Appendices

Complete Formula Reference

Complete Formula Reference

This appendix provides a comprehensive reference of all formulas used in VIC circuit design and analysis. Formulas are organized by category for easy lookup.

1. Resonance Formulas

Formula	Equation	Units
Resonant Frequency	f? = 1 / (2??(LC))	Hz
Angular Frequency	?? = 2?f? = 1/?(LC)	rad/s
Period	T = 1/f? = 2??(LC)	seconds
Inductance (given f_0, C)	L = 1 / (4?²f?²C)	Henries
Capacitance (given f_0, L)	C = 1 / (4?²f?²L)	Farads

2. Q Factor and Magnification

Formula	Equation	Notes
Q Factor (inductive)	Q = 2?fL / R = ?L/R	At frequency f
Q Factor (capacitive)	Q = 1 / (2?fCR) = 1/(?CR)	At frequency f
Q from Z_0	Q = Z?/R = (1/R)?(L/C)	Series RLC
Voltage Magnification	$V_{out} = Q \times V_{in}$	At resonance
Characteristic Impedance	Z? = ?(L/C)	Ohms

3. Bandwidth and Damping

Formula	Equation	Notes
Bandwidth (-3dB)	$BW = f?/Q = R/(2?L)$	Hz
Decay Time Constant	$? = 2L/R$	seconds
Damping Factor	$? = R/(2L)$	rad/s
Damped Frequency	$f_d = ?(f?^2 - ?^2/(4?^2))$	Hz
Ringdown Cycles (to 1%)	$N ? 0.733 \times Q$	cycles

4. Capacitance Formulas

Formula	Equation	Notes
Parallel Plate	$C = ???_r A/d$	$\varepsilon_0 = 8.854\times10^{-12}$ F/m
Concentric Cylinders	$C = 2????_r L / \ln(r_o/r_i)$	L = length
Capacitors in Series	$1/C_{total} = 1/C? + 1/C? + ...$	
Capacitors in Parallel	$C_{total} = C? + C? + ...$	
Energy in Capacitor	$E = ½CV^2$	Joules

5. Inductance Formulas

Formula	Equation	Notes
Solenoid (air core)	$L = ??N^2A/l$	$\mu_0 = 4\pi\times10^{-7}$ H/m
Wheeler's Formula	$L(\mu H) = N^2r^2 / (9r + 10l)$	r, l in inches
A_L Method	$L = A_L \times N^2$	A_L in nH/turn^2
Inductors in Series	$L_{total} = L? + L?$ (no coupling)	
Mutual Inductance	$M = k?(L?L?)$	k = coupling coefficient
Energy in Inductor	$E = ½LI^2$	Joules

6. Resistance and Wire

Formula	Equation	Notes
Wire Resistance	R = ?L/A	ρ = resistivity
Wire Area (AWG)	A = ?(d/2)^2	d from wire tables
Skin Depth	? = ?(?/(?f?))	meters
Copper Skin Depth	?(mm) ? 66/?f(Hz)	Quick approximation
Power Dissipation	P = I^{2}R = V^2/R	Watts

7. Impedance Formulas

Element	Impedance	Phase
Resistor	Z = R	0°
Capacitor	Z = 1/(j?C) = -j/(2?fC)	-90°
Inductor	Z = j?L = j2?fL	+90°
CPE	Z = 1/(Q(j?)^n)	-n×90°
Warburg	Z = ?/?? × (1-j)	-45°

8. Electric Double Layer

Formula	Equation	Notes
Helmholtz Capacitance	C_H = ???$_r$A/d	d ≈ 0.3 nm
Debye Length	?$_D$? 0.304/?c (nm)	c in mol/L
Total EDL (series)	1/C = 1/C_{Stern} + 1/C_{diff}	

9. Cole-Cole Model

Complex Permittivity:

$?^* = ?_? + (?_s - ?_?) / [1 + (j??)^{(1-?)}]$

Effective Capacitance:

$C_{eff}(?) = C? \times [1 + (??)^{2(1-?)}]^{-1/2}$

10. Step Charging

Formula	Equation	Notes
Ideal N pulses	$V_{C,N} = 2N \times V_s$	Lossless
Maximum voltage	V_{max} ? $(4Q/?) \times V_s$	With losses
Half-cycle time	$t = ??(LC)$	For single pulse

Physical Constants

Constant	Symbol	Value
Permittivity of free space	??	8.854×10^{-12} F/m
Permeability of free space	??	$4\pi \times 10^{-7}$ H/m
Relative permittivity (water)	$?_r$	~80 at 20°C
Copper resistivity	$?_{Cu}$	1.68×10^{-8} Ω·m
Elementary charge	e	1.602×10^{-19} C
Boltzmann constant	k_B	1.381×10^{-23} J/K

Reference complete. Use with the VIC Matrix Calculator for automated calculations.

