Turbo-MMC: Minimizing the Submodule Capacitor Size in Modular Multilevel Converters with a Matrix Charge Balancer

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Background & Motivation

- Submodule Capacitors in Modular Multilevel Converters
  - Buffer pulsating power at low frequencies
  - The voltage ripple of submodule capacitors: $\Delta V_{pp} \propto 1/f_o$ and I_o
- Modular Multilevel Converter based Motor Drive
  - Design submodule capacitor for maximum I_o and lowest f_o.
  - Capacitors take more than 50% of total size and weight.

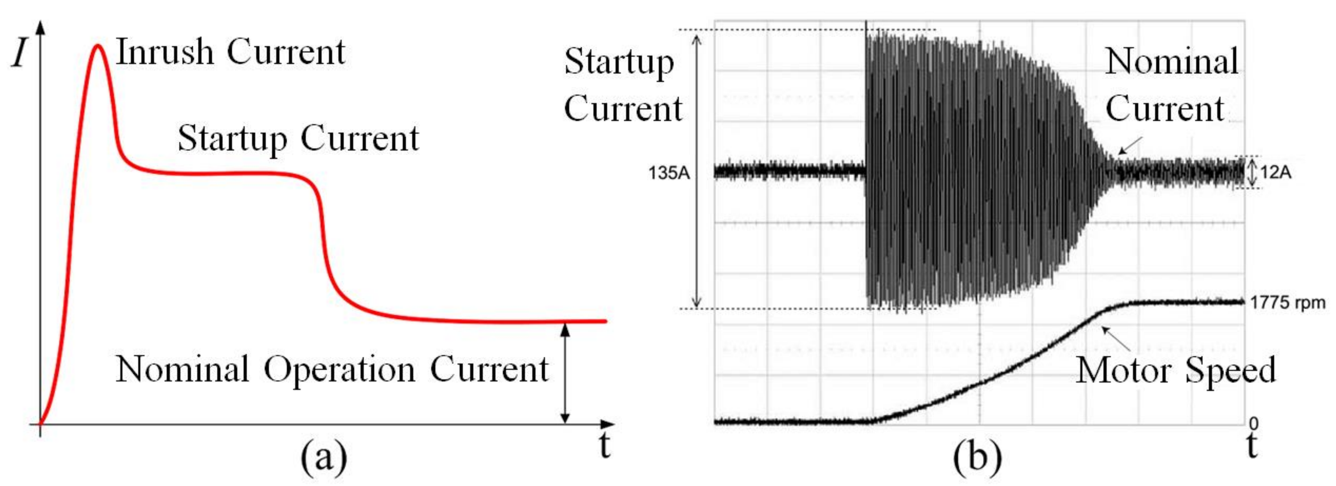


Fig. 1: Typical startup process of a 3-ϕ ac induction motor: (a) phase current amplitude (b) phase current waveform and motor speed.

