The Shocking Truth

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The secrets of electricity revealed.

During the past 15 years, many fundamental music-technology concepts have been explained in “Square One” (originally titled “From the Top”). In 1997 *EM* technical editor Scott Wilkinson combined many of those columns into a comprehensive primer titled *Anatomy of a Home Studio: How Everything Really Works, from Microphones to MIDI,* published by EMBooks, an imprint of Artistpro.com (www.artistpro.com). Our readership has continued to grow, and new readers shouldn't be left behind. Rather than try to reinvent the wheel, we will periodically reprint excerpts from the book as “Square One Classics.” These articles will clarify the essential, unchanging concepts that make it possible to be an electronic musician.

Electricity can be mysterious to many people, even those who have worked with music technology for years. But to get the most from the tools of electronic music, you need to understand the fundamental concepts of electricity. For example, manufacturer specifications mean nothing without them. (Some specs mean nothing anyway, but that's another story.) How can you make an informed purchasing decision without understanding what the specifications mean?

For now, I'll concentrate on four basic properties of electricity: current, voltage, impedance, and power. Understanding these properties is essential if you want to know how electronic equipment works. It's also critical for comprehending other concepts, such as decibels (which I'll explain in the next column).

CURRENT AND VOLTAGE

Most audio signals consist of electrons flowing through a conductor, such as a copper wire. This flow of electrons is called a *current*. The amount of current is measured in units called *amperes*, or *amps* (abbreviated *A*), after French physicist Andre Ampere; it is represented by the letter *I* in electrical equations.

There are two types of current: direct and alternating. Direct current (DC) flows steadily in one direction through a conductor; alternating current (AC) changes direction in the conductor at various frequencies. Analog-audio signals are alternating currents with waveforms and frequencies that correspond to acoustic sounds. These audio signals are called analog because the current's waveform is analogous to the acoustic waveform it represents.

An *electromotive force* (EMF) causes current to flow. The name makes sense when you think about it: EMF is a force that makes electrons move. EMF is more commonly called *voltage*, which is measured in units called *volts*, after Italian physicist Alessandro Volta, and is abbreviated *V*. It is represented by the letters *V* or *E* in electrical equations. Voltage is produced in many different ways, such as chemical reactions in a battery.

For a helpful analogy, think of voltage as the height of a hill. Because there is a difference in height between the hill's top and bottom, a ball rolls down the hill under gravity's influence. When the ball is at the top of the hill, it has potential energy; that is, it has the potential to move down. As it rolls down the hill, the potential energy is converted into kinetic energy, the energy of motion.

So the hill's top and bottom are at different heights, and the ball moves from one to the other. The same is true for voltage and current. Any voltage source has two *poles*, and electrons flow from one to the other. There is a potential difference in voltage between these poles: the bigger the difference, the greater the potential for moving electrons. However, that potential can't be fulfilled until an electrical conductor connects the two poles. If you connect the poles in this way, you create a circuit — or closed loop — through which the current flows.

One common voltage source is a battery, which has positive and negative poles. If you connect a conductor to these poles, electrons flow from the negative pole to the positive pole (see *Fig. 1*). If you've played with magnets, you know that opposite poles attract and similar poles repel each other. The same is true for electrons, which are negatively charged. They are repelled by a battery's negative pole and attracted to its positive pole.

AC/DC

Because a battery's voltage produces a direct current, its voltage is specified in units of VDC. If the poles of a voltage source alternate between positive and negative (as they do in a wall's power outlet, for example), the current changes direction periodically, and the voltage is specified in VAC.

Measuring the voltage from a battery or other DC source is easy. Returning to the hill analogy, the higher the hill, the more potential energy the ball has. The battery's voltage is analogous to the height of the hill: the more voltage, the more potential it has for moving electrons. To measure a battery's voltage, simply attach the two leads from a voltmeter to the poles and read the voltage (see *Fig. 2*).

Measuring alternating voltages is not so straightforward. You could simply measure the highest voltage level as it varies up and down, but what if the peak level changes from one cycle to the next, as it does at the output of most audio equipment? Taking the average of several peaks is better, but engineers have devised a more accurate way to measure alternating voltages: *root mean square* (RMS).

Here's how RMS voltage is calculated. (The process sounds complicated, but don't worry — you never have to do it. I'm describing it to explain what RMS means.) First, measure the instantaneous voltage value at many points during one complete cycle; that is similar to digital-audio recording. Then, square each voltage value (that is, multiply the value by itself). Next, calculate the average of those squared values and take the square root of that average. If the voltage variation takes the form of a sine wave with constant amplitude (as the voltage from a wall outlet does), the calculation becomes simpler: multiply the peak value by 0.707.

This is relatively complicated, but it yields a meaningful voltage value, even in the face of different peak levels over time. Fortunately, you don't need to worry about this process; anyone who wants to measure an alternating voltage can simply connect a voltmeter to the poles of the voltage source. The voltmeter does the squaring and averaging, giving you a readout in VRMS or VAC.

