Energy Efficiency

Energy Efficiency Analysis

Understanding energy flow in VIC circuits helps optimize performance and evaluate system efficiency. This page covers how to analyze energy storage, transfer, and dissipation in resonant VIC systems.

Energy in Resonant Circuits

In an LC resonant circuit, energy oscillates between the inductor and capacitor:

Energy Storage:

E_L = ½LI² (energy in inductor)
E_C = ½CV² (energy in capacitor)

At Resonance:

$E_{total} = E_{L,max} = E_{C,max} = ½CV_{peak}^2$

Peak Energy (example):

> - C = 10 nF, V_{peak} = 1000 V
> - E = ½ × 10×10⁻⁹ × 1000² = 5 mJ

Energy Flow Diagram

```
                     Input Power
                          │
                          ↓
     ┌─────────────────────────────────────────────┐
     │              VIC CIRCUIT                     │
     │                                              │
     │  ┌──────┐      ┌──────┐      ┌──────┐       │
```

```
    │  │ L1   │──────│ L2   │──────│ WFC  │       │
    │  │ DCR  │      │ DCR  │      │ ESR  │       │
    │  └──────┘      └──────┘      └──────┘       │
    │      │             │             │          │
    │      ↓             ↓             ↓          │
    │  Heat Loss    Heat Loss     Heat Loss       │
    │  (copper)     (copper)      (solution)      │
    │                                  │          │
    │                                  ↓          │
    │                           Electrochemical   │
    │                           Work (desired)    │
    └─────────────────────────────────────────────┘
```

Loss Mechanisms

Loss Type	Formula	How to Minimize
Choke DCR Loss	$P = I^2 R_{DCR}$	Use larger wire, copper
Solution Resistance	$P = I^2 R_{sol}$	Optimize water conductivity
Core Loss	$P \propto f^\alpha \times B^\beta$	Choose low-loss core material
Skin Effect Loss	Increases R at high f	Use Litz wire at high f
Dielectric Loss	$P = \omega C V^2 \times \tan(\delta)$	Use low-loss capacitors

Q Factor and Efficiency

Q factor is directly related to energy efficiency per cycle:

Energy Loss Per Cycle:

$?E_{cycle} = 2? \times E_{stored} / Q$

Interpretation:

> > - Q = 10: Lose 63% of energy per cycle

> > - Q = 50: Lose 13% of energy per cycle
> > - Q = 100: Lose 6% of energy per cycle
> > - Q = 200: Lose 3% of energy per cycle

Energy Retention:

After n cycles: $E(n) = E? \times e^{(-2?n/Q)}$

Power Flow Analysis

Input Power

$P_{in} = V_{in} \times I_{in} \times \cos(?)$

For pulsed operation:

$P_{avg} = (1/T) \times ?V(t)I(t)dt$

Dissipated Power

$P_{diss} = I_{rms}^2 \times R_{total}$

Where $R_{total} = R_{DCR1} + R_{DCR2} + R_{sol} + R_{other}$

Useful Power

Power available for electrochemical work:

$P_{useful} = P_{in} - P_{diss}$

Or, for the WFC specifically:

$P_{wfc} = V_{wfc} \times I_{wfc} \times \cos(?_{wfc})$

Efficiency Calculations

Efficiency Type	**Formula**	**Typical Values**

Resonant Tank η	$\eta = Q/(Q+1) \approx 1 - 1/Q$	90-99% for high Q
Power Transfer η	$\eta = P_{wfc}/P_{in}$	50-90%
Voltage Multiplication η	V_{out}/V_{in} (at resonance)	10-100× typical

Energy Balance Verification

To verify your analysis is correct, energy must balance:

Steady State:

$$P_{in} = P_{DCR1} + P_{DCR2} + P_{sol} + P_{core} + P_{other}$$

Check:

- Sum all loss mechanisms
- Compare to measured input power
- Large discrepancy indicates missing loss or measurement error

Loss Breakdown Example

Component	Resistance	Power Loss (at 1A)	% of Total
L1 DCR	2.5 Ω	2.5 W	25%
L2 DCR	3.0 Ω	3.0 W	30%
$R_{solution}$	4.0 Ω	4.0 W	40%
Other (core, leads)	0.5 Ω	0.5 W	5%
Total	**10 Ω**	**10 W**	**100%**

Improving Efficiency

High-Impact Improvements:

1. **Reduce largest loss first:** In example above, R_{sol} is 40%—optimize water conductivity
2. **Use larger wire:** Each AWG step down reduces DCR by ~25%
3. **Choose better core:** Low-loss ferrite vs. iron powder
4. **Optimize water conductivity:** Not too high (electrolysis), not too low (resistance loss)
5. **Reduce connection resistance:** Good solder joints, clean contacts

Diminishing Returns:

Once a loss mechanism is <10% of total, further improvement has limited benefit. Focus on the dominant losses.

Thermal Considerations

All dissipated power becomes heat:

Component	Heat Concern	Mitigation
Choke windings	Wire insulation damage	Adequate wire size, ventilation
Ferrite core	Curie temp, permeability change	Keep below rated temperature
Water/WFC	Boiling, capacitance drift	Monitor temperature, allow cooling
Capacitors	ESR heating, life reduction	Use low-ESR types, derate

VIC Matrix Calculator: The simulation module calculates expected power dissipation in each component. Use this to identify thermal hotspots and verify your design won't overheat during operation.

Next: Experimental Validation Methods →

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