Norton's, which does the same thing but is based on current rather than voltage. Since you can solve any electrical problem with either equation, I suggest you focus on one or the other. The most important rule when Thevenizing is this: Voltage sources are shorted, current sources are opened.

Direct Current and Alternating Current

The term direct current is used to describe current that flows in only one direction. Direct current moves only one way, from positive to negative. A battery is a common direct-current device. A battery is also a constant-voltage device, so it will apply whatever current is needed to maintain its output voltage. So, we have 12 V hooked up to 1 Ω of resistance, then that would be 12 amps of current. A DC source will always try to move current in the same direction. One thing to note is that the current coming out of the source always needs to get back to the source somehow. The ground connection on the schematic should be thought of as a label that connects the signal back to the source. If the signal does not get back to the source, then there is no current flow.

AC or alternating current came about as the interaction of magnets and electricity were discovered. In an AC circuit, the current repetitively changes direction every so often. That means current increases in flow to a peak, then decreases to zero current flow, then increases in flow in the opposite direction to a peak, then back to zero, and the whole process repeats. The current alternates the direction of flow in a sinusoidal fashion, so of course it is called alternating current. This type of current most commonly comes from big AC generators at your local hydroelectric dam. AC power came into being due to this ease of generation. When you move a coil of wire past a magnet, the current first climbs as the strength of the field increases, then as the field decreases and switches polarity, the current also decreases and switches polarity. The voltage and current change in a sinusoidal fashion naturally as the coil passes by the magnets. As long as you keep moving the coil, AC power will continue to be generated.

Capacitive and Inductive Reactance (Resistance) (Unit 6)

The cap is an infinite resistor at DC or zero frequency. As frequency increases, the "resistance" (technically known as reactance) of the cap gets lower and lower, approaching zero. This capacitive reactance is known as XC and its unit is ohms, just as for a resistor. The inductor is just the opposite. It starts with 0 Ω of resistance at a zero frequency and then increases to infinity along with the frequency. Inductive reactance is called XL. You can hook them up to an AC source and vary the frequency to see how current flow is affected.

Low Pass Filter (Unit 6)

This circuit is known as a low-pass filter because it passes low frequencies while reducing or attenuating high frequencies. All you really need to know to understand is the voltage-divider rule and how a capacitor reacts to frequency. If this were a simple voltage divider, you could figure out, based on the ratio of the resistors, how much voltage would appear at the output. Remember that the cap is like a resistor that depends on frequency and try to extrapolate what will happen as frequency sweeps from zero to infinity. At low frequencies the cap doesn't pass much current, so the signal isn't affected much. As frequency increases, the cap will pass more and more current, shorting the output of the resistor to ground and dividing the output voltage to smaller and smaller levels. There is a magic point at which the output is half the input. It is when the frequency equals $1/(2\pi RC)$. This frequency is called the cut-off frequency.

You can make a low-pass filter with an inductor and resistor, too. You swap the position of the components. That's because the inductor (being the opposite of a cap) passes the lower frequencies and blocks the higher frequencies. It performs the same function as the low-pass RC circuit but in a slightly different manner.

High Pass Filter (Unit 6)

Swapping the cap and the resistor in the low-pass circuit creates another type of circuit called a high-pass filter that means the circuit passes high frequencies while blocking low ones. The cap acts like a larger resistor at low frequencies, making the voltage divider knock down the output. At higher frequencies the cap passes more current as it becomes a short, causing a higher voltage at the output. To sum up, the high-pass and low-pass filters take advantage of the frequency response of either a capacitor or an inductor. This is done by combining them with a resistor to create a voltage divider that attenuates the unwanted frequencies while allowing the desired ones to pass.

Gates (Unit 3 in Electrical Engineering 101 3rd Edition)

The NOT gate inverts whatever signal you put into it; put in a 1, get a 0 out, and vice versa. The AND gate is described by the rule that all inputs need to be true or 1 in order for the output to be true. However, if either is false, the output must be false. The OR gate is defined as follows: If one of the inputs is true or high or 1, then the output becomes 1. If both inputs are zero or low, then the output becomes zero. There are more gates, but they are all built from these three basic gates. If you understand these, you can derive the rest. The NAND gate means NOT AND, and it is what it says. Invert the output of an AND gate with the NOT gate and you have a NAND gate. The NOR gate means the NOT OR gate. It is made by inverting the output of the OR gate, just like the NAND gate. XOR means exclusive or. You can think of it in this way: if both inputs are either 1 or zero, the output becomes zero. If not, then the output is 1.

Semiconductor (Unit 3)

First, what is a semiconductor? A *Conductor* in this case refers to the conduction of electricity. Think of a semiconductor as a material that partially conducts electricity or a material that is only semi-good at conducting electricity.

Diodes

A diode is made of two types of semiconductors pushed together. They are known as type P and type N. They are created by a process called doping. In doping silicon, impurity is created in the crystal that affects the structure of the crystal. The type of impurity created can cause some very cool effects in silicon as it relates to electron flow. Some dopants will create a type N structure in which there are some extra electrons simply hanging out with nowhere to go. Other dopants will create a type P structure in which there are missing electrons, also called holes.

Due to the interaction of the holes and the free electrons, a diode allows current to flow in only one direction. A perfect diode would conduct electricity in one direction without any effect on the signal. A diode has two important characteristics to consider: the forward voltage drop and the reverse breakdown voltage.