Glossary of Terms

Appendix B: Wire Gauge & Material Tables

Complete reference tables for wire properties used in VIC choke design. All values at 20°C (68°F) unless noted.

AWG Wire Gauge Reference

AWG	Diameter (mm)	Diameter (in)	Area (mm²)	Area (kcmil)	Cu Ω/1000ft	Cu Ω/km
10	2.588	0.1019	5.261	10.38	0.9989	3.277
12	2.053	0.0808	3.309	6.530	1.588	5.211
14	1.628	0.0641	2.081	4.107	2.525	8.286
16	1.291	0.0508	1.309	2.583	4.016	13.17
18	1.024	0.0403	0.823	1.624	6.385	20.95
20	**0.812**	**0.0320**	**0.518**	**1.022**	**10.15**	**33.31**
22	0.644	0.0253	0.326	0.642	16.14	52.96
24	**0.511**	**0.0201**	**0.205**	**0.404**	**25.67**	**84.22**
26	0.405	0.0159	0.129	0.254	40.81	133.9
28	**0.321**	**0.0126**	**0.081**	**0.160**	**64.90**	**212.9**
30	0.255	0.0100	0.051	0.101	103.2	338.6
32	0.202	0.0080	0.032	0.063	164.1	538.3
34	0.160	0.0063	0.020	0.040	260.9	856.0
36	0.127	0.0050	0.013	0.025	414.8	1361

AWG	Diameter (mm)	Diameter (in)	Area (mm²)	Area (kcmil)	Cu Ω/1000ft	Cu Ω/km
38	0.101	0.0040	0.008	0.016	659.6	2164
40	0.080	0.0031	0.005	0.010	1049	3441

Highlighted rows indicate commonly used gauges for VIC chokes.

Wire Material Resistivity

Material	Resistivity ρ (Ω·m)	Relative to Cu	Temp Coefficient α (/°C)
Silver (Ag)	1.59×10^{-8}	0.95×	0.0038
Copper (Cu)	1.68×10^{-8}	1.00× (reference)	0.00393
Gold (Au)	2.44×10^{-8}	1.45×	0.0034
Aluminum (Al)	2.65×10^{-8}	1.58×	0.00429
Brass	$6\text{-}9 \times 10^{-8}$	4-5×	0.002
Steel	1.0×10^{-7}	6×	0.005
Stainless Steel	6.9×10^{-7}	41×	0.001
Nichrome	1.1×10^{-6}	65×	0.0004

Temperature Correction

Resistance at Temperature T:

```
R(T) = R?? × [1 + ?(T - 20)]
```

Example (Copper wire):

- R_{20} = 10 Ω at 20°C
- At 50°C: R = 10 × [1 + 0.00393(50-20)] = 10 × 1.118 = 11.18 Ω
- At 80°C: R = 10 × [1 + 0.00393(80-20)] = 10 × 1.236 = 12.36 Ω

Magnet Wire Specifications

Magnet wire has enamel insulation. Overall diameter includes insulation:

AWG	Bare Dia. (mm)	Overall Dia. (mm)	Turns/cm	Turns/inch
18	1.024	1.09	9.2	23.3
20	0.812	0.87	11.5	29.2
22	0.644	0.70	14.3	36.3
24	0.511	0.56	17.9	45.4
26	0.405	0.45	22.2	56.4
28	0.321	0.36	27.8	70.6
30	0.255	0.29	34.5	87.6
32	0.202	0.24	41.7	106

Current Capacity Guidelines

For chassis wiring (in open air):

AWG	Max Current (A)	AWG	Max Current (A)
10	15	24	1.4
12	9.3	26	0.9
14	5.9	28	0.55
16	3.7	30	0.35
18	2.3	32	0.22
20	1.8	34	0.14

AWG	Max Current (A)	AWG	Max Current (A)
22	2.1	36	0.09

For coils, derate by 50% due to limited cooling. Magnet wire rated for higher temperature can handle more current.