Pulsating Power in MMC

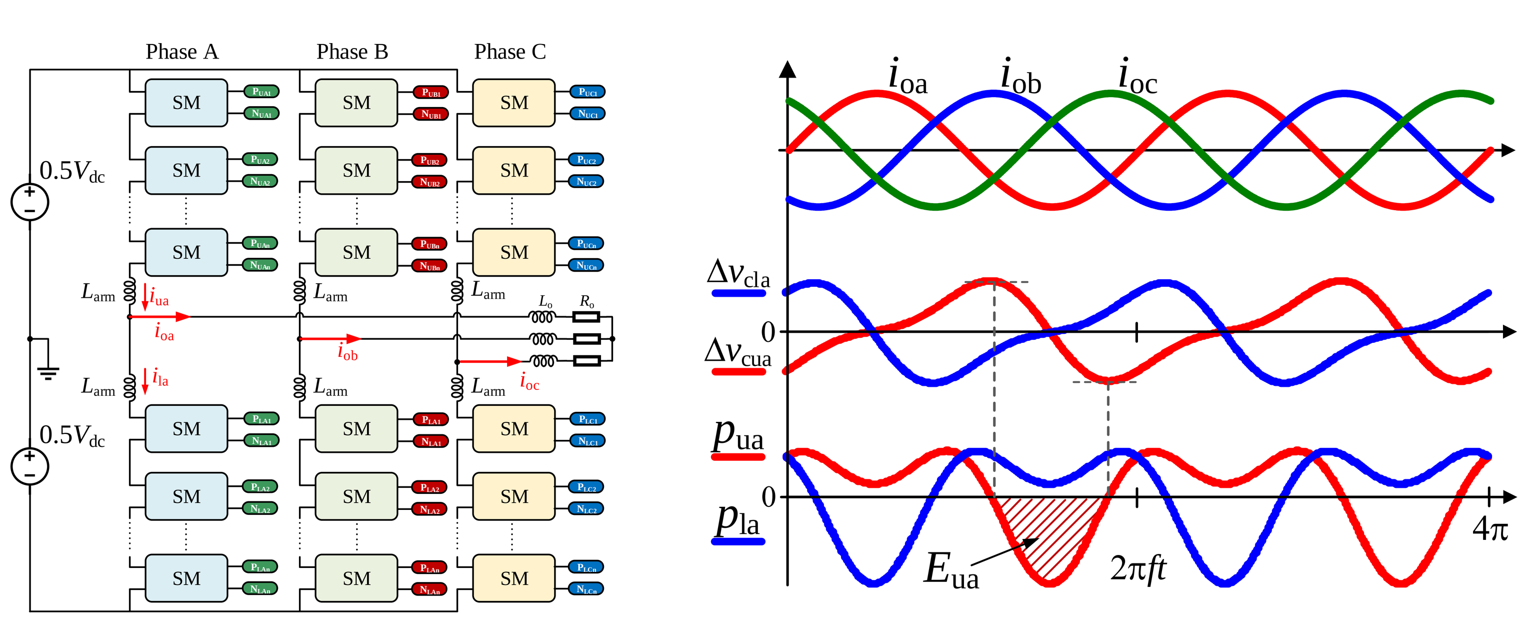
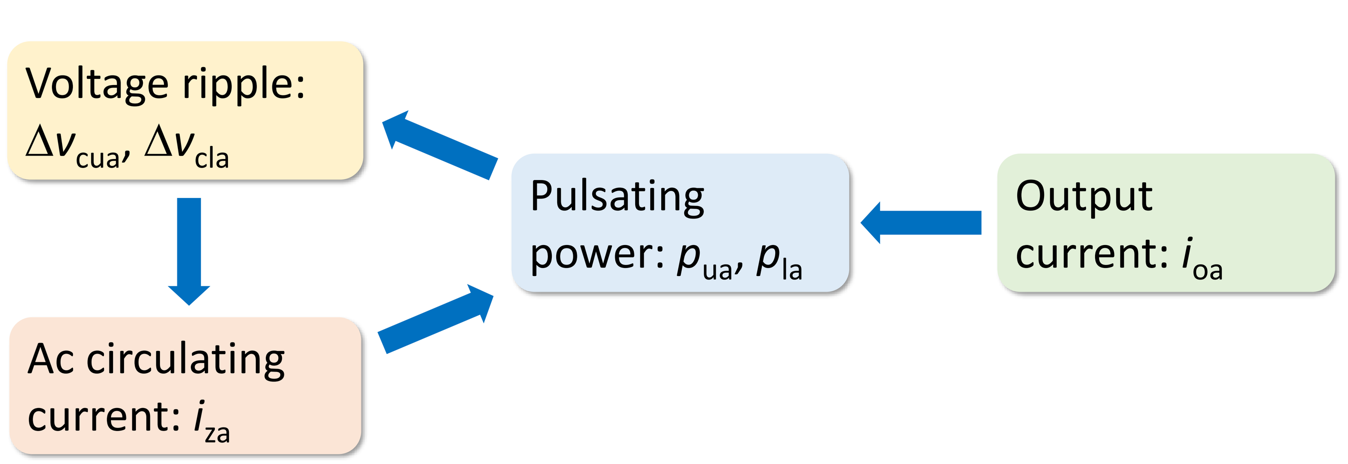


Fig. 2: Schematic of a 3-ϕ MMC and Voltage ripple and pulsating power of the submodule capacitors in Phase A.