IMPEDANCE

In virtually all electrical circuits, there is some opposition to the flow of current; even copper wire opposes it to some degree. (The only exception is a circuit made with superconducting material, which exhibits practically no opposition to current. As of this writing, superconductors only exist inside laboratories.)

The opposition to direct current is called *resistance*, which is measured in units called *ohms*, after German physicist Georg Ohm. Resistance is abbreviated with the Greek letter omega (•), and it is represented in electrical equations by the letter *R*.

The opposition to alternating current is called *impedance*, which is also measured in ohms, but it's represented in electrical equations by the letter *Z*. Impedance is the sum of DC resistance and the *reactance* of the circuit, also measured in ohms and represented by the letter *X*. (To be completely accurate, reactance includes two parts, capacitive and inductive reactance, but this is not important for now.) Among other things, reactance depends on the alternating current's frequency.

Here's an important thing to understand: a circuit's impedance determines the *load* it places on the voltage source. If the circuit's impedance is high, it doesn't let much current flow, which places little demand on the voltage source to move electrons. Therefore, high impedance puts a small load on the voltage source. However, if impedance is low, the circuit doesn't resist the flow of current, which places greater demand on the voltage source to move electrons. Low impedance places a large load on the source. Impedance and load are inversely related; if impedance is high, the load is small, and vice versa.

In audio connections, you should be aware of two points of impedance: a source device's *output impedance* and a destination device's *input impedance*. In general, the lower the input impedance of the destination device, the greater the source device's load. As a result, a destination device's input impedance should be at least ten times the source device's output impedance.

The output impedance of most professional microphones is low, generally in the range of 150•, so mic preamps should have an input impedance of about 1,500• or 1.5 kilo-ohms (k•). (Some mic preamps have an input impedance as high as 10 k•, but the range from 1.5 to 3 k• is more typical.) Line-level devices, such as synths, also exhibit low output impedances in the 50 to 100• range, and they operate well with any input impedance more than 1 k•. Older synths and some consumer hi-fi equipment often have output impedances in the 100• to 1 k• range, which requires the destination device to have an input impedance in the 1 to 10 k• range.

An electric guitar's output impedance depends on the pickup design, the settings of the volume and tone controls, and the frequency produced. When the volume knob is turned up (which is usually the case), the guitar's output impedance is typically 3 to 10 k• at low frequencies and 100 to 500 k• at 10 kHz. When the volume is down, the output impedance is more constant, but it still varies by a factor of ten from low to high frequencies.

In addition, guitars are very sensitive to the input impedance of an amp or DI box; the higher the input impedance, the better the frequency response. Typical guitar amps have an input impedance in the 1 megaohm (M•) range, which gives you a high-frequency response as high as 20 kHz with single-coil or humbucking pickups; low-impedance pickups provide even more high-frequency response.

The relationship between voltage, current, and impedance is defined by *Ohm's Law*, which was derived by Ohm in 1827. The law can be stated in three equivalent ways:

$V = I \times Z$

$I = V/Z$
$Z = V/I$

Among other things, Ohm's Law clarifies the concept of load. Take a look at the first form of the law. If the voltage remains constant, the current will be high if the impedance is low, and vice versa.

POWER

Another common electrical quantity is *power*, which measures how much work can be done by a given voltage and current through a particular impedance. It is represented by the letter *P* in electrical equations, measured in units called watts (after Scottish engineer James Watt), and abbreviated *W* in measurements. DC electrical power is defined by *Joule's Law*, which is named for British physicist James Joule:

$$P = V \times I$$

If voltage and current alternate — as in an audio signal — so does power. As a result, alternating power is often expressed in *watts RMS*. This should be familiar to anyone who has shopped for a power amplifier. Joule's Law is slightly different for AC circuits:

$$P = K \times V \times I$$

K is a constant called the *power factor*, which depends on the circuit's reactance. Its value is always in the range of +1 to -1.

Here's another analogy that illustrates these concepts. Imagine a water tower with a pipe and a valve that lets the water flow from the tank to turn a water wheel (see *Fig. 3*). The distance between the tank and the water wheel corresponds to voltage; the higher the tank above the wheel, the more potential there is for the water to flow. The flow of water through the pipe corresponds to current.

The valve can be opened to different degrees, allowing more or less water through. As you might guess, this corresponds to impedance. The water turns the water wheel, which lets the wheel perform work (say, grinding flour). This corresponds to power. If the valve is mostly closed (impedance is high), little water flows (current is low), and the wheel does little work (power is low). On the other hand, if the valve is mostly open (impedance is low), lots of water flows (current is high), and the wheel can do lots of work (power is high).

The concepts of voltage, current, impedance, and power are essential to understanding basic electrical circuits and specifications. Once those concepts feel familiar, you'll find making the proper connections between pieces of equipment much easier. You'll also be able to make more sense of manufacturer specifications, which should help you make better purchasing decisions.

EM technical editor Scott Wilkinson has been zapped more than once after carelessly touching the poles of an AC wall outlet.