Skin Depth Reference

At high frequencies, current flows near the wire surface. Skin depth δ:

```
? = ?(? / ?f????)
```

Skin Depth in Copper:

Frequency	Skin Depth (mm)	Max Useful Wire Dia.
1 kHz	2.1 mm	~4 mm (AWG 6)
10 kHz	0.66 mm	~1.3 mm (AWG 16)
50 kHz	0.30 mm	~0.6 mm (AWG 22)
100 kHz	0.21 mm	~0.4 mm (AWG 26)

Use wire diameter ≤ 2×δ for effective use of conductor cross-section. For larger currents at high frequencies, use Litz wire.

Quick Reference: DCR Calculation

For Copper Wire:

```
DCR (?) = Length (m) × Resistance (?/km) / 1000
```

DCR (?) = Length (ft) × Resistance (?/1000ft) / 1000

For Other Materials:

$DCR_{material} = DCR_{Cu} \times (?_{material}/?_{Cu})$

Wire Gauge Tables

Appendix C: Core Specifications

Reference specifications for magnetic cores commonly used in VIC choke design. Includes ferrite toroids, iron powder cores, and E-cores.

Core Material Overview

Material Type	μ_r Range	Frequency Range	Best For
MnZn Ferrite	800-10,000	1 kHz - 2 MHz	High L, moderate f
NiZn Ferrite	15-1,500	500 kHz - 100 MHz	High frequency
Iron Powder	8-100	10 kHz - 10 MHz	High current, low cost
MPP (Molypermalloy)	14-550	DC - 1 MHz	Low loss, stable
Kool Mμ	26-125	DC - 500 kHz	High current, moderate loss
Air Core	1	Any	No saturation, linear

Common Ferrite Materials

MnZn Ferrite Materials

Material	μ_i	B_{sat} (mT)	Frequency	Notes
Fair-Rite 77	2000	480	<1 MHz	General purpose, high μ
Fair-Rite 78	2300	480	<500 kHz	Very high μ
TDK N87	**2200**	**490**	**<500 kHz**	**Popular, low loss**

Material	μ_i	B_{sat} (mT)	Frequency	Notes
TDK N97	2300	410	<300 kHz	Very low loss
Ferroxcube 3C90	2300	470	<200 kHz	Low loss at high B
Ferroxcube 3F3	2000	440	<500 kHz	Higher frequency

Iron Powder Core Mix Chart

Iron powder cores (Micrometals/Amidon) are identified by color code:

Mix	Color	μ_r	Frequency Range	Application
-26	Yellow/White	75	DC - 1 MHz	EMI/RFI filters
-2	**Red/Clear**	**10**	**250 kHz - 10 MHz**	**RF, resonant circuits**
-6	Yellow/Clear	8.5	3 - 40 MHz	Higher frequency
-1	Blue/Clear	20	500 kHz - 5 MHz	Medium frequency
-3	Gray/Clear	35	50 kHz - 500 kHz	Medium μ, low f
-52	Green/Blue	75	DC - 200 kHz	High μ, DC bias

Common Toroid Sizes

FT (Ferrite Toroid) Series

Size	OD (mm)	ID (mm)	H (mm)	A_L (77 mat)	A_L (43 mat)
FT-37	9.5	4.7	3.2	884	440
FT-50	12.7	7.1	4.8	1140	570
FT-82	**21.0**	**13.0**	**6.4**	**2170**	**557**
FT-114	29.0	19.0	7.5	2640	603
FT-140	35.5	23.0	12.7	3170	885

Size	OD (mm)	ID (mm)	H (mm)	A_l (77 mat)	A_l (43 mat)
FT-240	**61.0**	**35.5**	**12.7**	**4820**	**1075**

A_l values in nH/turn^2. Highlighted sizes are commonly used for VIC chokes.

T (Iron Powder Toroid) Series

Size	OD (mm)	ID (mm)	H (mm)	A_l (-2 mix)	A_l (-26 mix)
T-37	9.5	4.9	3.2	4.0	27
T-50	12.7	7.7	4.8	4.9	33
T-68	17.5	9.4	4.8	5.7	38
T-80	**20.2**	**12.6**	**6.4**	**8.5**	**55**
T-94	24.0	14.5	7.9	8.4	70
T-106	26.9	14.0	11.1	13.5	90
T-130	**33.0**	**19.7**	**11.1**	**11.0**	**96**
T-200	50.8	31.8	14.0	12.0	120

Inductance Calculations

Using A? Value:

```
L (nH) = A? × N²
```

```
N = ?(L / A?)
```

Example:

> - Want L = 10 mH = 10,000,000 nH
> - Using FT-240-77 (A_l = 4820 nH/turn^2)
> - N = $\sqrt{(10,000,000 / 4820)}$ = 45.6 turns
> - Use 46 turns for L ≈ 10.2 mH

Saturation Considerations

Saturation Flux Density (B_{sat}):

Material Type	B_{sat} (mT)
MnZn Ferrite	400-500
NiZn Ferrite	250-350
Iron Powder	800-1000
MPP	750

Calculating Peak Flux:

$B = (V \times t) / (N \times A_e)$

Where A_e is effective core area. Keep $B < 0.5 \times B_{sat}$ for linear operation.

