Chapter 1

Introducing Circuit Analysis

In This Chapter

- Understanding current and voltage
- Applying laws when you connect circuit devices
- Analyzing circuits with algebra and calculus
- Taking some mathematical shortcuts

Circuit analysis is like the psychoanalysis of the electrical engineering world because it's all about studying the behavior of circuits. With any circuit, you have an input signal, such as a battery source or an audio signal. What you want to figure out is the circuit's *output* — how the circuit responds to a given input.

A circuit's output is either a voltage or a current. You have to analyze the voltages and currents traveling through each element or component in the circuit in order to determine the output, although many times you don't have to find *every* voltage and *every* current within the circuit.

Circuit analysis is challenging because it integrates a variety of topics from your math and physics courses in addition to introducing techniques specific to determining circuit behavior. This chapter gives you an overview of circuit analysis and some of the key concepts you need to know before you can begin understanding circuits.

Getting Started with Current and Voltage

Being able to analyze circuits requires having a solid understanding of how voltage and current interact within a circuit. Chapter 2 gives you insight into how voltage and current behave in the types of devices normally found in circuits, such as resistors and batteries. That chapter also presents the basic features of circuit diagrams, or *schematics*.

The following sections introduce you to current and voltage as well as a direction-based convention that's guaranteed to come in handy in circuit analysis.

Going with the flow with current

Current is a way of measuring the amount of electric charge passing through a given point within a certain amount of time. Current is a flow rate. The mathematical definition of a current is as follows:

$$i = \frac{dq}{dt}$$

The variable i stands for the current, q stands for the electrical charge, and t stands for time.

The charge of one electron is 1.609×10^{-19} coulombs (C).

Current measures the flow of charges with dimensions of coulombs per second (C/s), or *amperes* (A). In engineering, the current direction describes the net flow of positive charges. Think of current as a *through variable,* because the flow of electrical charge passes through a point in the circuit. The arrow in Figure 1-1 shows the current direction.

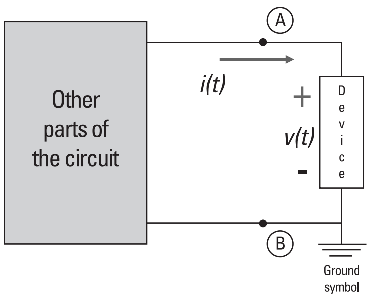

Figure 1-1: Current direction, voltage polarities, and the passive sign convention.

Illustration by Wiley, Composition Services Graphics

Measuring current through a device requires just one point of measurement. As an analogy, say you're asked to count the number of cars flowing through your long stretch of residential street for 10 minutes. You can count the number of cars from your home or your friend's home next door or the house across the street. You need just one location point to measure the flow of cars.

Two types of current exist: alternating current (AC) and direct current (DC). With AC, the charges flow in both directions. With DC, the charges flow in just one direction.

TIP

If you have trouble keeping AC and DC straight, try this mnemonic device: AC means "always changing," and DC means "doesn't change."

Recognizing potential differences with voltage

From physics, you know that plus and minus charges attract each other and that like charges repel each other. You need energy to separate the opposite charges. As long as the charges are separated, they have electric potential energy.

Voltage measures the amount of energy w required to move a given amount of charge q as it passes through the circuit. You can think of voltage as electric potential difference. Mathematically, voltage is defined as

$$v = \frac{dw}{dq}$$

Voltage has units of *volts* (V), which is the same as joules per coulomb (J/C). In a 12-volt car battery, the opposite charges on the battery terminals have a separation of 12 units of energy per unit of charge (or 12 V = 12 J/C). When terminals are separated, there's no current flow. If you provide a conducting path between the opposite charges, you now have charges flowing, resulting in an electric current.

REMEMBER

It takes two points to measure voltage across a device, just like it takes two points to measure height or distance. That's why you can think of voltage as an *across variable.*

Refer to Figure 1-1 to see the positive and negative voltage signs (called *polarities*) of a device, labeled at Terminals A and B.

Staying grounded with zero voltage

Because measuring voltage requires two points, you need a common reference point called a *ground.* You assign ground as 0 volts, where all other points in a circuit are measured with respect to ground. This is analogous to defining sea level as a reference point of 0 feet so you can measure the height of mountains. When the sea canyon is below sea level, you assign a negative algebraic sign. In circuits, the negative sign means the answer is less than the ground potential of 0 volts. Refer to Figure 1-1 to see an example of a typical ground symbol.

From algebra to calculus and back to algebra

When you're looking at simple circuits, such as a direct current (DC) circuit that involves only resistors and a constant battery source, you can get by with just algebra in your analysis. Because you don't have to worry about any fancy math, you can focus on analytical approaches such as node-voltage analysis (Chapter 5) and superposition (Chapter 7).

