Basic Electronics for Field Measurement
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Introduction

Electricity has been used for more than a century as a source of motive power and means of conveying information. While the two uses may seem very different at first glance, they are governed by the same basic principles. Technicians in the modern oil and gas field can find a cursory understanding of these basics to be a great benefit when working to install, expand, or troubleshoot today's measurement and automation systems.

Fundamentals of Electricity

Electricity is the energy present in nature due to the property known as charge possessed by subatomic particles known as electrons and protons. Protons, along with neutrons, for the nucleus of an atom. Electrons orbit around the nucleus in a cloud. It is this electron cloud and nucleus which form the complete atom. By definition, protons carry a positive charge while electrons carry a negative charge. Each proton found in nature carries exactly the same amount of charge as every other proton. Likewise, the charge of each electron is identical, and is also the exact opposite magnitude of that of a proton. Unlike protons which are bound by strong fundamental forces to the other protons and neutrons in the nucleus, electrons can travel between atoms with relative ease. It is this property of electrons which make them useful to us.

The flow of charge carried by electrons is known as current, and is measured at a specific point by the fundamental unit of Amps (A). Electrons move from areas of high electron concentration to areas of low concentration. Because the electrons have negative charge, this means they are moving from areas of negative charge to those which are relatively more positively charged. Current is defined as flowing from areas of positive charge to negative charge, and therefore in the direction opposite of electron travel. The difference in relative densities of electrons means they have different relative charges. The difference in charge between two points is known as a potential difference, or Voltage, and is measured in Volts (V). Every material found in nature presents a certain amount of opposition to the flow of electrons. This opposition is known as resistance, and can be quantified in the units of Ohms (Ω).

Today, electricity is used in two primary ways: as a source of energy with which to do work, and as a means to convey information from one place to another. Regardless of its purpose, electricity is used in two different forms: Alternating Current (AC) and Direct Current (DC). Alternating Current is called such because the direction in which the current flows changes periodically. With Direct Current, the direction is always the same. Both forms of current flow have a number of applications, and there are means of changing electricity from one form to another. For the sake of this paper, all that is required is an understanding of how each behaves. When using electricity to convey information, it is typically called a signal. Signals have properties of both voltage and current, although often one or the other is focused on.

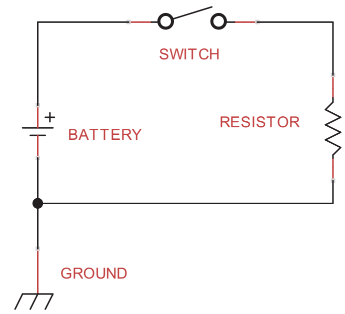
Electrical Circuits

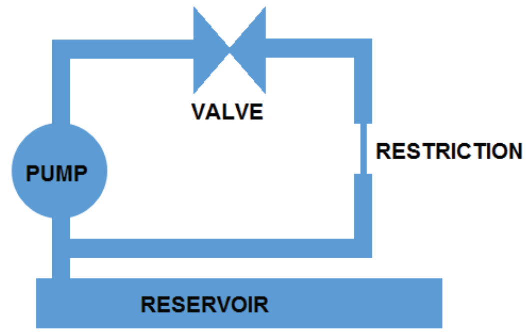
An electrical circuit is a combination of electrical devices, also referred to as components or elements, connected with wires. Elements can be a source of electrical power, dissipate that power, or change the way in which the voltage or current behaves. Wires are used to allow current to flow between elements, typically with as little resistance as possible. Elements that are capable of generating power are called active elements, and include devices such as batteries, generators, and solar panels. Elements that do not generate power, but otherwise affect the electricity flowing through them, are called passive elements. Passive elements include resistors, capacitors, diodes, and inductors, among others. A resistor is the simplest passive device, which opposes the flow of electricity through it, and turns electrical energy into heat. An example of a very simple circuit is a single lamp wired to a battery. The lamp's filament acts as a resistor, and the battery as a source of power.

In describing how a circuit is constructed, it is very important to understand the concepts of nodes, along with series and parallel wiring. A node is simply a part of a circuit where elements are connected. All points in a node have the same voltage, by definition. In the physical world, a node would consist of all of the wires which are connected directly together between two or more components. Series and parallel refer to the way in which multiple two-terminal devices are combined within a single circuit. With parallel wiring, the terminals of multiple devices are all connected to the same pair of nodes. In terms of batteries, which most people will find familiar, this means wiring together all of the "+" terminals at one node, and all of the "-" terminals at another. It's important to remember that all points on a node have the same voltage, which is why wiring batteries with different voltages in parallel with each other is a bad idea. With series connections, the "+" of one battery is tied to the "-" of another, and its "+" terminal tied to the "-" of a third, and so on. The devices which are wired together in combination need not be the same type in order to be referred to as being in series or parallel. A solar panel can be wired in parallel with a battery, and a switch can be wired in series with a lamp.