Temperature Effects

Material	Curie Temp (°C)	Max Operating (°C)	μ vs. Temp
MnZn Ferrite	200-250	100-120	Peaks near 80°C, then drops
NiZn Ferrite	300-500	150	Relatively stable
Iron Powder	770 (iron)	125 (coating limited)	Stable

Core Selection Guide for VIC

For Primary Choke (L1):

- Moderate L (1-50 mH typical)
- Moderate current handling
- Consider: FT-82-77, FT-114-77, T-106-26

For Secondary Choke (L2):

- May need higher L (10-100 mH) for high Q
- Lower current typically
- Consider: FT-140-77, FT-240-77

For High Frequency (>100 kHz):

- Use lower-μ materials to maintain SRF margin
- Consider: Iron powder -2 or -6 mix, NiZn ferrite

Quick Reference: Turns Calculation

Desired L	FT-82-77	FT-240-77	T-106-26
1 mH	21 turns	14 turns	105 turns

Desired L	FT-82-77	FT-240-77	T-106-26
5 mH	48 turns	32 turns	236 turns
10 mH	68 turns	46 turns	333 turns
25 mH	107 turns	72 turns	527 turns
50 mH	152 turns	102 turns	745 turns

Approximate values. Verify with actual A_l from manufacturer datasheet.

Core Specifications

Glossary of Terms

A comprehensive glossary of technical terms used throughout the VIC Matrix educational content and calculator.

A

A_L (Inductance Factor)
A core specification in nH/turn² that allows quick calculation of inductance: $L = A_L \times N^2$

Alpha (α) - Cole-Cole
Distribution parameter (0-1) in the Cole-Cole model. α=0 is ideal Debye relaxation; higher values indicate broader distribution of relaxation times.

Alpha (α) - Damping
Damping factor in an RLC circuit: $\alpha = R/(2L)$. Determines how quickly oscillations decay.

Amplitude
The maximum value of an oscillating quantity, such as voltage or current.

B

Bandwidth (BW)
The frequency range over which a resonant circuit responds effectively. $BW = f_0/Q$ for a series RLC circuit.

Bifilar Winding
A winding technique where two wires are wound together in parallel, creating tight magnetic coupling and significant inter-winding capacitance.

Blocking Electrode
An electrode where no Faradaic (electrochemical) reactions occur, behaving purely as a capacitor.

C

Capacitance (C)

The ability to store electric charge. Measured in Farads (F). C = Q/V where Q is charge and V is voltage.

Characteristic Impedance (Z_0)

The ratio √(L/C) for an LC circuit. Represents the impedance level of the resonant system.

Charge Transfer Resistance (R_{ct})

The resistance associated with electron transfer at an electrode surface during electrochemical reactions.

Choke

An inductor used in a circuit to block or impede certain frequencies while allowing others to pass. In VIC context, the resonating inductors.

Cole-Cole Model

A mathematical model describing frequency-dependent dielectric behavior with distributed relaxation times.

Constant Phase Element (CPE)

A circuit element with impedance $Z = 1/[Q(j\omega)^n]$, used to model non-ideal capacitor behavior in electrochemical systems.

Coupling Coefficient (k)

A measure of magnetic coupling between inductors (0-1). $k = M/\sqrt{L_1 L_2}$ where M is mutual inductance.

D

DCR (DC Resistance)

The resistance of an inductor measured with direct current. Primary contributor to inductor losses.

Debye Length (λ_D)

The characteristic thickness of the diffuse layer in an electrochemical double layer. Decreases with increasing ion concentration.

Diffuse Layer

The outer region of the electric double layer where ion concentration gradually returns to bulk values.

Dielectric

An insulating material that can be polarized by an electric field. Water is a dielectric with high permittivity ($\varepsilon_r \approx 80$).

Double Layer

See Electric Double Layer (EDL).

E

EDL (Electric Double Layer)

The structure formed at an electrode-electrolyte interface, consisting of a compact layer of ions and a diffuse layer extending into solution.

