Water Fuel Cell Design

WFC Introduction

Water Fuel Cell Basics

The Water Fuel Cell (WFC) is the heart of the VIC system—the component where electrical energy interacts with water. Understanding the WFC as an electrical component is essential for successful VIC circuit design.

What is a Water Fuel Cell?

A Water Fuel Cell consists of electrodes immersed in water, forming an electrochemical cell. Unlike conventional electrolysis cells designed for maximum current flow, the WFC in a VIC is treated as a capacitive load designed for maximum voltage development.

Basic WFC Components:

- **Electrodes:** Conductive plates or tubes (typically stainless steel)
- **Electrolyte:** Water (pure, tap, or with additives)
- **Container:** Housing to hold electrodes and water
- **Connections:** Electrical leads to the VIC circuit

WFC as an Electrical Component

Electrically, the WFC presents a complex impedance with both capacitive and resistive components:

```
Simplified WFC Equivalent Circuit:


     ┌─────────────────────────────────────┐
     │                                     │
(+)──┤   ┌─────┐    ┌─────┐    ┌─────┐    ├──(-)
     │   │C_edl│    │R_sol│    │C_edl│    │
     │   │     │    │     │    │     │    │
     │   └──┬──┘    └──┬──┘    └──┬──┘    │
     │      │          │          │       │
```

```
         │      └────┬─────┴─────┬────┘      │
         │           │           │           │
         │          ─┴─         ─┴─          │
         │          ─┬─ C_geo   ─┬─ R_leak   │
         │           │           │           │
         └───────────┴───────────┴───────────┘


    C_edl = Electric double layer capacitance (each electrode)
    R_sol = Solution resistance (water conductivity)
    C_geo = Geometric capacitance (parallel plate effect)
    R_leak = Leakage/Faradaic resistance
```

Capacitive vs. Resistive Behavior

Frequency	Dominant Behavior	Phase Angle	VIC Relevance
DC (0 Hz)	Resistive	0°	Conventional electrolysis
Low (1-100 Hz)	Mixed R-C	-20° to -60°	Transition region
Medium (100 Hz - 50 kHz)	Primarily capacitive	-60° to -85°	**VIC operating range**
High (>50 kHz)	Capacitive	-85° to -90°	Nearly ideal capacitor

Common WFC Configurations

1. Parallel Plate

Two flat plates facing each other with water between them.

- **Advantages:** Simple to build, easy to calculate
- **Disadvantages:** Limited surface area, edge effects
- **Typical spacing:** 1-5 mm

2. Concentric Tubes

Inner and outer cylinders with water in the annular gap.

- **Advantages:** Larger surface area, uniform field
- **Disadvantages:** Harder to machine precisely
- **Typical gap:** 0.5-3 mm

3. Tube Array

Multiple concentric tube pairs in parallel.

- **Advantages:** Maximum surface area, scalable
- **Disadvantages:** Complex construction, uniform spacing critical
- **Stanley Meyer's design:** Used 9 tube pairs

4. Spiral/Wound

Flat electrodes wound in a spiral with separator.

- **Advantages:** Very large surface area in compact volume
- **Disadvantages:** Complex to build, water flow issues

Key WFC Parameters

Parameter	Symbol	Typical Range	Effect
Electrode Area	A	10-1000 cm^2	$C \propto A$, affects gas production
Electrode Gap	d	0.5-5 mm	$C \propto 1/d$, $R \propto d$
Capacitance	C_{wfc}	1-100 nF	Sets resonant frequency with L2
Solution Resistance	R_{sol}	10 Ω - 10 kΩ	Affects Q factor

Water Properties Matter

The water used in the WFC significantly affects electrical behavior:

Water Type	Conductivity	R_{sol}	Notes
Deionized	<1 µS/cm	Very high	Nearly pure capacitor
Distilled	1-10 µS/cm	High	Low losses
Tap water	100-800 µS/cm	Medium	Variable by location
With NaOH/KOH	>10000 µS/cm	Low	Traditional electrolyte

VIC vs. Traditional Electrolysis

Traditional Electrolysis:

- DC voltage applied
- Current flows continuously
- Higher conductivity = more efficient
- Faraday's law determines gas production

VIC Approach:

- High-frequency pulsed/AC voltage
- Capacitive charging dominates
- Lower conductivity may be preferred
- Electric field stress is the focus

Key Insight: In VIC design, the WFC is treated primarily as a capacitor whose value must be matched to the choke inductance for resonance. The resistive component should be minimized for high Q, but some resistance is always present due to water's ionic conductivity.