But when you start looking at more complex circuits, such as an alternating current (AC) circuit, the math becomes more complex. AC circuits have time-varying sources, capacitors, and inductors, so you need calculus to deal with the changes of electrical variables over time. Applying connection constraints (Kirchhoff's laws) to AC circuits gives you differential equations, but never fear! The chapters in Part IV show you how to solve differential equations of first-order and second-order circuits when you have capacitors and inductors connected to resistors.

Of course, sometimes you can use advanced techniques to skip over calculus entirely. You can convert differential equations into simpler algebraic problems using the Laplace transform method, which I introduce in Chapter 16.

TECHNICAL STUFF

You may have seen a streetcar with one trolley pole and an electric bus with two trolley poles. Why the difference? The streetcar uses its wheels as its ground point, so current coming from the generator flows back to the generator through the earth via the wheels grounded at 0 volts. For the electric bus, you need two wires because current can't flow through the rubber tires.

Getting some direction with the passive sign convention

Along with the algebraic signs of your calculated answers, the *passive sign convention* orients you to what's happening in a circuit. Specifically, it tells you that current enters a passive device at its positive voltage terminal.

Here's how passive sign convention works: You assign plus and minus signs to each device to serve as reference marks. After you arbitrarily assign the polarities of a device, you define the current direction so that it enters the positive side. (You can see what I mean by referring to Figure 1-1.) If your answers for voltage or current are positive, then the polarities line up with your assigned polarities or current direction. If your answers come up negative, they're opposite to your assigned polarities or current direction. A negative answer isn't wrong; it's just reverse to your assigned reference marks.

REMEMBER

The way you assign your polarities and current direction doesn't control the circuit behavior. Rather, the algebraic signs of your answers tell you the actual directions of voltages and current in the circuit.

Beginning with the Basic Laws

A circuit is basically a collection of electrical devices, such as resistors, batteries, capacitors, and inductors, arranged to perform a certain function. Each component of a circuit has its own constraints. When you connect devices in any circuit, the devices follow certain laws:

- **Ohm's law:** This law describes a linear relationship between the voltage and current for a resistor. You can find details about resistors and Ohm's law in Chapter 2.
- **Kirchhoff's voltage law (KVL):** KVL says the algebraic sum of the voltage drops and rises around a loop of a circuit is equal to zero. You can find an explanation of voltage drops, voltage rises, circuit loops, and KVL in Chapter 3.
- **Kirchhoff's current law (KCL):** KCL says the algebraic sum of incoming and outgoing currents at a node is equal to zero. Chapter 3 provides info on applying KCL and defines nodes in a circuit.

With these three laws, you can solve for the current or voltage in any device.

TIP

Applying Kirchhoff's laws can become tedious, but you can take some shortcuts. Source transformation allows you to convert circuits to either parallel or series circuits. Then, with all the devices connected in series or in parallel, you can use the voltage divider and current divider techniques to find the voltage or current for any device. I cover these techniques in Chapter 4.

Surveying the Analytical Methods for More-Complex Circuits

When you have many simultaneous equations to solve or too many inputs, you can use the following techniques to reduce the number of simultaneous equations and simplify the analysis:

- **Node-voltage analysis:** A node is a point in the circuit. This technique has you apply Kirchhoff's current law (KCL), producing a set of equations that you use to find unknown node voltages. When you know all the node voltages in a circuit, you can find the voltage across each device. I cover node-voltage analysis in Chapter 5.

- **Mesh-current analysis:** Mesh-current analysis deals with circuits that have many devices connected in many loops. You use Kirchhoff's voltage law (KVL) to develop a set of equations with unknown mesh currents. Because you can describe the device currents in terms of the mesh currents, finding the mesh currents lets you calculate the current through each device in the circuit. See Chapter 6 for info on mesh-current analysis.
- **Superposition:** When you have multiple independent power sources in a linear circuit, superposition comes to your rescue. Analyzing linear circuits involves using only devices (such as resistors, capacitors, and inductors) and independent sources. By applying superposition, you can take a complex circuit that has multiple independent sources and break it into simpler circuits, each with only one independent source. The circuit's total output then is the algebraic sum of output contributions due to the input from each independent source. Turn to Chapter 7 for details on superposition.
- **Thévenin's and Norton's theorems:** Thévenin and Norton equivalent circuits are valuable tools when you're connecting and analyzing two parts of a circuit. The interaction between the source circuit (which processes and delivers a signal) and load circuits (which consume the delivered signal) offers a major challenge in circuit analysis. Thévenin's theorem simplifies the analysis by replacing the source circuit's complicated arrangement of independent sources and resistors with a single voltage source connected in series with a single resistor. Norton's theorem replaces the source circuit with a single current source connected in parallel with a single resistor. You can find out more about both theorems, including how to apply them, in Chapter 8.