The forward voltage is the amount of voltage needed to get current to flow across a diode. This is important to know because if you are trying to get a signal through a diode that is less than the forward voltage, you will be disappointed. Another overlooked fact is that the forward voltage times the current through the diode is the amount of power being dissipated at the diode junction (the junction is simply the place where the P and N materials meet). If this power exceeds the wattage rating of the diode, you will soon see the magic smoke coming out. For example, you have a diode with a forward-voltage rating of 0.7 V and the circuit draws 2 A. This diode will be dissipating 1.4W of energy as heat (just like a resistor).

Although a perfect diode could block any amount of voltage, every diode has its price. If the voltage in the reverse direction gets high enough, current will flow. The point at which this happens is called the breakdown voltage or the peak inverse voltage. This voltage usually is pretty high, but keep in mind that it can be reached, especially if you are switching an inductor or motor in your circuit.

Transistor

The next type of semiconductor is made by tacking on another type P or type N junction to the diode structure. It is called a BJT, for bipolar junction transistor, or transistor for short. They come in two flavors: NPN and PNP. At first glance you would probably say, “This is just a couple of diodes hooked up back-to-back? You would be correct. It is a couple of diodes tied together, and yes, that prevents current flow. That is, unless you apply a current to the middle part, also known as the *base* of the transistor. When a current is applied to the base, the junction is energized and current flows through the transistor. The other connections on the transistor are called the collector and the emitter.

The NPN needs current to be pushed into the base to turn the transistor on, whereas the PNP needs current to be pulled out of the base to turn it on. In other words, the NPN needs the base to be more positive than the emitter, whereas the PNP needs the base to be more negative than the emitter. Remember the similarity to the diode? It is so close that the base-to-emitter junction behaves exactly like a diode, which means that you need to overcome the forward-voltage drop to get it to conduct.

Transistors are current-driven devices; they require significant current flow to operate. Most times the current flow needed in the base is 50 to 100 times less than the amount flowing through the emitter and collector, but it is significant compared to what are called voltage-driven devices.

FETs

FETs, or field effect transistors, were developed more recently than transistors and diodes. FETs have some properties that make them very desirable components. The primary reason is that the output of a FET is basically a resistance that varies depending on the voltage at the input. The outputs on an FET are called the drain and source, whereas the input is known as the gate. One very cool thing about an FET is the drain-to-source connection. It acts just like a resistor that you control by the voltage at the gate. This in effect makes it an electronically controlled variable resistor. For this reason, it is common to find FETs in circuits creating variable gain control. When used in switch mode, a term you should pay attention to is RDSon. This is the resistance drain to source when the device is turned all the way on. The lower this number, the less power you will lose across the device as heat. The voltage across the device will be the current times RDSon, and the power dissipated in heat will be this voltage times the current through the device.

DC-DC Converters (Unit 4 in Power Electronics Circuit Analysis and Design 2nd Ed)

There are basically three types of DC-DC converters that are 2nd order and using a FET and a diode: Buck Converters (Step-down), Boost Converter (Step-Up) and Buck-Boost Converter (Step up and down). Throughout these converters to obtain the steady-state characteristic equations, we will assume that power switching devices and the converter components are lossless. Moreover, the exact steady-state analysis of these converters requires solving second-order nonlinear systems. Such analysis is complex, and because of the nature of the output voltage, it is not necessary. Since these converters' function is to produce dc output, the output voltage Vo(t) consists of the desired dc and the undesired ac components. Practically, the output ripple due to switching is very small (less than 1%) compared to the level of the dc output voltage.

As a result, we will assume the output ripple voltage is small and can be neglected when evaluating converter voltage gains, i.e., vo¼Vo. In other words, the ripple-free output voltage assumption is made since the output time constant for the filter capacitor and the output resistor, RC, is very large. Moreover, the analysis will be based on the converter operating in steady-state condition, i.e., the converter currents and voltages have reached their steady-state values. Since we assumed ideal capacitors and inductors, the average inductor voltage and the average capacitor current are zero. In fact, this is a representation of Faraday's law, which states that voltage time during charging equals voltage time during discharging. This is also known as the volt-second principle. These two relations suggest that the total energy stored in the capacitor or the inductor over one switching cycle is zero. The voltage gain in DC-DC converters depends on the Duty Cycle. The duty cycle is defined as the ratio of ON time to the total period of the converter.

OP-AMP (Unit 10 in Electronic Devices and Circuit Theory 11th Ed)

An operational amplifier, or op-amp, is a very high gain differential amplifier with high input impedance (typically a few megohms) and low output impedance (less than 100 ohms). Typical uses of the operational amplifier are to provide voltage amplitude changes (amplitude and polarity), oscillators, filter circuits, and many types of instrumentation circuits. An op-amp contains a number of differential amplifier stages to achieve a very high voltage gain. The plus (+) input produces an output that is in phase with the signal applied, whereas an input to the minus (-) input results in an opposite-polarity output.

The basic circuit connection using an op-amp is shown in Figure A. The circuit shown provides operation as a constant-gain multiplier. An input signal *V*1 is applied through resistor *R*1 to the minus input. The output is then connected back to the same minus input through resistor *Rf.* The plus input is connected to the ground. Since signal *V*1 is essentially applied to the minus input, the resulting output is opposite in phase to the input signal. Therefore, this circuit is called Inverting Amplifier. If we use the ideal op-amp equivalent circuit, replacing *Ri* by an infinite resistance and *Ro* by a zero resistance, The result shows that the ratio of overall output to input voltage is dependent only on the values of resistors *R*1 and *Rf.*

The connection of an op-amp circuit that works as a noninverting amplifier is shown in Figure B. It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability. To determine the voltage gain of the circuit, we can use the equivalent representation. This must be equal to the output voltage, through a voltage divider of *R*1 and *Rf.*