Next: Electrode Geometry & Spacing →

Electrode Geometry

Electrode Geometry & Spacing

The physical design of WFC electrodes directly determines its electrical characteristics—capacitance, resistance, and field distribution. Proper geometry is essential for achieving target resonant frequencies and efficient operation.

Parallel Plate Electrodes

The simplest configuration with straightforward calculations:

Capacitance:

$$C = ???_r A / d$$

For Water ($?_r$? 80):

$$C\ (pF)\ ?\ 708 \times A(cm^2) / d(mm)$$

Example:

> - 10 cm × 10 cm plates = 100 cm^2
> - 2 mm gap
> - C = 708 × 100 / 2 = 35,400 pF = 35.4 nF

Concentric Tube Electrodes

Cylindrical geometry provides more surface area:

Capacitance:

$$C = 2????_r L / \ln(r_{outer}/r_{inner})$$

Simplified (for small gap relative to radius):

$C\ ?\ ???_r \times 2?r_{avg}L\ /\ d$

Where $d = r_{outer} - r_{inner}$

Example:

> - Inner tube: 20 mm OD
> - Outer tube: 22 mm ID
> - Length: 100 mm
> - Gap: 1 mm
> - C ≈ 708 × π × 2.1 × 10 / 1 = 46.7 nF

Tube Array Configurations

Multiple tubes in parallel increase total capacitance:

```
 Top View of 9-Tube Array:

        ┌───┐
      ┌─┤   ├─┐
    ┌─┤ └───┘ ├─┐
  ┌─┤ └───────┘ ├─┐
┌─┤ └───────────┘ ├─┐
│ └───────────────┘ │
│   Alternating     │
│   + and − tubes   │
└───────────────────┘

 Each concentric pair adds to total capacitance.
 C_total = C₁ + C₂ + C₃ + ... (tubes in parallel)
```

Electrode Spacing Trade-offs

Gap Size	Capacitance	Resistance	Field Strength	Practical Issues
Very small (<0.5 mm)	Very high	Low	Very high	Bubble blocking, arcing risk
Small (0.5-1.5 mm)	High	Medium-low	High	**Sweet spot**
Medium (1.5-3 mm)	Medium	Medium	Medium	Easy to build

Gap Size	Capacitance	Resistance	Field Strength	Practical Issues
Large (>3 mm)	Low	High	Low	Needs more voltage

Electric Field Calculation

Field Strength (uniform field approximation):

```
E = V / d
```

Example:

> - V = 1000 V (from VIC magnification)
> - d = 1 mm = 0.001 m
> - E = 1000 / 0.001 = 1,000,000 V/m = **1 MV/m**

Note: Water breakdown occurs at ~30-70 MV/m, so typical VIC fields are well below breakdown.

Surface Area Considerations

Larger electrode area provides:

- Higher capacitance (more energy storage)
- Lower current density (longer electrode life)
- More sites for gas evolution
- Better heat dissipation

But requires:

- Larger choke inductance (to maintain resonant frequency)
- More water volume
- Larger enclosure

Dimensional Design Process

Step 1: Determine Target Capacitance

From resonant frequency and available inductance:

$C_{target} = 1 / (4?^2f?^2L?)$

Step 2: Choose Geometry Type

Plates, tubes, or array based on available materials and space.

Step 3: Select Gap Distance

Balance capacitance needs with practical concerns (1-2 mm typical).

Step 4: Calculate Required Area

$A = C \times d / (???_r)$

Step 5: Dimension the Electrodes

For plates: Choose L × W. For tubes: Choose radius and length.

