Formulas/Laws/Rules

(Assembled from various sources)

I am attempting to create a useful reference for most of the formulas/laws/theorems used by the amateur radio operator. Most references that I have found are catch-all's, such as the CRC manuals that include physics, chemistry, etc., or are designed for engineers with formulas hams will never need.

This reference is envisioned as a "memory jogger" not how they were derived or specifically how to use them. A few shortcuts and notes are included, as well as examples for the harder to understand formulas, and I feel confident they are correct but I have not verified them. Notes and shortcuts will be denoted in italics if they are from other sources or GHW if they are mine (as below).

I am having difficulty figuring out the best way to organize the information. So far the best I have come up with is to present them in the order you probably learned them.

1. **DC Circuits**
2. **AC Circuits**
3. **Antennas**
4. **DC Network Analysis**

If I have left out a formula you feel should be included or you have any suggestion for re-organizing the reference, send me an email (kj7ziz-g@proton.me), your help is appreciated.

GHW- *The hardest part from my perspective.*

Most laws and theorems are easy to state and understand. Such as **Kirchhoff's Current Law (KCL):** *"The algebraic sum of all currents entering and exiting a node must equal zero."* But, in actual usage are much more complicated. Most of these laws/theorems require you to analyze a circuit and formulate multiple equations that are solved by the use of simultaneous equations.

For me, the hardest part is in analyzing the circuit to "break" it down into its proper applicable parts, being consistent in my labeling, keeping track of what part I just solved (re-drawing the circuit and re-labeling if necessary), and writing equations that are correct. For instance you may have C_t (current total) and several branch currents (C_1, C_2, C_3…C_n). All of which you must keep track of which you are currently solving and which you have combined to solve for another.

Once the equations are written, the simultaneous solving becomes easy.

DC circuit equations and laws

Ohm's and Joule's Laws

- **Ohm's Law:**

  $E = IR$ $I = E/R$ $R = E/I$

- **Joule's Law:**

  $P = IE$ $P = E^2/R$ $P = I^2R$

  Where:
  E = Voltage in volts
  I = Current in amperes (amps)
  R = Resistance in ohms
  P = Power in watts

  NOTE*: the symbol "V" ("U" in Europe) is sometimes used to represent voltage instead of "E". In some cases, an author or circuit designer may choose to exclusively use "V" for voltage, never using the symbol "E." Other times the two symbols are used interchangeably, or "E" is used to represent voltage from a power source while "V" is used to represent voltage across a load (voltage "drop").*

Kirchhoff's Laws:

- "**The** *algebraic sum of all voltages in a loop must equal zero."*
  Kirchhoff's Voltage Law (KVL)
- *"The algebraic sum of all currents entering and exiting a node must equal zero."*
  Kirchhoff's Current Law (KCL)

Series circuit rules:

- *Components in a series circuit share the same current*. $I_{total} = I_1 = I_2 = \ldots I_n$
- *Total resistance in a series circuit is equal to the sum of the individual resistances, making it greater than any of the individual resistances*. $R_{total} = R_1 + R_2 + \ldots R_n$
- *Total voltage in a series circuit is equal to the sum of the individual voltage drops*. $E_{total} = E_1 + E_2 + \ldots E_n$

Parallel circuit rules:

- Components *in a parallel circuit share the same voltage*. $E_{total} = E_1 = E_2 = \ldots E_n$
- *Total resistance in a parallel circuit is less than any of the individual resistances*. $R_{total} = 1 / (1/R_1 + 1/R_2 + \ldots 1/R_n)$

- *Total current in a parallel circuit is equal to the sum of the individual branch currents.* $I_{total} = I_1 + I_2 + \ldots I_n$

Series and parallel component equivalent values

Series and parallel resistances:

Resistances:

- $R_{series} = R_1 + R_2 + \ldots R_n$
- $R_{parallel} = 1/(1/R_1 + 1/R_2 + \ldots 1/R_n)$

Series and parallel inductances

Inductances:

- $L_{series} = L_1 + L_2 + \ldots L_n$
- $L_{parallel} = 1/(1/L_1 + 1/L_{2} + \ldots 1/L_n)$

Where:
L = Inductance in henrys

Series and parallel capacitances

Capacitances

- $C_{series} = 1/(1/C_1 + 1/C_2 + \ldots 1/C_n)$
- $C_{parallel} = C_1 + C_2 + \ldots C_n$

