

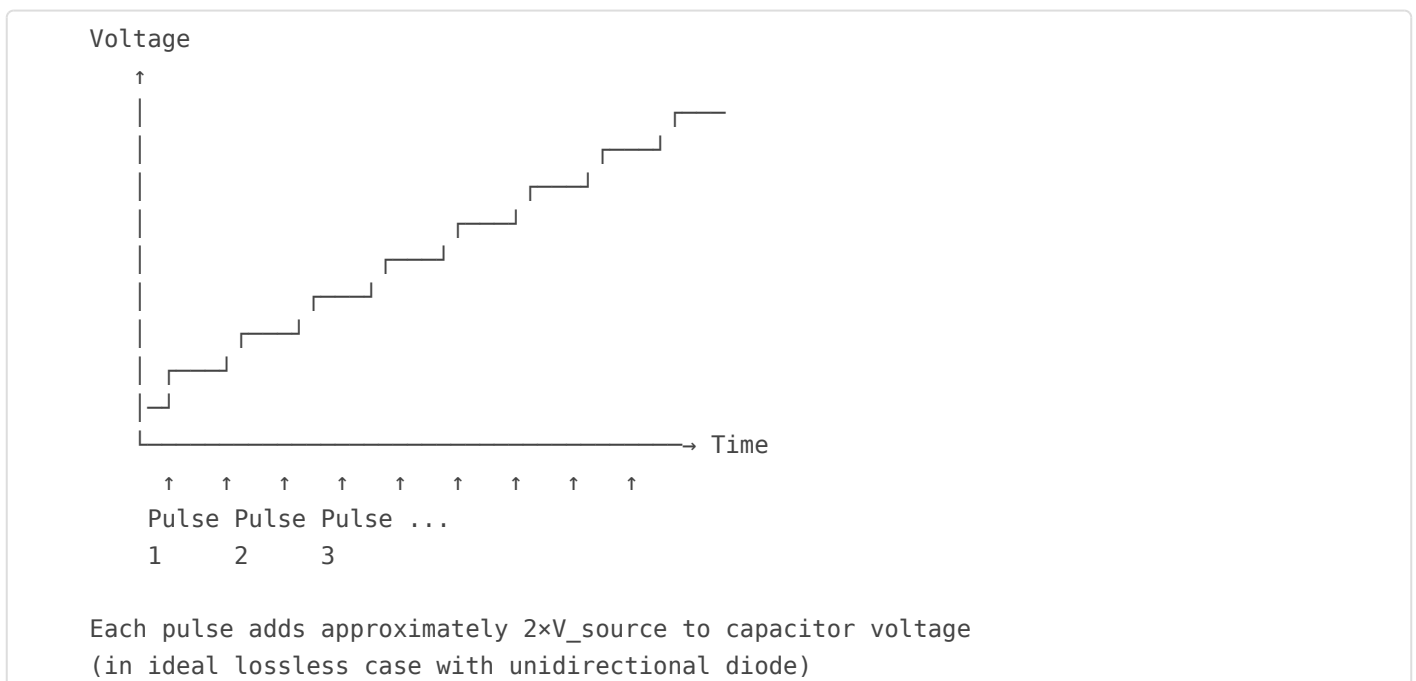
Step Charging

Step-Charging Ladder Effect

Step-charging, also known as the "staircase" or "ladder" effect, refers to the progressive buildup of voltage across a capacitor through successive resonant pulses. This technique can achieve voltage levels far beyond what single-pulse resonant charging provides.

The Concept

Instead of maintaining continuous oscillation, step-charging applies discrete pulses that each add a quantum of energy to the capacitor. The voltage builds up incrementally:

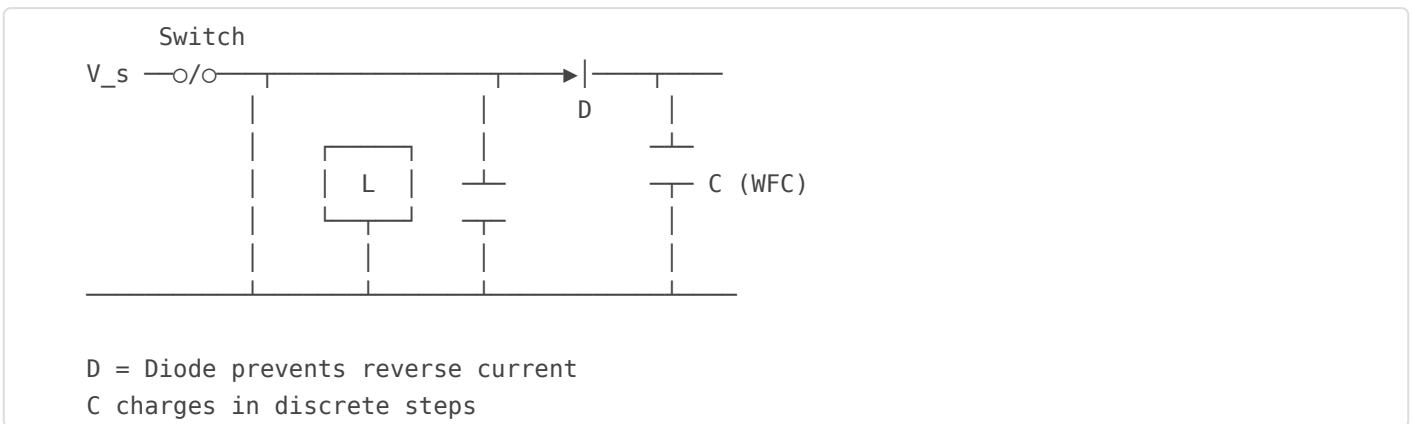


How Step-Charging Works

Step-by-Step Process:

1. **Pulse 1:** Capacitor charges from 0 to $2V_s$ (resonant half-cycle)
2. **Hold:** Diode prevents discharge back through inductor
3. **Pulse 2:** Starting from $2V_s$, capacitor charges to $\sim 4V_s$
4. **Hold:** Energy stored, waiting for next pulse
5. **Continue:** Each pulse adds $\sim 2V_s$ (minus losses)

Circuit for Step-Charging



Voltage After N Pulses

Ideal Case (no losses):

$$V_{C,N} = 2N \times V_{\text{source}}$$

With Losses (exponential decay factor):

$$V_{C,N} = 2V_s \times (e^{-\pi/(2Q)})^k \text{ for } k=0 \text{ to } N-1$$

Converges to Maximum:

$$V_{C,\text{max}} = 2V_s / (1 - e^{-\pi/(2Q)})$$

$$\text{For high } Q: V_{C,\text{max}} \approx (4Q/\pi) \times V_{\text{source}}$$

Maximum Voltage vs. Q Factor

Q Factor

$V_{\text{max}}/V_{\text{source}}$

Pulses to 90%

| | | |
|-----|-------|-----|
| 10 | ~12.7 | ~6 |
| 20 | ~25.5 | ~12 |
| 50 | ~63.7 | ~30 |
| 100 | ~127 | ~60 |

Comparison: Continuous vs. Step Charging

| Aspect | Continuous Resonance | Step Charging |
|----------------|--------------------------|----------------------------|
| Max voltage | $Q \times V_s$ (AC peak) | $(4Q/\pi) \times V_s$ (DC) |
| Waveform | Sinusoidal | Staircase |
| Power delivery | Constant | Pulsed |
| Complexity | Simpler | Needs diode/timing |

Step-Charging in VIC Systems

Meyer's designs allegedly used step-charging principles:

- **Unidirectional charging:** Diode prevents energy return to source
- **Pulse timing:** Gated pulses at resonant frequency
- **Voltage accumulation:** Progressive buildup across WFC
- **Controlled discharge:** Occasional reset or bleed-off of accumulated voltage

Pulse Train Design

Optimal Pulse Parameters:

- **Pulse duration:** $\pi\sqrt{LC}$ = half resonant period

- **Pulse frequency:** $f_{\text{pulse}} < f_{\text{resonant}}/2$
- **Duty cycle:** Typically 10-50%
- **Gap between pulses:** Allow ring-down and settling

Energy Considerations

Energy Stored After N Pulses:

$$E_{C,N} = \frac{1}{2}C(V_{C,N})^2 = \frac{1}{2}C(2NV_s)^2 = 2CN^2V_s^2$$

Energy Delivered per Pulse:

$$\Delta E = E_{C,N} - E_{C,N-1} = 2CV_s^2(2N-1)$$

Each successive pulse adds more energy because it's working against a higher voltage!

Practical Implementation

Driver Circuit Requirements:

1. **High-speed switching:** MOSFET or IGBT driver
2. **Precise timing:** Microcontroller or pulse generator
3. **High-voltage diode:** Fast recovery, rated for expected voltages
4. **Voltage monitoring:** Feedback to prevent over-voltage

Safety Considerations:

- Voltages can reach dangerous levels quickly
- Energy stored in capacitor can be lethal
- Include bleed resistor for safe discharge
- Implement hardware over-voltage protection

VIC Matrix Simulation

The VIC Matrix Calculator can simulate step-charging behavior:

- **Step-charge simulation:** Predicts voltage after N pulses
- **Loss modeling:** Accounts for resistance and dielectric losses
- **Time to saturation:** How many pulses to reach maximum voltage

- **Energy efficiency:** Tracks energy delivered vs. stored

Key Insight: Step-charging combines the voltage doubling of resonant charging with the cumulative effect of multiple pulses. With sufficient Q factor, extremely high voltages can be developed across the WFC—voltages that would be impossible to achieve directly from the source.

Chapter 4 Complete. Next: Choke Design & Construction →

Revision #1

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