Practical Design Example

Target: f? = 10 kHz, L? = 50 mH available

Required capacitance:

$C = 1/(4?^2 \times 10000^2 \times 0.05) = 5.07\ nF$

Using parallel plates with 1.5 mm gap:

$A = 5.07 \times 10?? \times 0.0015 / (8.854\times10?^{12} \times 80) = 10.7\ cm^2$

Electrode size: ~3.3 cm × 3.3 cm plates (quite small!)

For more practical size, use 1 mm gap:

$A = 7.1\ cm^2\ ?\ 2.7 \times 2.7\ cm$ plates

Note: Very small WFC! May need to increase L_2 *for practical electrode sizes.*

Edge Effects

Real electrodes have fringing fields at edges that increase effective capacitance:

- For parallel plates, add ~0.9d to each edge dimension
- For tubes, end effects can add 5-10% to capacitance
- Guard rings can reduce edge effects in precision applications

Electrode Alignment

Critical Requirements:

- **Parallelism:** Plates must be parallel for uniform field
- **Concentricity:** Tubes must be truly concentric
- **Uniform gap:** Variations cause hot spots and non-uniform current
- **Insulating spacers:** Use non-conductive materials (PTFE, ceramic)

Gas Evolution Considerations

When gas is produced, it affects the electrical characteristics:

- Bubbles displace water, reducing effective capacitance
- Bubble layer increases resistance
- Vertical orientation helps bubbles rise and escape
- Perforated electrodes allow better bubble release

VIC Matrix Calculator: The Water Profile section calculates WFC capacitance from your electrode dimensions. Enter geometry type, dimensions, and spacing to get accurate capacitance values for circuit design.

Next: Water Conductivity & Dielectric Properties →

Water Properties

Water Conductivity & Dielectric Properties

Water's electrical properties—conductivity and dielectric constant—directly affect WFC performance in VIC circuits. Understanding these properties helps predict circuit behavior and optimize design.

Dielectric Constant of Water

Water has an exceptionally high dielectric constant due to its polar molecular structure:

Relative Permittivity ($?_r$):

> > | | |
> > |---|---|
> > | **Pure water at 20°C:** | $\varepsilon_r \approx 80$ |
> > | **Pure water at 25°C:** | $\varepsilon_r \approx 78.5$ |
> > | **Pure water at 100°C:** | $\varepsilon_r \approx 55$ |

Temperature Dependence:

$?_r(T) \ ? \ 87.74 - 0.40 \times T(°C)$

Why Water's $?_r$ is High

Water molecules are polar (have positive and negative ends). In an electric field, they align with the field, effectively multiplying the field's ability to store charge. This is why water-based capacitors have such high capacitance per unit volume.

Comparison with Other Materials

Material	ε_r	Relative Capacitance
Vacuum/Air	1	1× (reference)
PTFE (Teflon)	2.1	2.1×
Glass	4-10	4-10×
Ceramic	10-1000	10-1000×
Water	**80**	**80×**

Water Conductivity

Conductivity measures how easily current flows through water:

Conductivity (?) Units:

> > - Siemens per meter (S/m)
> > - Microsiemens per centimeter (μS/cm) - most common
> > - Millisiemens per centimeter (mS/cm)

1 S/m = 10,000 μS/cm = 10 mS/cm

Resistivity (? = 1/?):

ρ (Ω·cm) = 1,000,000 / σ (μS/cm)

Conductivity of Different Waters

Water Type	σ (μS/cm)	ρ (Ω·cm)	Source

Ultra-pure (Type I)	0.055	18,000,000	Lab grade
Deionized	0.1-5	200,000-10,000,000	DI systems
Distilled	1-10	100,000-1,000,000	Distillation
Rain water	5-30	33,000-200,000	Natural
Tap water (typical)	200-800	1,250-5,000	Municipal
Well water	300-1500	670-3,300	Ground water
Sea water	50,000	20	Ocean
0.1M NaOH	~20,000	~50	Electrolyte

Calculating Solution Resistance

For Parallel Plates:

$R_{sol} = ? \times d / A = d / (? \times A)$

Example:

> - Tap water: $\sigma = 500\ \mu S/cm = 0.05\ S/m$
> - Electrode area: $100\ cm^2 = 0.01\ m^2$
> - Gap: 2 mm = 0.002 m
> - $R_{sol} = 0.002 / (0.05 \times 0.01) = 4\ \Omega$

Effect on Q Factor

Solution resistance directly impacts circuit Q:

$Q_{total} = 2?fL / (R_{choke} + R_{sol} + R_{other})$

Example Impact:

Water Type	R_{sol}	Q (if $R_{choke}=5\Omega$)
Distilled (σ=5 μS/cm)	~400 Ω	Q ≈ 1.5
Tap (σ=500 μS/cm)	~4 Ω	Q ≈ 70
Electrolyte (σ=20000 μS/cm)	~0.1 Ω	Q ≈ 125

Insight: Very pure water has high Q losses! For VIC resonance, moderate conductivity may be optimal.

Frequency Dependence

Both ε_r and σ vary with frequency:

Frequency	ε_r Effect	σ Effect
DC - 1 MHz	Constant (~80)	Constant (DC value)
1 MHz - 1 GHz	Begins to decrease	May increase
>1 GHz	Decreases significantly	High dielectric loss

For VIC frequencies (1-100 kHz), these effects are negligible.

Temperature Effects Summary

- **ε_r:** Decreases ~0.4% per °C (capacitance drops as water heats)
- **σ:** Increases ~2% per °C (resistance drops as water heats)
- **Net effect:** Resonant frequency increases slightly with temperature

Measuring Water Properties

Conductivity Meters:

- TDS meters (approximate, assume NaCl)
- True conductivity meters (more accurate)
- Laboratory grade (calibrated, temperature compensated)

DIY Measurement:

1. Use known electrode geometry cell
2. Measure AC resistance at 1 kHz (to avoid polarization)
3. Calculate σ from geometry and resistance

VIC Matrix Calculator: Enter water conductivity in the Water Profile section. The calculator computes solution resistance and shows its impact on circuit Q. Temperature compensation is also available.

Next: Calculating WFC Capacitance →

Cell Capacitance

Calculating WFC Capacitance

Accurate calculation of WFC capacitance is essential for VIC circuit design. This page provides formulas and methods for determining the effective capacitance of various electrode configurations.

Total WFC Capacitance Model

The WFC has multiple capacitance contributions:

Series Model (simplified):

$1/C_{total} = 1/C_{edl,anode} + 1/C_{geo} + 1/C_{edl,cathode}$

For Practical VIC Frequencies:

At kHz frequencies, $C_{edl} >> C_{geo}$, so:

C_{total} ? C_{geo}

The geometric capacitance dominates for typical electrode gaps (>0.5 mm).

Geometric Capacitance Formulas

Parallel Plates

$C =$???$_r A / d$

Quick Formula for Water:

$C (nF) = 0.0708 \times A(cm^2) / d(mm)$

Example:

> - A = 50 cm^2, d = 1 mm
> - C = 0.0708 × 50 / 1 = 3.54 nF

Concentric Cylinders

$C = 2????_{r}L / ln(r_{o}/r_{i})$

Quick Formula for Water:

$C\ (nF) = 4.45 \times L(cm) / ln(r_{o}/r_{i})$

Thin Gap Approximation (when gap << radius):

$C\ (nF)\ ?\ 0.0708 \times 2?r_{avg}(cm) \times L(cm) / d(mm)$

Multiple Tubes (Array)

$C_{total} = n \times C_{single\ tube\ pair}$

Where n is the number of tube pairs in parallel.