Where:
C = Capacitance in farads

Capacitor sizing equation

- $C = \varepsilon A/d$

Where"
C = Capacitance in Farads
ε = Permittivity of dielectric (absolute, not relative)
A = Area of plate overlap in square meters
d = Distance between plates in meters

- $\varepsilon = \varepsilon_0 K$

Where,
ε_0 = Permittivity of free space
ε_0 = 8.8562 x 10-12 F/m
K = Dielectric constant of material between plates (see table below)

Dielectric constants			
Dielectric	K	Dielectric	K
Vacuum	1.0000	Quartz, fused	3.8
Air	1.0006	Wood, maple	4.4

PTFE, Teflon	2.0	Glass	4.9-7.5
Mineral oil	2.0	Castor oil	5.0
Polypropylene	2.20-2.28	Wood, birch	5.2
ABS resin	2.4 - 3.2	Mica, muscovite	5.0-8.7
Polystyrene	2.45-4.0	Glass-bonded mica	6.3-9.3
Waxed paper	2.5	Porcelain, steatite	6.5
Transformer oil	2.5-4	Alumina Al2O3	8-10.0
Wood, oak	3.3	Water, distilled	80
Hard Rubber	2.5-4.8	Ta2O5	27.6
Silicones	3.4-4.3	Ba2TiO3	1200-1500
Bakelite	3.5-6.0	BaSrTiO3	7500

A formula for capacitance in picofarads using practical dimensions:

- $C = 0.0885K(n-1)\ A/d = 0.225K(n-1)A'/d'$

Where:
C = Capacitance in picofarads
K = Dielectric constant
A = Area of one plate in square centimeters
A' = Area of one plate in square inches
d = Thickness in centimeters
d' = Thickness in inches
n = Number of plates

*** add pics for above & below or make in gimp!**

Inductors

- **Faraday's laws:** Voltage induced depends on rate of change of magnetic flux. For an EMF caused by a moving magnet, change of flux is proportional to strength of magnet, speed of magnet or coil, number of turns of coil and area of cross-section of coil.

- **Lenz's law:** The direction of induced EMF is such that it always opposes the change (movement in this example, or change of current through a coil) that causes it.

The voltage of the back-EMF can be calculated from the rate of change of current through the conductor and the details of construction of the conductor such as straight wire or coil, number of turns of coil, use of a magnetic core and so on (called inductance or, more correctly, self-inductance , symbol L).

  - L is defined in the equation:

    $E = L\ (dI/dt)$

    Where:
    E is the amount of back-EMF

L is inductance
dI/dt is the rate of change of current

*The symbol'd' is used here to mean a small change of the quantity that follows – the notation of calculus. If E is measured in volts and dI /dt is the rate of change of current in amps per second, then L is in units of henries (H),

Example: What back-EMF is developed when a current of 3A through a 0.5 H coil is reduced to zero in 20 ms?

The amount of back-EMF is found from:
$E = L\,(dI/dt) = 0.5 \times (3/20 \times 10^{-3}) = 75$ V

*The large EMF (equal to L(dI/dt)) which is generated when current is suddenly switched off in an inductive circuit can have destructive effects, causing sparking at contacts or breakdown of semiconductor junctions.

Inductor sizing equation

- $L = N^2\mu A/l$
- $\mu = \mu_r\mu_0$

Where:
L = Inductance of coil in Henrys
N = Number of turns in wire coil (straight wire = 1)
μ = Permeability of core material (absolute, not relative)
μ_r = Relative permeability, dimensionless (μ0=1 for air)
μ_0 = 1.26 x 10 -6 T-m/At permeability of free space
A = Area of coil in square meters = πr2
l = Average length of coil in meters
Wheeler's formulas for inductance of air core coils which follow are useful for radio frequency inductors. The following formula for the inductance of a single layer air core solenoid coil is accurate to approximately 1% for 2r/l < 3. The thick coil formula is 1% accurate when the denominator terms are approximately equal. Wheeler's spiral formula is 1% accurate for c>0.2r. While this is a "round wire" formula, it may still be applicable to printed circuit spiral inductors at reduced accuracy.