- Pulsating power = ac output power + circulating power
- Reduce the voltage ripple in SM capacitors:
  - Sophisticated control strategy for power management
  - Active pulsating power balancing

Turbo MMC with a Matrix Charge Balancer

- Balance energy among submodule capacitors

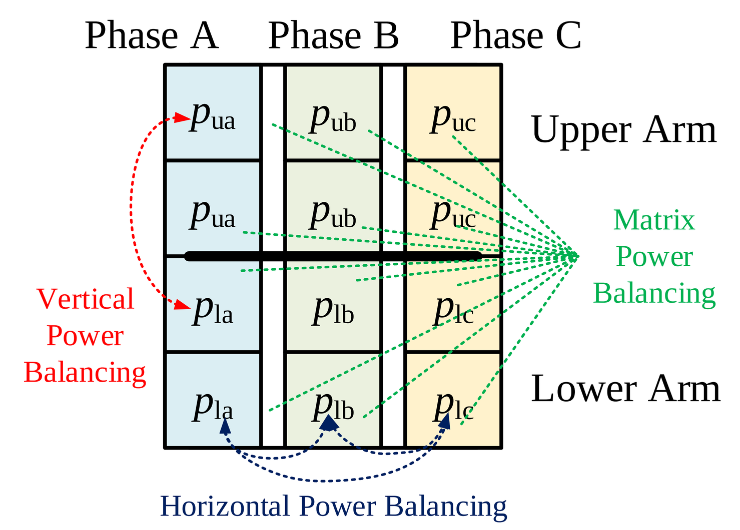


Fig. 3: Three ways of balancing the pulsating power.

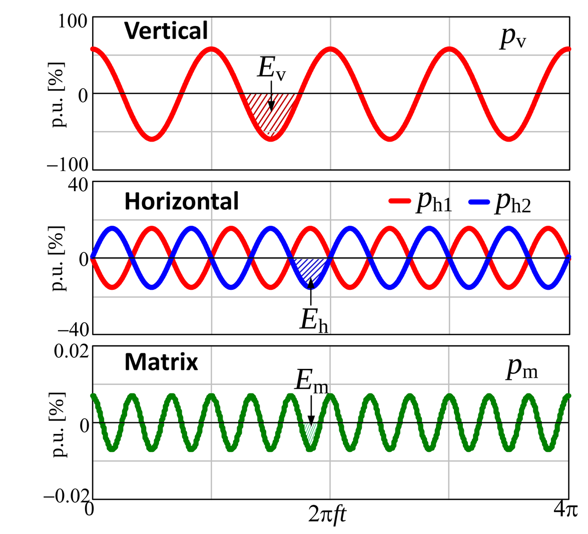
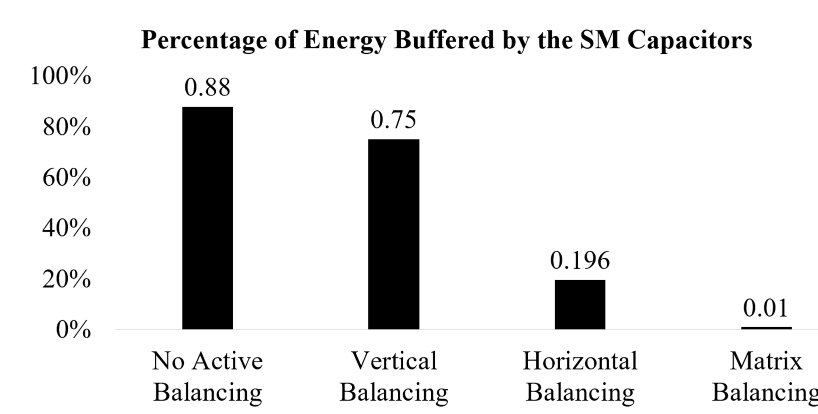


Fig. 4: Percentage of residual unbalanced pulsating power.