Meyer's 9-Tube Array Example:

> - 9 concentric tube pairs
> - Each pair: C ≈ 5 nF
> - Total: C = 9 × 5 = 45 nF

Capacitance Calculator Table

Area (cm^2)	**Gap 0.5mm**	**Gap 1.0mm**	**Gap 1.5mm**	**Gap 2.0mm**
25	3.54 nF	1.77 nF	1.18 nF	0.89 nF
50	7.08 nF	3.54 nF	2.36 nF	1.77 nF
100	14.2 nF	7.08 nF	4.72 nF	3.54 nF
200	28.3 nF	14.2 nF	9.44 nF	7.08 nF

Area (cm²)	Gap 0.5mm	Gap 1.0mm	Gap 1.5mm	Gap 2.0mm
500	70.8 nF	35.4 nF	23.6 nF	17.7 nF

Including EDL Effects

For more accurate modeling at lower frequencies or smaller gaps:

EDL Capacitance per Electrode:

$C_{edl} = c_{dl} \times A$

Where $c_{dl} \approx$ 20-40 μF/cm² for stainless steel in water.

Total with EDL:

$1/C_{total} = 1/C_{geo} + 2/C_{edl}$

(Factor of 2 because both electrodes have EDL)

Example:

> - A = 100 cm², d = 1 mm, c_{dl} = 25 μF/cm²
> - C_{geo} = 7.08 nF
> - C_{edl} = 25 μF/cm² × 100 cm² = 2500 μF = 2.5 mF
> - 1/C = 1/7.08nF + 2/2.5mF ≈ 1/7.08nF
> - C_{total} ≈ 7.08 nF (EDL negligible)

Measuring WFC Capacitance

Method 1: LCR Meter

- Most accurate method
- Measure at 1 kHz and 10 kHz (should be similar)
- Provides both C and R (ESR)
- Temperature affects reading

Method 2: RC Time Constant

1. Connect WFC in series with known resistor R
2. Apply step voltage
3. Measure time to reach 63% of final voltage
4. $C = \tau / R$

Method 3: Resonant Frequency

1. Connect WFC with known inductor L
2. Drive with variable frequency
3. Find resonant peak
4. $C = 1 / (4\pi^2 f_0^2 L)$

Capacitance Variations

WFC capacitance can change during operation:

Factor	Effect on C	Typical Change
Temperature increase	C decreases (ε_r drops)	-0.4%/°C
Gas bubble formation	C decreases (less water)	-5% to -30%
Water level drop	C decreases	Proportional
Electrode coating	C may decrease	Variable
Applied voltage	Minor change	±5%

Design Workflow

1. Determine Required C

$C_{wfc} = 1 / (4?^2 f?^2 L?)$

2. Choose Electrode Gap

1-2 mm is typical. Smaller = higher C, larger = lower C.

3. Calculate Required Area

$A = C \times d / (???_r) = C(nF) \times d(mm) / 0.0708\ (cm^2)$

4. Design Electrodes

Choose plate dimensions or tube sizes to achieve area.

5. Verify by Measurement

Build prototype and measure actual capacitance.

VIC Matrix Calculator: The Water Profile section calculates WFC capacitance automatically. Enter electrode type, dimensions, and gap. The calculator also shows how the capacitance affects resonant frequency and provides warnings if values are outside recommended ranges.

Next: Matching WFC to Circuit →

Resonant Matching

Matching WFC to Circuit

For optimal VIC performance, the WFC must be properly matched to the circuit—its capacitance must resonate with the secondary choke at the desired operating frequency. This page covers the matching process and strategies for achieving good resonance.

The Matching Problem

In a VIC circuit, we have three interdependent parameters:

$$f? = 1 / (2??(L? \times C_{wfc}))$$

Design Challenge:

> - **f_0** is set by the pulse generator (typically 1-50 kHz)
> - **C_{wfc}** is constrained by electrode geometry and water properties
> - **L_2** must be designed to complete the resonant match

Matching Strategies

Strategy 1: Design L? for Given WFC

When WFC geometry is fixed (existing cell):

1. Measure C_{wfc} with LCR meter

2. Choose target frequency f_0
3. Calculate required L_2:

$$L? = 1 / (4?^2 f?^2 C_{wfc})$$

Example:

- C_{wfc} = 10 nF (measured)
- f_0 = 10 kHz (desired)
- $L_2 = 1 / (4\pi^2 \times 10^{42} \times 10^{-8}) = 25.3$ mH

Strategy 2: Design WFC for Given L?