EIS (Electrochemical Impedance Spectroscopy)
: A technique for characterizing electrochemical systems by measuring impedance across a range of frequencies.

ESR (Equivalent Series Resistance)
: The resistive component of a capacitor's impedance, causing power dissipation.

F

Faradaic Reaction
: An electrochemical reaction involving electron transfer at an electrode, such as water electrolysis.

Ferrite
: A ceramic magnetic material used for inductor cores, suitable for high-frequency applications.

Frequency (f)
: The number of complete oscillation cycles per second. Measured in Hertz (Hz).

G-H

Helmholtz Layer
: The compact inner layer of the EDL, where ions are closest to the electrode surface.

Hysteresis
: Energy loss in magnetic materials due to the lag between applied field and magnetization.

I

Impedance (Z)
: The total opposition to alternating current, including both resistance and reactance. Measured in Ohms (Ω).

Inductance (L)
: The property of a conductor that opposes changes in current by storing energy in a magnetic field. Measured in Henries (H).

IHP (Inner Helmholtz Plane)
: The plane passing through the centers of specifically adsorbed ions in the EDL.

L-M

LC Circuit
: A circuit containing an inductor and capacitor, capable of oscillating at a resonant frequency.

Mutual Inductance (M)

The inductance linking two coils, allowing energy transfer between them.

N-O

Nyquist Plot

A plot of imaginary vs. real impedance (-Z'' vs Z') used in EIS analysis.

OHP (Outer Helmholtz Plane)

The plane of closest approach for solvated (hydrated) ions in the EDL.

P

Parasitic Capacitance

Unintended capacitance in an inductor, arising from turn-to-turn and layer-to-layer effects.

Permittivity (ε)

A measure of how much electric field is reduced in a material compared to vacuum. $\varepsilon = \varepsilon_0\varepsilon_r$.

Permeability (μ)

A measure of how well a material supports magnetic field formation. $\mu = \mu_0\mu_r$.

PLL (Phase-Locked Loop)

A control system that maintains frequency lock with a reference signal, used to track resonance.

Q

Q Factor (Quality Factor)

A dimensionless parameter indicating the "sharpness" of resonance. $Q = \omega L/R = Z_0/R$. Higher Q means narrower bandwidth and higher voltage magnification.

R

Randles Circuit

An equivalent circuit model for electrochemical cells consisting of R_s, C_{dl}, R_{ct}, and Z_W.

Reactance

The imaginary part of impedance. Inductive reactance $X_L = \omega L$; capacitive reactance $X_C = 1/(\omega C)$.

Resonance

The condition where inductive and capacitive reactances are equal, resulting in maximum energy storage and voltage magnification.

Ringdown
The decay of oscillations after excitation stops, characterized by the time constant $\tau = 2L/R$.

S

Self-Resonant Frequency (SRF)
The frequency at which an inductor's parasitic capacitance resonates with its inductance. Above SRF, the inductor behaves as a capacitor.

Skin Effect
The tendency of AC current to flow near the surface of a conductor, increasing effective resistance at high frequencies.

Solution Resistance (R_s)
The ionic resistance of the electrolyte between electrodes.

Step Charging
A technique using multiple resonant pulses to progressively build voltage on a capacitor.

Stern Layer
The combined compact and diffuse layer model of the EDL.

T

Tank Circuit
A parallel LC circuit that "tanks" or stores energy, oscillating between magnetic and electric forms.

Tau (τ) - Time Constant
The characteristic time for decay. For an RLC circuit: $\tau = 2L/R$.

Toroidal Core
A doughnut-shaped magnetic core providing a closed magnetic path and good field containment.

V

VIC (Voltage Intensifier Circuit)
A resonant circuit configuration using chokes and capacitors to develop high voltage across a water fuel cell.

Voltage Magnification
The ratio of voltage across a reactive element to the source voltage at resonance. Equals Q for a series RLC circuit.

W

Warburg Impedance (Z_W)

Impedance arising from diffusion of electroactive species, characterized by 45° phase angle and $Z \propto 1/\sqrt{\omega}$.

WFC (Water Fuel Cell)

An electrochemical cell where water serves as the medium between electrodes, acting as a capacitive-resistive load in VIC circuits.

Z

Z_0 (Characteristic Impedance)

The natural impedance level of an LC circuit: $Z_0 = \sqrt{(L/C)}$. Also Q × R for a series RLC circuit.

Zero-Current Switching (ZCS)

A switching technique where transistors turn off when current is zero, minimizing switching losses.

Glossary compiled for the VIC Matrix educational series.