- **Vertical**: partially balance power
- **Horizontal**: completely balance the output power, partially balance the circulating power
- **Matrix:** completely balance power

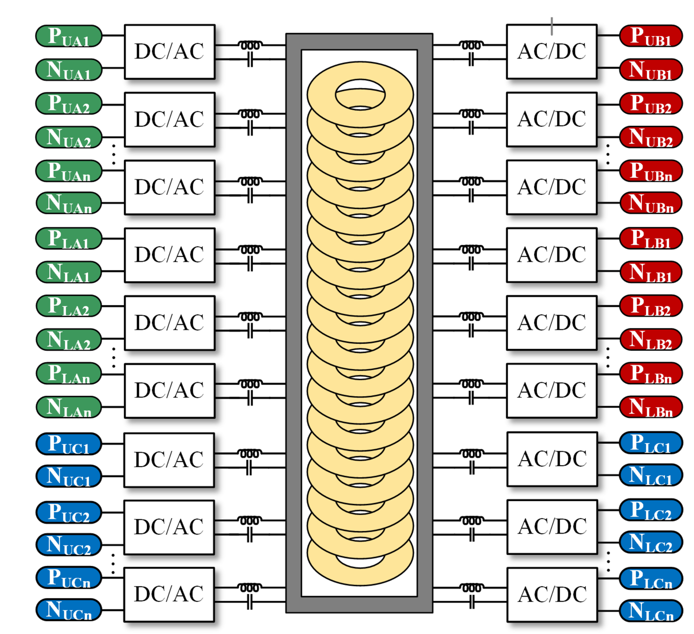


Fig. 5: A matrix charge balancer implemented as a multi-active-bridge converter with a single magnetic core.

Control Strategy for Turbo Operation

- Power flow controlled by modulating the phase-shift:

$$P_i = \frac{V_i}{2\pi f_{mab} N_w^2}\sum_{j\neq i}\frac{V_j}{L_{ij}}(\Phi_j-\Phi_i)\left(1-\frac{|\Phi_j-\Phi_i|}{\pi}\right)$$

- Power flow controlled by time domain multiplexing.

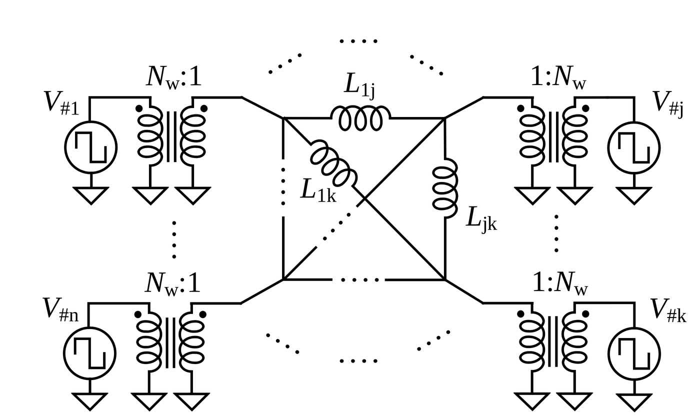


Fig. 6: Simplified ac power flow model of a matrix charge balancer.

- Deliver energy from/to a submodule capacitor by closed-loop control with hysteresis in voltage ripple

