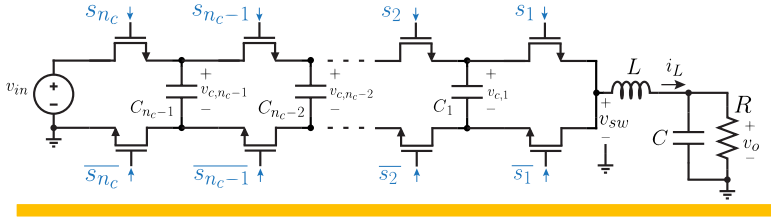
Closed-Loop Balancing Control and Capacitor Voltage Estimation for the Flying Capacitor Multilevel Converter

Berkeley Power and Energy Center

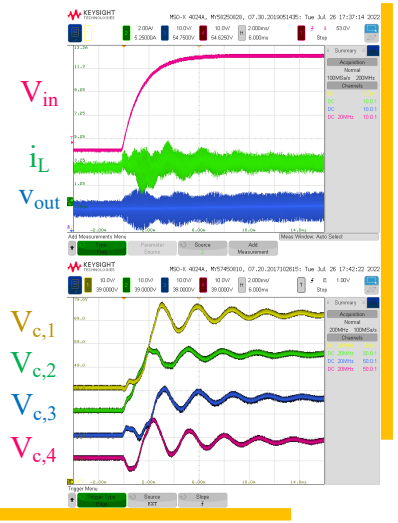
Balancing Control Motivation

Open-loop balancing of capacitor voltages is unreliable

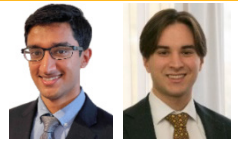
- Capacitor voltages during large-signal transients exhibit underdamped dynamics
- Peak switch stress may be greater than $\frac{V_{in}}{N-1}$ and can cause switch overvoltage in high-performance designs using low-voltage switches



Natural Balancing



Capacitor Voltage Estimation



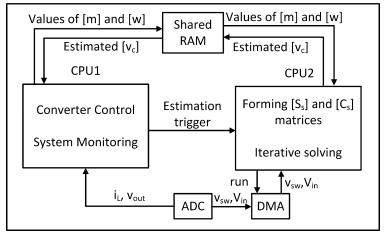
- Active balancing requires measurement of capacitor voltages
- Measuring each capacitor voltage with its own differential sensor is expensive
- Can instead measure switched-node voltage with single-ended sensor and calculate capacitor voltages
- Solve system of equations iteratively with reduced computation burden
- Demonstrated on industry-standard Texas Instruments C2000 DSP

$$\begin{bmatrix} v_{sw}^{I} \\ v_{sw}^{II} \\ v_{sw}^{III} \\ v_{sw}^{IV} \\ v_{sw}^{V} \\ v_{sw}^{VI} \end{bmatrix} = \begin{bmatrix} s_1^{I} & 0 & 0 & 0 & 0 & 0 \\ 0 & s_1^{II} & 0 & 0 & 0 & 0 \\ 0 & 0 & s_1^{III} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_1^{IV} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_1^{V} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_1^{VI} \end{bmatrix} \begin{bmatrix} V_{in}^{I} \\ V_{in}^{II} \\ V_{in}^{III} \\ V_{in}^{IV} \\ V_{in}^{V} \\ V_{in}^{VI} \end{bmatrix} + \begin{bmatrix} s_2^{I} - s_1^{I} & s_3^{I} - s_2^{I} \\ s_2^{II} - s_1^{II} & s_3^{II} - s_2^{II} \\ s_2^{III} - s_1^{III} & s_3^{III} - s_2^{III} \\ s_2^{IV} - s_1^{IV} & s_3^{IV} - s_2^{IV} \\ s_2^{V} - s_1^{V} & s_3^{V} - s_2^{V} \\ s_2^{VI} - s_1^{VI} & s_3^{VI} - s_2^{VI} \end{bmatrix} \begin{bmatrix} v_{c1} \\ v_{c2} \end{bmatrix}$$

First cell's switch states

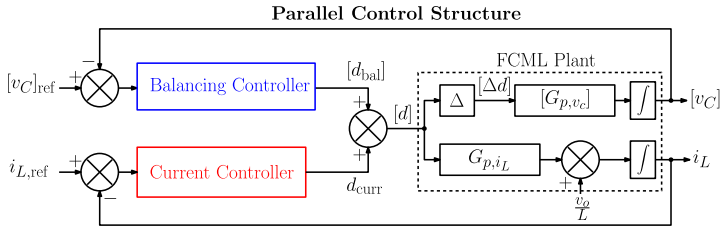
Capacitor connection matrix

Digital Signal Processor



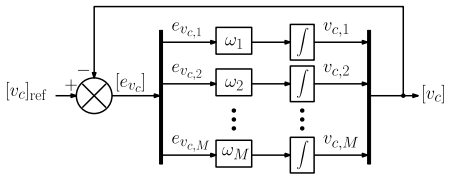
Closed-Loop Control

Parallel Control Structure

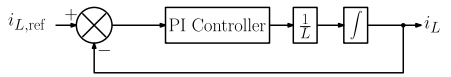


Equivalent Controllers after Decoupling and Feedback Linearization

Decoupled Balancing Control Loops



Decoupled Current Control Loop

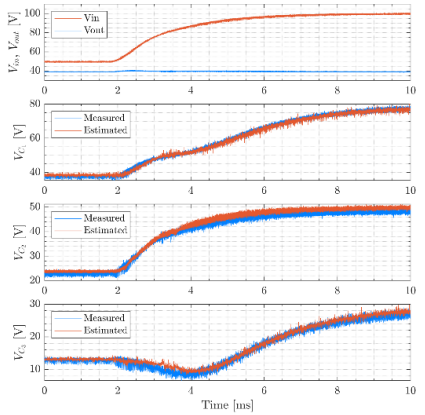


- Model average behavior of FCML converter to obtain "plant" for control
- Structure of plant informs controller design: duty ratios can be controlled differentially to steer capacitor voltages
- Balancing controller runs in parallel with controller(s) regulating load voltage
- Closed-loop system is decoupled – controllers operate without mutual interaction

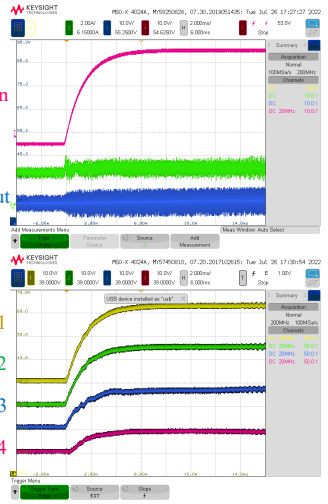
Experimental Verification

- Active balancing ensures capacitor voltages track nominal values during supply transients
- Single-sensor estimation of capacitor voltages is reliable and low-cost

Estimation



Active Balancing



References:
[1] R. K. Iyer, et al., "A High-Bandwidth Parallel Active Balancing Controller for Current-Controlled Flying Capacitor Multilevel Converters," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC).
[2] I. Z. Petric, et al., "A Real-Time Estimator for Capacitor Voltages in the Flying Capacitor Multilevel Converter," 2022 IEEE 23rd Workshop on Control and Modeling for Power Electronics (COMPEL).

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