EDL in WFC

EDL Effects in Water Fuel Cells

This page integrates everything we've learned about the Electric Double Layer and applies it specifically to water fuel cell design in VIC circuits. Understanding these effects is crucial for accurate circuit modeling and optimization.

The Complete WFC Electrical Model

A water fuel cell is not a simple capacitor. Its complete electrical model includes:

```
  ┌────────────────────────────────────────────┐
  │                                            │
  │   ┌─────┐   ┌─────┐   ┌─────┐   ┌─────┐   │
──┤   │C_dl1│   │R_ct1│   │R_sol│   │C_dl2│   ├──
  │   │     │   │     │   │     │   │     │   │
  │   └──┬──┘   └──┬──┘   │     │   └──┬──┘   │
  │      │         │      │     │      │      │
  │      └────┬────┘      │     │      └──────┤
  │           │           │     │             │
  │       ┌───┴───┐       │     │      ┌─────┐│
  │       │ W₁    │       │     │      │C_geo││
  │       └───────┘       │     │      └─────┘│
  │                       │     │             │
  │      Anode EDL        │     │  Cathode EDL│
  └────────────────────────────────────────────┘
```

Components:

- **C_{dl1}, C_{dl2}:** Double layer capacitances at each electrode
- **R_{ct1}, R_{ct2}:** Charge transfer resistances (reaction kinetics)
- **W_1, W_2:** Warburg impedances (diffusion)
- **R_{sol}:** Solution resistance
- **C_{geo}:** Geometric capacitance

Frequency-Dependent Behavior

The WFC impedance changes dramatically with frequency:

Frequency Range	Dominant Element	WFC Behavior
Very low (<1 Hz)	Warburg diffusion	$Z \sim 1/\sqrt{f}$, 45° phase
Low (1-100 Hz)	Charge transfer R_{ct}	Resistive behavior
Medium (100 Hz - 10 kHz)	EDL capacitance C_{dl}	Capacitive, EDL dominant
High (10 kHz - 1 MHz)	Solution R + geometric C	RC network behavior
Very high (>1 MHz)	Geometric C_{geo}	Pure capacitance

EDL Time Constant

The EDL has a characteristic response time:

$$?_{EDL} = R_{sol} \times C_{dl}$$

The EDL fully forms in approximately $5\times\tau_{EDL}$.

Example:

> > - $R_{sol} = 100\ \Omega$ (tap water, small cell)
> > - $C_{dl} = 10\ \mu F$
> > - $\tau_{EDL} = 100 \times 10\times10^{-6} = 1$ ms
> > - Full formation time ≈ 5 ms

Implication: At frequencies above $1/(2\pi\tau) \approx 160$ Hz, the EDL cannot fully form and its effective capacitance decreases.

Effective WFC Capacitance

At VIC operating frequencies (typically 1-50 kHz), the effective WFC capacitance is:

Simplified Model:

$1/C_{eff} = 1/C_{geo} + 1/C_{dl,eff}$

Where $C_{dl,eff}$ is the frequency-reduced EDL capacitance.

Typical VIC Frequency Range:

- At 1 kHz: $C_{dl,eff} \approx 0.3\text{-}0.7 \times C_{dl}(DC)$
- At 10 kHz: $C_{dl,eff} \approx 0.1\text{-}0.3 \times C_{dl}(DC)$
- At 50 kHz: $C_{dl,eff} \approx 0.05\text{-}0.15 \times C_{dl}(DC)$

Non-Linear Capacitance Effects

The EDL capacitance depends on applied voltage:

- **Low voltage (<100 mV):** Capacitance relatively constant
- **Medium voltage (100 mV - 1V):** Capacitance increases with voltage
- **High voltage (>1V):** Electrochemical reactions begin, behavior becomes complex

VIC Implication:

As voltage across the WFC increases during resonant charging, the capacitance changes. This can cause:

- Resonant frequency shift during operation
- Detuning from optimal operating point
- Need for adaptive frequency control (PLL)

Temperature Effects in WFC

Parameter	Temperature Effect	Typical Change
Water ε_r	Decreases with T	-0.4% per °C

Parameter	Temperature Effect	Typical Change
Solution conductivity	Increases with T	+2% per °C
EDL thickness	Increases with T	+0.2% per °C
Reaction rate	Increases with T	~Doubles per 10°C

Practical WFC Design Considerations

Electrode Material Selection

- **316 Stainless Steel:** Good corrosion resistance, moderate C_{dl}
- **304 Stainless Steel:** Lower cost, slightly lower performance
- **Titanium:** Excellent stability, oxide layer affects EDL
- **Platinized electrodes:** Highest activity, highest C_{dl}

Electrode Spacing

Trade-offs:

- **Narrow gap (0.5-1mm):** Higher C_{geo}, but higher R_{sol}, risk of bridging
- **Wide gap (3-5mm):** Lower C_{geo}, lower R_{sol}, easier construction
- **Optimal (1-2mm):** Balances capacitance, resistance, and practicality

Water Treatment

- **Distilled water:** Low conductivity, thick diffuse layer, lower total C
- **Tap water:** Higher conductivity, thinner diffuse layer, higher C
- **With electrolyte:** Highest conductivity, Helmholtz-dominated C

Measuring WFC Capacitance

To accurately characterize your WFC:

1. **Use an LCR meter:** Measure at multiple frequencies (100 Hz, 1 kHz, 10 kHz)
2. **Perform EIS:** Electrochemical Impedance Spectroscopy gives complete picture

3. **Measure at operating conditions:** Temperature and voltage matter
4. **Account for cables:** Long leads add inductance and capacitance

Integration with VIC Matrix Calculator

The VIC Matrix Calculator accounts for EDL effects through:

- **Water Profile settings:** Conductivity, temperature, electrode material
- **EDL capacitance model:** Calculates C_{dl} based on electrode area
- **Frequency correction:** Adjusts effective capacitance for operating frequency
- **Cole-Cole parameters:** Models frequency dispersion (see Chapter 3)

Design Recommendation: For initial VIC designs, use the geometric capacitance as the primary estimate. Include EDL effects when fine-tuning or when using very close electrode spacing. The Cole-Cole model (next chapter) provides more accurate frequency-dependent behavior.

Chapter 2 Complete. Next: Electrochemical Impedance →

Revision #1
Created 2026-01-01 20:37:44 UTC by Chris Bake
Updated 2026-01-01 20:37:58 UTC by Chris Bake