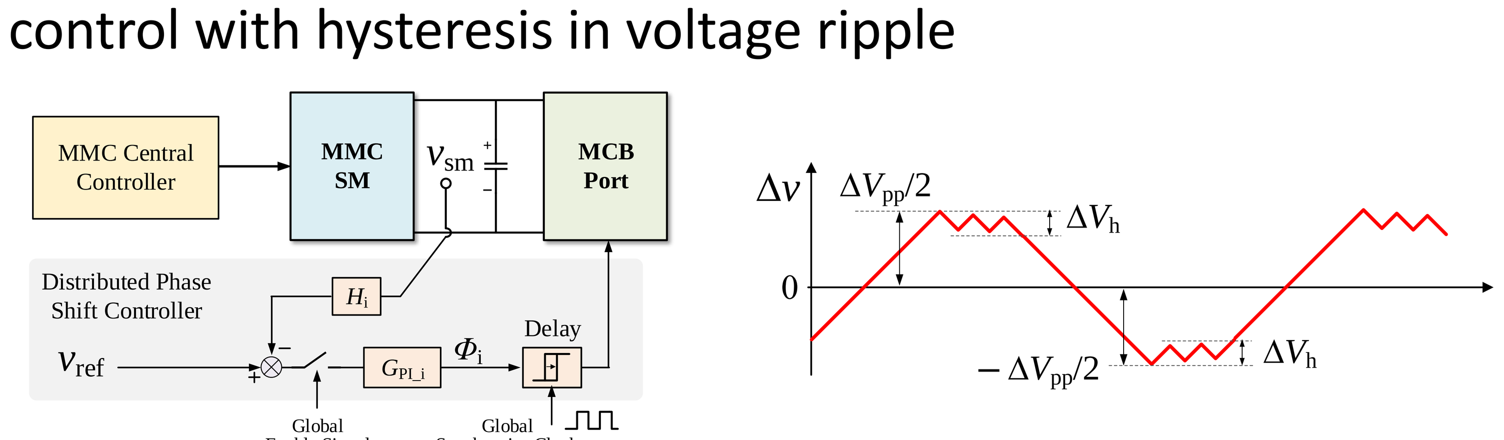
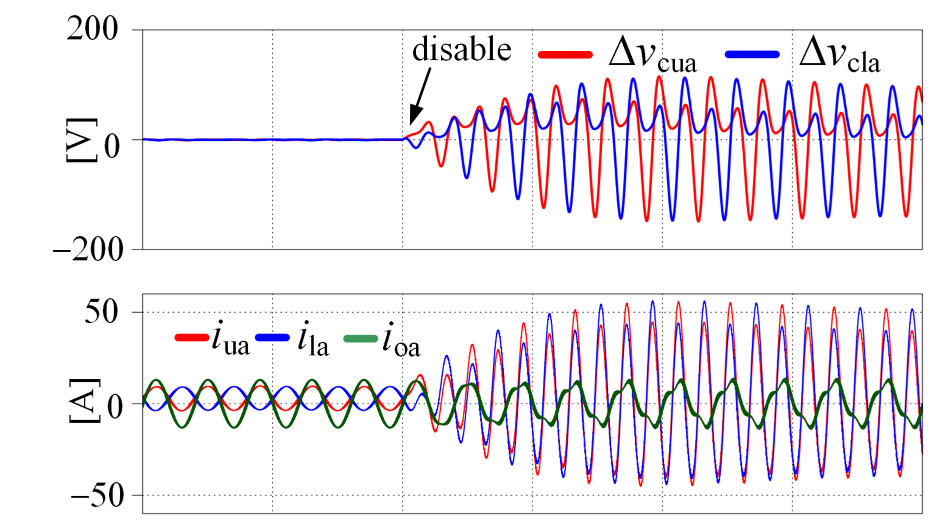


Fig. 7: Distributed phase-shift control with a ripple voltage hysteresis for submodule capacitor voltage.

Simulation and Experiments

Simulation Parameters	
V_{dc}	700V
P_o	6kW
f_{mmc}	10kHz
f_{mab}	100kHz
L_{arm}	4mH
C_{sm}	1mF
L_b	5μH
C_b	0.1mF
SM Number	4