The Hydraulic Analogy

Because electrons are too small to view with the naked eye and react very quickly, electricity is a difficult phenomenon to view directly. While a light bulb can be seen to illuminate when current passes through it, an observer cannot see the electrons carrying the charge or even the direction of current flow. For this reason it can be helpful to those learning about electronics for the first time to think of basic circuits in terms of an analogous system. A very common analogy is one in which electricity is replaced by water, wires replaced by pumps, and other electrical circuit elements replaced by their water equivalents. In such an analogy, voltage is represented by water pressure and current is represented by the flow of water. A source of power can be thought of as a pump, and an electrical resistor can be shown with a restriction in the pipe. A simple diagram is shown below:



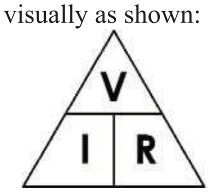


Ohm's and Kirchhoff's Laws

It is often necessary to calculate the current through a point or the voltage across a device. This can be to determine if a device is being supplied with the voltage it needs, to see if a signal will be strong enough when it reaches a receiver, to measure the amount of power required by a system, or countless other number of reasons. In order to do this, one must understand the relationship between voltage and current, and how it is affected by different circuit elements. The most basic relationship is known as *Ohm's Law*, after the German physicist Georg Ohm, who discovered it in 1826 and after whom the unit of electrical resistance is named. The law can be represented as:

$$I = \frac{V}{R}$$

Where I is the current, measured in Amps, V is the voltage in Volts, and R is the Resistance in Ohms. Stated in plain English, the current through a device is equal to the voltage across it divided by the resistance of that device. Thus, current can be increased by increasing the voltage or decreasing the resistance, and the resulting change is directly proportional. It can sometimes be helpful to represent this relationship visually as shown:



If trying to solve for one of the three values while the other two are known, simply cover up the unknown value. If you're left with V over I or V over R, simply divide the voltage by the current or resistance respectively to find the unknown value. If trying to solve for voltage, cover the V. This will leave I|R showing. Multiply those two values to find the voltage across the element in question.

Power is an important part of circuit analysis. Many devices in a system are limited in either the amount of power they can generate or dissipate. Often if this power limit is exceeded damage or injury can result. In an electrical circuit, the amount of power dissipated or absorbed by a component is equal to the voltage across its terminals multiplied by the current passing through it. This power is measured in Watts. Sometimes the current or voltage across a device isn't immediately known. However, if two of the three variables from Ohm's law are known, the third can be calculated and then the power in question can be determined. The resulting math can be simplified into the following equations:

$$P = VI = \frac{V^2}{R} = I^2R$$

There are two more relationships, which together with Ohm's law form the foundation of understanding electrical circuits. Both were described by German physicist Gustav Kirchhoff, and came to be known as Kirchhoff's voltage law and Kirchhoff's current law. *Kirchhoff's voltage law* states that the sum of the voltage drops and rises around a closed loop in a circuit is equal to zero. This means that if you were to draw out the electrical circuit in question and follow an arbitrary path until you end up where you started, the total of all the voltage drops across any passive devices encountered would equal the total of voltages added by active devices.

Kirchhoff's current law states that the sum of currents entering a node or closed boundary is equal to zero. In a simple two-device connection, this means that the current entering the node from one device is the same amount of current leaving the node into the other device. A "closed boundary" expands on this to include multiple circuit elements which could have multiple nodes connecting them. The sum of all currents entering this network of devices must be zero. Another way to think about Kirchhoff's current law is that electrical current cannot be created or destroyed in part of a circuit, only split and combined. While some active elements are referred to as current sources, it is important to know that any current leaving a current source is also entering it at the other end.

These fundamental circuit laws apply equally well in a first-order treatment of the hydraulic analogy. Ohm's law in the analogy shows us that the amount of water passing through a restricted section of pipe is directly proportional to the pressure applied across that section. It is inversely proportional to the degree of the restriction. Kirchhoff's voltage law shows that any closed loop path results in pressure drops and increases such that the sum is equal to zero. Kirchhoff's current law means that the amount of water entering a section of piping is the same amount as that which leaves.