***Add pics**

$L = N^2r^{2/}9_r + 10\cdot l$ $\qquad$ $L = 0.8N^2r^2/6r + 9\cdot l + 10c$ $\qquad$ $L = N^2r^2/8_r + 11_c$

Where:
L = Inductance of coil in microhenrys
N = Number of turns of wire
r = Mean radius of coil in inches
l = Length of coil in inches
c = Thickness of coil in inches

TIME CONSTANT EQUATIONS

The inductance in henries of a square printed circuit inductor is given by two formulas where p=q, and p6=q.

$L = 85 \cdot 10^{-10} D N^{5/3}$

Where:
D = dimension, cm
N = number turns
p=q

$L = 27 \cdot 10^{-10} (D^{8/3}/p^{5/3})(1+R^{-1})^{5/3}$

Where:
D = coil dimension in cm
N = number of turns
R= p/q

The wire table provides “turns per inch” for enamel magnet wire for use with the inductance formulas for coils.

AWG gauge	turns inch	AWG gauge	turns inch	AWG gauge	turns inch	AWG gauge	turns inch
10	9.6	20	29.4	30	90.5	40	282
11	10.7	21	33.1	31	101	41	327
12	12.0	22	37.0	32	113	42	378
13	13.5	23	41.3	33	127	43	421
14	15.0	24	46.3	34	143	44	471
15	16.8	25	51.7	35	158	45	523
16	18.9	26	58.0	36	175	46	581
17	21.2	27	34.9	37	198		
18	23.6	28	72.7	38	224		
19	26.4	29	81.6	39	248		

Time constant equations

Value of time constant in series RC and RL circuits:

Time constant in seconds = RC or Time constant in seconds = L/R

- **Calculating voltage or current at specified time**
  Universal Time Constant Formula

  Change = (Final-Start)(1 – (1/e$^{t\tau}$)

  Where:
  Final = Value of calculated variable after infinite time (its ultimate value)
  Start = Initial value of calculated variable

e = Euler's number (2.7182818)
t = Time in seconds
τ = Time constant for circuit in seconds

- **Calculating time at specified voltage or current**

  $t = -\tau$ (1n (1- (Change/Final-Start)))

AC circuit equations

- **Inductive reactance**

  $X_L = 2\pi fL$

  Where:
  X_L = Inductive reactance in ohms
  f = Frequency in hertz
  L = Inductance in henrys

- **Capacitive reactance**

  $X_C = 1/2\pi fC$

  Where:
  X_C = Inductive reactance in ohms
  f= Frequency in hertz
  C = Capacitance in farads

- **Impedance in relation to R and X**

  $Z_L = R + {}_jX_L$

  $Z_C = R - {}_jX_C$

- **Ohm's Law for AC**

  E = IZ   I = E/Z   Z = E/I

  Where:
  E = Voltage in volts
  I = Current in amperes (amps)
  Z = Impedance in ohms

- **Series and Parallel Impedances**

  $Z_{series} = Z_1 + Z_2 + . . . Z_n$

  $Z_{parallel} = 1/ (1/Z_1 + 1/Z_2 + \ldots 1/Z_{n)}$

  NOTE: All impedances must be calculated in complex number form for these equations to work.

- **AC power**

P = true power $P = I^2R$ $P = E^2/R$

Measured in units of ***Watts***

Q = reactive power $Q = I^2X$ $Q = E^2/X$

Measured in units of ***Volt-Amps-Reactive (VAR)***

S = apparent power $S = I^2Z$ $S = E^2/Z$ S = IE

Measured in units of ***Volt-Amps***

P = (IE) (power factor) $S = \sqrt{P^2 + Q^2}$

Power factor = cos (Z phase angle)

Antennas

- **Frequency**

  f = 1/T

  Where:
  f = frequency
  T = period

- **Wavelength**

  λ = c/f

  Where:
  c = (speed of light) = 299,792,458 meters/sec (This is usually rounded to 300,000,000 m/s) = 186,000 mph
  f = frequency measured in Hertz (cycles per second)

- **Resonance**

  $f_{resonant} = 1/2\pi\sqrt{LC}$

  NOTE*: This equation applies to a non-resistive LC circuit. In circuits containing resistance as well as inductance and capacitance, this equation applies only to series configurations and to parallel configurations where R is very small.*

- **Length of antenna in feet**

  Length of wire in feet = 468/f or Length = 246/f

  Note: *This does not account for the velocity factor 468 or 246 should be multiplied by the velocity factor of the wire.*

  Where:

468 is for 1/2 wave length (0.95 vf usually works for initial lengths giving $\lambda = 445/f$ as the formula)
246 is for ¼ wave length (0.95 vf usually works for initial lengths giving $\lambda = 234/f$ as the formula)
f = frequency in Hertz (cycles per second)

Helpful Math Trick F:\Books\Electronics\Antennas\Notes

Here's a simple math trick to figure out if 468 isn't correct for your area. When the dipole is installed at the length of the standard equation determine the SWR at resonance. For example, resonance happens to be14.234 Mhz. Slightly higher than calculated. Here's the math to figure out a new constant.

where:

Original Length: 33ft.
New Resonant Freq: 14.234 MHz
33 x14.234˜=470
Now the equation for a dipole at your location is: Lfeet = 470/f MHz
Do the calculation one more time using the new constant to determine the new length and the new dipole will be resonant at the design frequency.

- **Decibels**

$A_{V(dB)} = 20 \log A_{V(ratio)}$ $\qquad$ $A_{V(ratio)} = 10^{A_V(dB)/20}$

$A_{I(dB)} = 20 \log A_{I(ratio)}$ $\qquad$ $A_{I(ratio)} = 10^{A_I(dB)/20}$

$A_{P(dB)} = 10 \log A_{P(ratio)}$ $\qquad$ $A_{P(ratio)} = 10^{A_P(dB)/10}$

DC Network Analysis

The major methods/theorems for DC network analysis are given below. **(Add the theorems)**

- Branch Current Method

The branch current method is a network analysis technique in which branch current directions are assigned arbitrarily, and then Ohm's law and Kirchhoff's current and voltage laws are applied systematically to solve for the unknown currents and voltages.

- Millman's Theorem

  *In Millman's Theorem, the circuit is re-*drawn as a *parallel* network of *branches, each branch containing a resistor or series battery/resistor combination. Millman's Theorem is applicable only to those circuits which can be redrawn accordingly.*

- Superposition Theorem

  The superposition theorem states that any linear circuit with more than one power source can be analyzed by summing the currents and voltages from each individual power source.

- Thevenin's Theorem

  Thevenin's theorem states that any linear circuit, no matter how complex, can be simplified to an equivalent circuit consisting of a single voltage source with a series resistance connected to a load.

- Norton's Theorem

  Norton's theorem states that any linear circuit can be simplified to an equivalent circuit consisting of a single current source and parallel resistance that is connected to a load.

- Maximum Power Transfer Theorem

  The Maximum Power Transfer Theorem is not so much a means of analysis as it is an aid to system design. Simply stated, the maximum amount of power will be dissipated by a load resistance when that load resistance is equal to the Thevenin/Norton resistance of the network supplying the power. If the load resistance is lower or higher than the Thevenin/Norton resistance of the source network, its dissipated power will be less than the maximum.

- Δ-Y and Y-Δ Conversions

  In many circuit applications, components are encountered connected together in one of two ways to form a three-terminal network: the "Delta," or Δ (also known as the "Pi," or π) configuration, and the "Y" (also known as the "T") configuration.

It is possible to calculate the proper values of resistors necessary to form one kind of network (Δ or Y) that behaves identically to the other kind, as analyzed from the terminal connections alone. That is, if we had two separate resistor networks, one Δ and one Y, each with its resistors hidden from view, with nothing but the three terminals (A, B, and C) exposed for testing, the resistors could be sized for the two networks so that there would be no way to electrically determine one network apart from the other. In other words, equivalent Δ and Y networks behave identically.

There are several equations used to convert one network to the other:

To convert a Delta (Δ) to a Wye (Y)

$$R_A = \frac{R_{AB}R_{AC}}{R_{AB} + R_{AC} + R_{BC}}$$

$$R_B = \frac{R_{AB}R_{BC}}{R_{AB} + R_{AC} + R_{BC}}$$

$$R_C = \frac{R_{AC}R_{BC}}{R_{AB} + R_{AC} + R_{BC}}$$

To convert a Wye (Y) to a Delta (Δ)

$$R_{AB} = \frac{R_AR_B + R_AR_C + R_BR_C}{R_C}$$

$$R_{BC} = \frac{R_AR_B + R_AR_C + R_BR_C}{R_A}$$

$$R_{AC} = \frac{R_AR_B + R_AR_C + R_BR_C}{R_B}$$