Introducing Transistors and Operational Amplifiers

Although transistors and operational amplifiers (op amps) are modeled with dependent sources, they're referred to as *active devices* because they require power to work. Transistors, which are made of semiconductor material, are used primarily as current amplifiers (see Chapter 9). Op amps are linear devices consisting of many transistors, resistors, and capacitors. They're used to perform many mathematical and processing operations, including voltage amplification (see Chapter 10). You can think of op amps as very high-gain DC amplifiers.

TECHNICAL STUFF

The op amp is one of the leading linear active devices in modern circuit applications. This device does mathematical operations (addition, subtraction, multiplication, division, integration, derivatives, and so on) quickly because it does them electronically. You put together basic op-amp circuits to build mathematical models.

Dealing with Time-Varying Signals, Capacitors, and Inductors

Circuits deal with signals that carry energy and information. *Signals* are time-varying electrical quantities processed by the circuit. Throughout the book, you deal with linear circuits, where the output signal is proportional to the input signal.

Chapter 11 introduces you to signal sources that change with time (unlike batteries, whose signals don't change with time). Signals that change in time can carry information about the real world, like temperature, pressure, and sound. You can combine basic functions such as sine and exponential functions to create even more interesting signals.

When you add passive, energy-storing elements (such as capacitors and inductors) to a circuit, the analysis gets a little tougher because now you need differential equations to analyze the circuit's behavior. In fact, the circuits created with capacitors and inductors get their names from the differential equations that result when you apply Kirchhoff's laws in the course of analysis:

- *First-order circuits,* which have a resistor and capacitor or a resistor and inductor, are described with first-order differential equations. The capacitor's current is related to the first derivative of the voltage across the capacitor, and the inductor's voltage is related to the first derivative of the current through the inductor. See Chapter 13 for help analyzing first-order circuits.
- *Second-order circuits* consist of capacitors, inductors, and resistors and are described by second-order differential equations. Flip to Chapter 14 for pointers on analyzing these circuits.

Avoiding Calculus with Advanced Techniques

I don't know about you, but I hate using calculus when I don't have to, which is why I'm a fan of the advanced circuit analysis techniques that allow you to convert calculus-based problems into problems requiring only algebra.

Phasors make your life simple when you're dealing with circuits that have capacitors and inductors, because you don't need differential equations to analyze circuits in the phasor domain. Phasor analysis investigates circuits that have capacitors and inductors in the same way you analyze circuits that have only resistors. This technique applies when your input is a sine wave (or a sinusoidal signal). See Chapter 15 for details on phasors.

Analyzing circuits with software

When circuits get too complex to analyze by hand, today's software offers many capabilities. Here are some commonly used software tools:

- **SPICE:** This software was originally developed at the Electronics Research Laboratory of the University of California, Berkeley. SPICE stands for Simulation Program for Integrated Circuit Emphasis. PSpice is a PC version of SPICE, and several companies, such as Cadence (`www.cadence.com`) and Linear Technology (`www.linear.com`), produce various versions of SPICE. Both companies offer demos and free versions of their software.
- **National Instrument's Multisim:** This is one of the granddaddies of circuit analysis software as well as a great tool for beginners. It also has a cool feature that shows changing voltages in real time of the circuit. The trial version pretty much lets you do anything you want. A student version is available as well. Visit `www.ni.com/multisim/` for more information.
- **Ngspice:** This tool is a widely used open-source circuit simulator from Sourceforge. The free Ngspice software (available at `ngspice.sourceforge.net`) is developed by many users, and its code is based on several major open-source software packages.

Chapter 16 describes a more general technique that's handy when your input isn't a sinusoidal signal: the Laplace transform technique. You use the Laplace transform to change a tough differential equation into a simpler problem involving algebra in the Laplace domain (or *s*-domain). You can then study the circuit's behavior using only algebra. The *s*-domain method I cover in Chapter 17 gives you the same results you'd get from calculus methods to solve differential equations, which you find in Chapters 13 and 14. The algebraic approach in the *s*-domain follows along the same lines as the approach you use for resistor-only circuits, only in place of resistors, you have *s*-domain impedances.

A major component found in older entertainment systems is an electronic filter that shapes the frequency content of signals. In Chapter 18, I present low-pass, high-pass, band-pass, and band-stop (or band-reject) filters based on simple circuits. This serves as a foundation for more-complex filters to meet more stringent requirements.

Chapter 18 also covers Bode diagrams to describe the frequency response of circuits. The Bode diagrams help you visualize how poles and zeros affect the frequency response of a circuit. The frequency response is described by a transfer (or network) function, which is the ratio of the output signal to the input signal in the *s*-domain. The *poles* are the roots of the polynomial in the transfer function's denominator, and the *zeros* are the roots of the polynomial in the numerator.