Looking at electric circuits, it is necessary to understand how some basic circuit elements behave when combined in series or parallel. The following properties are a result of the aforementioned laws, but it is sufficient to simply remember them without understanding their derivation. The simplest circuit element is the resistor. Many loads, such as lamps, behave like resistors and can be treated as such for the purposes of circuit analysis. When resistors are combined in series, they can be treated as a single resistor with a resistance equal to the sum of the individual resistances. This is assuming the nodes which join them do not connect to any other elements in the circuit. When resistors are wired in parallel, their effective resistance is found with the following equation:

$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots}$$

Where R1, R2, and R_3 are the individual resistances. When the resistors all have the same value, this equation simplifies considerably. In that case, just divide the resistance by the total number of resistors to find the equivalent resistance.

Power sources such as batteries can be combined in multiple ways to achieve different results. A battery can be considered a voltage source. That is, the voltage across its terminals is fairly constant regardless of how much current it is putting out. If two similar batteries are wired in series, each will contribute their respective voltage, and the result is like a battery with twice the voltage but the same current capacity. If instead the batteries are wired in parallel, the combined output voltage remains the same, but the current capacity is doubled. Solar panels work in a similar fashion- wire them in series and their output voltage increases. Wire them in parallel and the current capacity increases.

Field Applications

For a technician in the modern oil and gas industry, these fundamentals are most often applied in two ways when designing or installing a system.

The first is in providing power for a system, whether the source of that power is a solar panel, wind turbine, or AC power. The second is in connecting field transmitters to their respective controllers. Designing power systems often involves sizing battery arrays to ensure that the necessary equipment is provided adequate power in the event that the main source is lost. This may mean overnight and during cloudy days in solar-powered systems, or utility power or generator loss in AC systems. The two specifications to look at first when sizing a battery array are the batteries' voltage and its capacity, measured in Amp-Hours (AH). If a battery has a capacity of 10 AH, it means that from a fully charged state, it would take 10 hours to fully drain the battery if the load is 1A. Alternately, a 10A load would drain the battery in 1 hour. As already discussed, the voltage across two batteries wired in series is equal to the sum of the individual voltages. Two batteries wired in parallel have the same output voltage but double the effective capacity. To achieve both a higher voltage and greater capacity, a combination of series and parallel wiring is required. Sizing an array of solar panels works similarly, although with solar panels or wind generators the current capability measured in Amps would be the specification of concern rather than the capacity. To determine the exact battery and solar or wind capacity required involves knowing the load voltage, average current, and backup time required. A detailed examination of this is beyond the scope of this paper.

When looking at how transmitters are connected to their controller, electricity is used both for powering the device and for transmitting information. In the case of loop-powered devices, the same electric current is used for both purposes. With other devices, the power and signal are kept separate. Some transmitters send their data back to the controller via an analog electrical signal, while others send the information digitally. With an analog signal, the voltage or current sent to the controller corresponds to the variable being measured. Both the transmitter and controller are configured to read a certain span, and calibrated in a way that a particular voltage or current corresponds to the low end of the scale, and another value corresponds to the high end. Commonly these signals are either 4-20mA (mA is the abbreviation for milliamps, or one one-thousandth of an Amp) or 1-5V. In an example where a temperature between 0º and 100º is being measured and transmitted with current, the transmitter would send a 4mA signal when the temperature is 0º, a 20mA signal when the temperature is 100º, and some value between the two when the temperature is between 0º and 100º. Likewise a transmitter using a voltage signal would send a voltage varying between 1 V and 5 V with temperature. Many transmitters are only capable of transmitting their data as either a voltage or a current, and this is not selectable. Likewise some controllers can only read voltage, not current. In a situation where a transmitter sends current to a controller which must read voltage, a resistor can be used to convert the current to a voltage. If a 4-20mA signal needs to be converted to a 1-5V signal, which is fairly common, Ohm's Law tells us that a 250Ω resistor will do this, because 5V divided by 250Ω equals .02A (20mA), and 1V divided by 250Ω equals .004A (4mA). This resistor would be connected between the sensing terminal on the controller and ground.

With digital transmitters, the signal current or voltage does not directly represent the variable being measured. Rather it varies between high and low, which is interpreted by the controller as a 1 or 0. This type of signal is known as a discrete signal, the opposite of continuous or analog. The information carried by this discrete signal is said to be encoded digitally. In order for a controller to read from a digital transmitter, the controller must "speak the same language" as the transmitter, as there are many different ways to communicate digitally.

