The Irresistible Ohm's Law and How it Rules Your Power System

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   Resistor Energy Ratings, Technology and Construction Types

The Irresistible Ohm's Law and How it Rules Your Power System

Ohm's law is one of those fundamental mathematical relations students learn in introductory electronics classes, and it is arguably one of the most memorable equations in physics and engineering. It is often used by engineers as a tool to describe a multitude of resistive and reactive effects in electronics, forming the basis of a convenient language for describing interactions between signals and circuits in electronics. Ohm's law hasn't gone away and continues to be a central part of electrical analysis for designers and engineers.

For power systems engineers, Ohm's law is important for determining accurate power distribution and dissipation so that appropriately rugged components can be selected. To see the importance of Ohm's law, we'll explore its usage alongside other fundamental physical laws for component design, systems analysis, and component selection.

BRIEF HISTORY OF OHM'S LAW

George Ohm originally formulated the law that bears his name empirically using experimental data. His work involved measurements of voltage and current through a variety of materials, and his work showed a tendency for the current through a circuit element to be directly proportional to the electromotive force (voltage) given to the same circuit element. Such a simple, universal relation was codified as the equation $V/I = R$. The nature of electrical resistance R was still not fully understood, and his discovery did not receive the recognition it deserved until 15 years later, when he was awarded the Copley Medal by the Royal Society.

The most well-known form of Ohm's law, $V = IR$, remains the version taught to electrical engineers to this day. However, a more general form of Ohm's law would be given by James Clerk Maxwell in his 1865 paper *A Dynamical Theory of the Electromagnetic Field*, published by the Royal Society. In it, he includes within his 8 equations a definition for Ohm's law in linear media in terms of a more general current density and the electric field: $J = \sigma E$. This more general relation accounts for the fact that the electric field and current density can vary in space, an important point that allows us to rewrite many wave propagation and high frequency phenomena in a more convenient language of circuit elements.

Today, we teach engineers the simpler equation $V = IR$ and confine Ohm's law to circuit analysis. Thanks to its fundamental use in circuit analysis, Ohm's law is used to describe observations around everything from wave propagation to crosstalk in a variety of electrical

systems, both for resistive and reactive systems. It's also a fundamental design equation, particularly for power systems that require careful selection of appropriate resistors to ensure safety and reliability.

HOW OHM'S LAW IS USED
Ohm's law doesn't tell the entire story of electromagnetism and its use in circuits, but it gets used alongside Kirchhoff's laws and other relations from Maxwell's equations for design and analysis tasks. Also related to Ohm's law is Watt's law, or P = VI, named after James Watt following his death. Together, these equations can be used to comprehensively understand and predict power distribution in systems design in three ways:

Circuit analysis: Ohm's law and Kirchoff's laws form the foundation of circuit analysis as implemented in SPICE or calculated by hand. The goal in circuit analysis is to determine the current and voltage distribution in a system, as well as to calculate power dissipation in each component. For power systems, which may include large resistors, Ohm's law is critical for determining where power is dissipated and how much power is dissipated in each circuit element, both of which are important parts of system reliability.

$$\text{Ohm's law: } V = IR$$
$$\text{Kirchhoff's voltage law: } \sum V_i = 0$$
$$\text{Kirchhoff's current law: } \sum I_i = 0$$

Field solvers: The more general form of Ohm's law, the associated Poisson's equation for charge density, and a continuity equation for electric charge can be used in a method of moments field solver to calculate impedance and associated network parameters. This is an advanced area of signal integrity in electronics packaging and PCB design, but the same concepts, and even the same mathematical techniques, can be used to calculate the resistance of a simple resistor.

$$\text{Ohm's law from Maxwell's equations: } J = \sigma E$$
$$\text{Poisson's equation: } \nabla^2 = \rho/\varepsilon$$
$$\text{Continuity: } \nabla \cdot J = -\frac{\partial \rho}{\partial t}$$

Component design: There is a simple design equation for resistors, which is derived from the general form of Ohm's law in Maxwell's equations using a line integral and the work-energy theorem from mechanics. For those who aren't physicists, there is no need to know all the math, but it is important to know how to use the result. Component designers can use a basic resistor design equation to determine the appropriate resistor aspect ratio (length to cross-section area ratio) required to reach a resistance target for a given material and conductivity, or vice versa.

$$R = \frac{\rho L}{A}$$

Power resistors are probably the easiest components to analyze with the standard resistance equation. Power resistor vendors use a combination of these methods, as well as thermal analysis and measurements, to ensure their products have the intended resistance and power dissipation specifications within required tolerances. At some point, however, Ohm's law is no longer correct, and designers should consider the limits of their components when designing their systems.