When using a pre-wound or available choke:

1. Measure L_2 with LCR meter
2. Choose target frequency f_0
3. Calculate required C_{wfc}:

$$C_{wfc} = 1 / (4?^2 f?^2 L?)$$

4. Design electrodes to achieve that capacitance

Strategy 3: Tune with Additional Capacitor

When exact match isn't achievable:

If C_{wfc} is too low:

Add capacitor in parallel with WFC

$C_{total} = C_{wfc} + C_{tune}$

If C_{wfc} is too high:

Add capacitor in series with WFC (less common)

$1/C_{total} = 1/C_{wfc} + 1/C_{series}$

Impedance Matching Considerations

Beyond frequency matching, impedance levels affect energy transfer:

Secondary Characteristic Impedance:

$Z? = ?(L?/C_{wfc})$

Example Comparison:

> > | L_2 | C_{wfc} | f_0 | Z_0 |
> > |---|---|---|---|
> > | 10 mH | 25 nF | 10 kHz | 632 Ω |
> > | 50 mH | 5 nF | 10 kHz | 3162 Ω |
> > | 100 mH | 2.5 nF | 10 kHz | 6325 Ω |

Higher Z_0 = Higher voltage for same energy

Primary-Secondary Matching

For dual-resonant VIC with both L1-C1 and L2-WFC tanks:

Configuration	Condition	Effect
Same frequency	$f_{0_{pri}} = f_{0_{sec}}$	Maximum voltage magnification

Configuration	Condition	Effect
Slight offset	$f_{0_\text{sec}} \approx 0.95\text{-}1.05 \times f_{0_\text{pri}}$	Broader response, easier tuning
Harmonic	$f_{0_\text{sec}} = 2\times$ or $3\times f_{0_\text{pri}}$	Secondary resonates on harmonic

Finding Resonance

Method 1: Frequency Sweep

1. Connect oscilloscope across WFC
2. Sweep generator frequency slowly
3. Watch for voltage peak
4. Note frequency of maximum amplitude

Method 2: Phase Measurement

1. Monitor current and voltage simultaneously
2. At resonance, current and voltage are in phase (phase = 0°)
3. Below resonance: capacitive (current leads)
4. Above resonance: inductive (current lags)

Method 3: Minimum Current

For a series resonant circuit driven from a voltage source:

- Current is minimum at anti-resonance (parallel resonance)
- May need to reconfigure measurement

Troubleshooting Mismatch

Symptom	Likely Cause	Solution
No clear resonance peak	Very low Q (high losses)	Reduce water conductivity, lower DCR
Resonance far from expected	Wrong L or C values	Measure components, recalculate
Resonance drifts during operation	Temperature change, bubbles	Allow warmup, improve gas venting

Symptom	Likely Cause	Solution
Multiple resonance peaks	Coupled modes, parasitics	Check for stray coupling

Fine Tuning Tips

For L? Adjustment:

- Add/remove turns (large adjustment)
- Adjust core gap if gapped (medium)
- Use adjustable ferrite slug (fine)

For C_{wfc} Adjustment:

- Add parallel capacitor (increases C)
- Change water level (changes effective area)
- Adjust electrode spacing (if possible)

For Frequency Adjustment:

- PLL feedback to track resonance
- Variable frequency oscillator
- Multiple operating modes

Complete Matching Checklist

1. ☐ Measure or calculate C_{wfc}
2. ☐ Measure or calculate L_2
3. ☐ Calculate expected $f_0 = 1/(2\pi\sqrt{(L_2C)})$
4. ☐ Verify f_0 is within driver frequency range
5. ☐ Calculate $Z_0 = \sqrt{(L_2/C)}$
6. ☐ Estimate R_{total} (DCR + solution R)
7. ☐ Calculate $Q = Z_0/R$
8. ☐ Build circuit and measure actual resonance
9. ☐ Fine-tune as needed
10. ☐ Verify Q meets design goals

VIC Matrix Calculator: The Simulation tab performs complete matching analysis. Enter your choke and WFC parameters, and it calculates resonant frequency, Q factor, voltage magnification, and shows warnings if components are mismatched.

Chapter 6 Complete. Next: The VIC Matrix Calculator →