Tools For The Technician

One of the most important tools for a technician in the modern electronic oilfield is a digital multimeter. These devices have the ability to measure voltage between two points, current through a device, resistance across a device, and sometimes many other useful variables. Without proper knowledge on how to operate a multimeter, however, it offers little insight. A typical multimeter can be seen below.

From www.Fluke.com

The main components include a display, a knob for selecting the type of measurement used, and connections for the measurement leads. Which terminals the leads get connected to depend on which type of measurement is needed. The way in which the leads connect to the circuit depends on the measurement type as well. When measuring voltage, the leads are plugged into the appropriate terminals on the multimeter, with the test end of the leads touching the circuit at the two points between which the voltage is desired while the circuit is live. Note that both leads must connect to the circuit, since voltage must be measured between two points. A voltage at a point without a reference is a meaningless value. Often when talking about voltage in a circuit, a node is deemed the ground, and all point voltages are referenced to the ground node. When measuring resistance, the same terminals on the multimeter are used, but the component or components to be measured must be isolated from the rest of the circuit in a way which ensures no current will flow from the circuit through the component being tested. Any stray current will interfere with correct measurement. If the readout on the multimeter is close to 0, this indicates there is nearly no resistance between the two nodes being tested. These two nodes can be said to be short-circuited.

To measure current, a different pair of terminals on the multimeter is used, although usually one of the terminals is common to all types of measurement. Often there are two terminals to select from when measuring current, a high-current and a low-current. The current limits of each will be clearly labeled. These inputs are internally fused, and measuring more current than the terminal is rated for will likely blow the fuse. The meter must be placed in series with the circuit in order to read. This requires disconnecting part of the circuit and placing the meter leads across the gap. Multimeters can usually measure voltage and current in both AC and DC circuits, although these often require different selections on the meter. Some multimeters are equipped with a current clamp, which gets placed around a wire at the point at which the current measurement is to be made. This eliminates the need to disconnect the circuit and does not require current to flow through the multimeter. This is especially useful when troubleshooting live circuits which cannot be disconnected.

Another useful tool for the technician is a loop calibrator. While some multimeters have a current source built in and can be used as a loop calibrator, many do not. A loop calibrator is used to precisely measure or source current in 4-20mA control loop. Whenever there is a need for accuracy, it is important that when a transmitter sends a 20mA signal, the controller perceives it as such. Some transmitters and some controllers have the ability to have their inputs and outputs calibrated. To calibrate an output, you would use a loop calibrator to measure current inline just like with a multimeter and verify that what the transmitter shows is being output is the same as what is measured. To calibrate an input, the loop calibrator is used as a source of precise current, and the measured current at the end device is verified to be the same as what is being sourced by the calibrator.

To verify the output of a transmitter while it is measuring a process, one must able to measure the output and know the span it's configured to measure. The output of the device should be the same proportion of the output range as the process variable is to the span. That is, if the process variable is 25% of the span, the output should be 25% of the output range. This becomes slightly more complicated with signals which don't begin at 0 V or 0 A, which is common. The appropriate output of an analog transmitter can be found with the following equation:

$$Output \ = \ O_L + \frac{(P - P_L) * (O_H - O_L)}{P_H - P_L}$$

Where P, P_H, and P_L are the current process variable and the high and low span limits, respectively, and O_H and O_L are the upper and lower output limits respectively. This simplifies with common 4-20mA and 1-5V signals to look like the following:

$$Output\ (1 - 5\ V) = 1 + 4(\frac{P - P_L}{Span})$$

$$Output\ (4 - 20\ mA) = 4 + 16(\frac{P - P_L}{Span})$$

If nothing else, it is important to remember that when the process variable is at 50% of the span, the output should be 3V for a 1-5V signal, or 12mA for a 4-20mA signal.

Conclusion

While a thorough study of electricity takes years, a basic understanding of how it works can be invaluable to a technician in an oilfield where measurement and control systems are increasingly of an electronic type. Many textbooks and handbooks are available to help the interested gain a deeper understanding of the topic. While the microchips used inside electronic equipment are ever-changing, the field-level application remains fairly constant, making resources which may have been written a decade or more ago still very relevant today.

References

Alexander, C., and Sadiku, M. (2004), Fundamentals of Electric Circuits. New York: McGraw-Hill.

Multimeter image from *http://www.Fluke.com*