OHM'S LAW AND NONLINEAR SYSTEMS
Ohm's law is applicable to any circuit element as it serves to define a resistance or impedance for a specific voltage and current measurement. However, the relation between voltage, current, and frequency is not always linear. Semiconductors, complex devices with amplification and feedback, power systems, and high frequency systems can have resistance that is a nonlinear function of the input voltage/current and/or frequency.

Depending on the input voltage/current, device construction, and operating parameters, semiconductor devices can be operated in linear or nonlinear ranges. In power regulators, Ohm's law only works up to the limits imposed by a regulator circuit. In contrast to resistive linear regulators, semiconductor-based regulators will have some saturation current that limits the power that can be delivered to a downstream load.

In terms of using Ohm's law in systems, we now have resistance being a function of input voltage and/or current, such as would happen in a transistor or diode. This is undesirable behavior for resistors, the result is that power delivery throughout the system, including to passive linear components, is a nonlinear function of the input voltage and load connected to the system output. Designers need to consider power delivery limits, voltage drop throughout a system, and how these affect the real vs. reactive power delivery during evaluation and analysis when selecting components for power systems.

OHM'S LAW IN POWER SYSTEMS

Compared to other areas of electronics design, power systems designers need to use Ohm's law throughout the design process, as well as Kirchhoff's laws and Watt's law for power dissipation. Designers don't need to go to the same lengths as component manufacturers in their use of Ohm's law or resistance formulas. However, they do need to use Ohm's law to ensure their components are selected appropriately and can handle the required power dissipation during operation.

Components in power systems are always in danger of failure due to overstress, large transients, ESD, or power surges, and power systems designers can't use just any off-the-shelf components for power delivery, regulation, sensing, and conditioning. Power systems designers need to select components in several categories that can withstand power and thermal demands.

Power resistors come in large and small resistance values, as well as several form factors and power dissipation ratings, depending on their place in power systems. In power systems design, a design engineer needs to consider both Ohm's law itself to determine an appropriate resistance. Power resistors (and other resistors in a design) must be chosen such that their power ratings exceed the real power dissipated according to Watt's law for some given safety factor. With SPICE and stress simulations, designers can get an accurate assessment of power dissipation, even in the nonlinear regime for a high-power regulator and select components appropriately.

Current sense resistors are smaller resistance components that are meant to have minimal voltage drop. In general, these are placed in series with a load component, and the voltage drop across these components can be measured with a differential amplifier. Inside a logic circuit or MCU, the sense resistance and the measured voltage are divided to determine the current passing through the resistor. Current sense resistors must have tight tolerances around the nominal resistance to ensure accurate current determination.

Surge protection components are components that are designed to withstand high energy dissipation over a particular time period, or high power at a specific peak voltage or current. These components include gas discharge tubes, silicon avalanche diodes, metal oxide varistors, wirewound resistors, and other components.

Surge protection resistors can come in high or low resistance values, being designed to withstand either high voltage, high current, high energy, or high power. The table below summarizes some applications of surge protection components.

Surge protection requirement	Application area
High energy	Ceramics, wirewound resistors
High current	Wirewound
High voltage	Thick-film, metal oxides, ceramic components
High power	Wirewound open-element
General purpose	Carbon composition molded, wirewound

While Ohm's law is the starting place for determining power distribution in a design, components should not only be selected to ensure they can withstand power demands as calculated in a design. Industry standards also set requirements on peak power that surge protection devices must be capable of withstanding. IEC standards generally applicable unless devices will be deployed in more specialized settings, such as automotive or aerospace.

CONCLUSION

Ohm's law isn't going away, and it remains a fundamental part of electrical engineering and physics. Power systems designers will continue to use Ohm's law as part of component selection and design evaluation in their systems analysis software. Similarly, power component designers and vendors rely on Ohm's law as the first step in setting resistance and power ratings for their components.

When you're looking for power resistors, sense resistors, and surge protectors that are reliable at high voltage, high power, high temperature, high current, or high energy, look at Ohmite's power resistor product lines. Ohmite offers a range of power resistors targeting these applications and more with standardized through-hole or surface-mount products. Ohmite also offers custom resistor assemblies for demanding applications where flexibility, form factor, and integration are critical.

Contact Ohmite today to learn more about our power products, EMI filters, and thermal management materials.

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