

all electrical engineering equation and formulas

Published: September 19, 2026 | Index ID: #-

Introduction

Electrical engineering is a discipline built on a rich tapestry of mathematical relationships that describe how voltage, current, resistance, and other electrical quantities interact. Whether you're a student tackling your first circuit lab, a professional designing power distribution systems, or an enthusiast exploring the fundamentals of electromagnetism, having a clear grasp of the core equations and formulas is essential. This guide compiles the most widely used equations in the field—ranging from simple Ohm's Law to Maxwell's equations—into a single, organized reference. By the end of this article, you'll have a solid toolkit to analyze circuits, predict power consumption, and understand the behavior of electromagnetic waves in various media.

Fundamental Circuit Relationships

Ohm's Law

$$V = I \times R$$

Where V is voltage (volts), I is current (amperes), and R is resistance (ohms). This foundational relationship is the starting point for virtually every circuit analysis.

Kirchhoff's Laws

- KCL (Kirchhoff's Current Law): The algebraic sum of currents entering a node equals zero.
- KVL (Kirchhoff's Voltage Law): The algebraic sum of voltage drops around any closed loop equals zero.

These laws enable the systematic solution of complex networks by setting up simultaneous equations.

Power in DC Circuits

$$P = V \times I$$

Alternatively, using Ohm's Law:

- $P = I^2 \times R$
- $P = V^2 / R$

These forms are interchangeable depending on which variables are known.

Alternating Current (AC) Fundamentals

Sinusoidal Voltage and Current

$$v(t) = V_m \sin(\omega t - \phi_v)$$

$$i(t) = I_m \sin(\omega t - \phi_i)$$

Where V_m and I_m are the peak values, ω is angular frequency (rad/s), and ϕ is the phase angle.

Impedance of Passive Elements

- Resistor: $Z_R = R$
- Inductor: $Z_L = j\omega L$

- Capacitor: $Z_C = 1 / (j\omega)$

Here, j is the imaginary unit, $\omega = 2\pi f$ and f is frequency in hertz.

Complex Power

$$S = V \times I^*$$

Where $S = P + jQ$ is the apparent power, P is real power, and Q is reactive power. The asterisk denotes the complex conjugate of the current phasor.

Power Factor

$$PF = \cos(\theta)$$

A power factor of 1 indicates purely resistive load; values below 1 reflect inductive or capacitive behavior.

Energy Storage Elements

Capacitor Energy

$$E = \frac{1}{2} C V^2$$

Inductor Energy

$$E = \frac{1}{2} L I^2$$

Transient Analysis

RC Discharge

$$V(t) = V_0 e^{-t/RC}$$

RL Rise

$$I(t) = (V/L) (1 - e^{-tR/L})$$

RLC Oscillation

$$V(t) = V_0 e^{-\zeta \omega_d t} \cos(\omega_d t + \phi)$$

Where ζ is the damping factor and $\omega_d = \omega \sqrt{1 - \zeta^2}$ is the damped natural frequency.

Transformers and Mutual Inductance

Transformer Turns Ratio

$$a = N_1 / N_2 = V_1 / V_2 = I_2 / I_1$$

Where N is the number of turns, and subscripts 1 and 2 refer to primary and secondary windings.

Mutual Inductance

$$V_2 = M (dI_1/dt)$$

With V being the induced voltage, M the mutual inductance, and I the current in the primary coil.

Transmission Line Theory

Characteristic Impedance

$$Z = \sqrt{(R + j\omega L)^2 + (\omega C)^{-2}}$$

Propagation Constant

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Where α is the attenuation constant and β is the phase constant.

Voltage and Current along the Line

$$V(z) = V_0 e^{-(\alpha + j\beta)z}$$

$$I(z) = (V_0 / Z_0) e^{-(\alpha + j\beta)z}$$

Electromagnetic Field Equations

Maxwell's Equations (Integral Form)

1. Gauss's Law for Electricity: $\oint \mathbf{E} \cdot d\mathbf{A} = Q_{enc} / \epsilon_0$
2. Gauss's Law for Magnetism: $\oint \mathbf{B} \cdot d\mathbf{A} = 0$
3. Faraday's Law of Induction: $\oint \mathbf{E} \cdot d\mathbf{l} = -d/dt \int \mathbf{B} \cdot d\mathbf{A}$
4. Ampère's Law (with Maxwell's addition): $\oint \mathbf{H} \cdot d\mathbf{l} = I_{enc} + d/dt \int \mathbf{D} \cdot d\mathbf{A}$

Maxwell's Equations (Differential Form)

1. $\nabla \cdot \mathbf{E} = \rho / \epsilon_0$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$
4. $\nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D} / \partial t$

Wave Equation for Electric Field

$$\nabla^2 \mathbf{E} + \mu_0 \epsilon_0 \omega^2 \mathbf{E} = 0$$

Electromagnetic Wave Speed

$$c = 1 / \sqrt{\mu_0 \epsilon_0}$$

Power Electronics Basics

DC–DC Converter Efficiency

$$\eta = P_{out} / P_{in}$$

Inverter Output Voltage

$$V_{out} = V_{dc} \times (4/\pi) \sin(\omega t)$$

For a single phase full bridge inverter using a square wave input.

Rectifier Average Output

- Full wave: $V_{dc} = (2V_m) / \pi$
- Half wave: $V_{dc} = V_m / \pi$

Control and Signal Processing

Transfer Function of a First Order System

$$H(s) = K / (s + \omega_c)$$

Where K is the system gain and τ time constant.

Root Locus Condition

$$1 + K G(s) = 0$$

Laplace Transform of Common Signals

- Step: $1/s$
- Impulse: 1
- Exponential decay: $1 / (s + a)$

Key Material Properties

Resistivity

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

Where A is cross sectional area and l the length.

Magnetic Permeability

$$\mu = \mu_0 \mu_r$$

Dielectric Constant

$$\epsilon = \epsilon_0 \epsilon_r$$

Where C is capacitance of the dielectric and C_0 of vacuum.

Practical Application Tips

- Always double check units before plugging numbers into formulas; mismatched units can lead to erroneous results.
- Use phasor notation for AC analysis; it turns differential equations into algebraic ones, simplifying the design process.
- Apply Kirchhoff's laws early to reduce the number of unknowns and set up solvable systems.
- Leverage simulation tools (e.g., SPICE, MATLAB) to validate analytical results, especially for higher order circuits.
- Remember safety margins—components often operate below their rated limits to ensure longevity and reliability.

Conclusion

Mastering the equations that govern electrical phenomena is more than an academic exercise; it's the foundation upon which reliable, efficient, and innovative systems are built. From the simple voltage–current relationship of Ohm's Law to the complex interplay of fields described by Maxwell's equations, each formula unlocks a deeper understanding of how energy moves and transforms. By internalizing these relationships, engineers can design better circuits

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