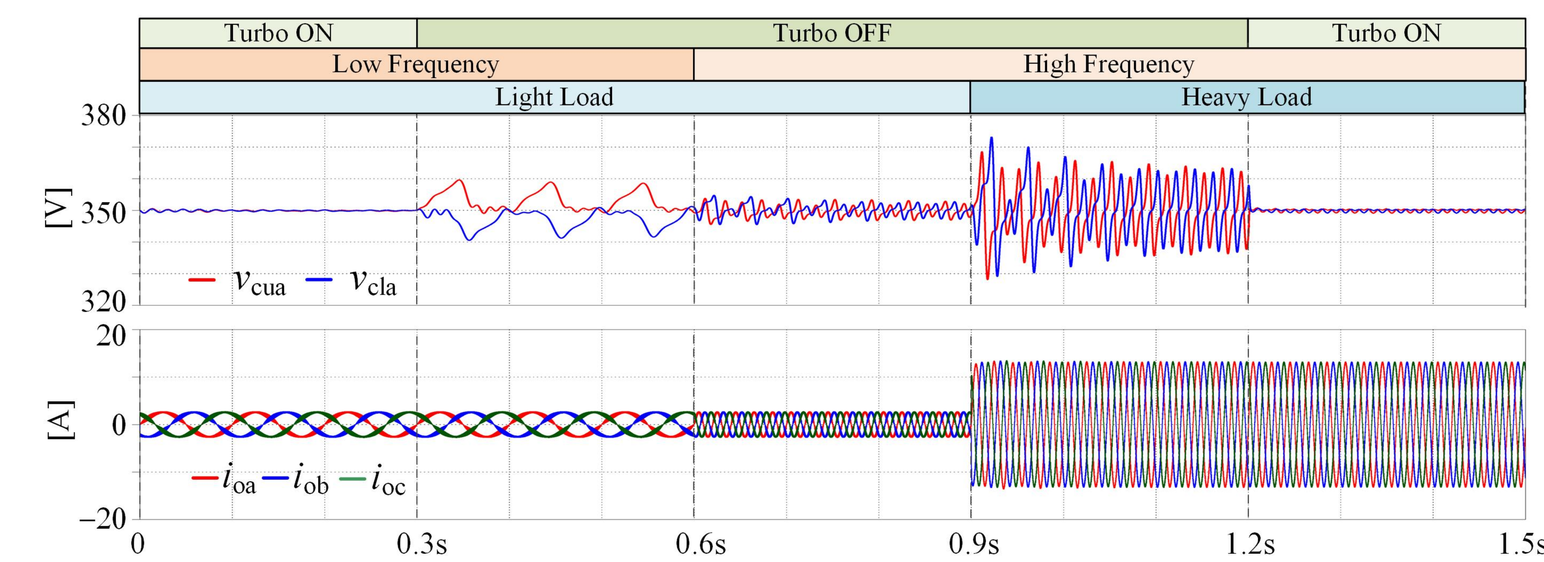


Fig. 8: Simulated capacitor voltage ripple of the Turbo-MMC in five operating modes: (1) 0.0s -- 0.3s, low frequency (10 Hz) startup with Turbo mode ON, 20% load (1200 W); (2) 0.3s -- 0.6s, light load operation with Turbo mode OFF; (3) 0.6s -- 0.9s, output frequency increased to 50Hz with Turbo mode OFF; (4) 0.9s -- 1.2s, output load steps up to 100% (6000 W); (5) 1.2s -- 1.5s, high frequency heavy load operation with Turbo mode ON.

Experiment Parameters	
V_{dc}	24V
P_o	30W
f_{mmc}	50kHz
f_{mab}	200kHz
L_{arm}	7mH
C_{sm}	1mF
L_b	0.1μH
C_b	0.1mF
SM Number	4

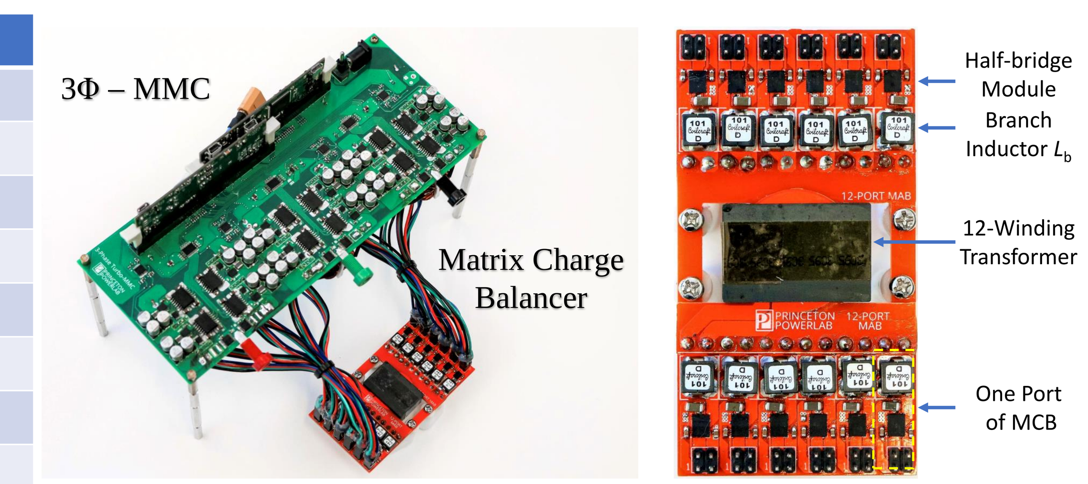


Fig. 9: A Turbo-MMC prototype

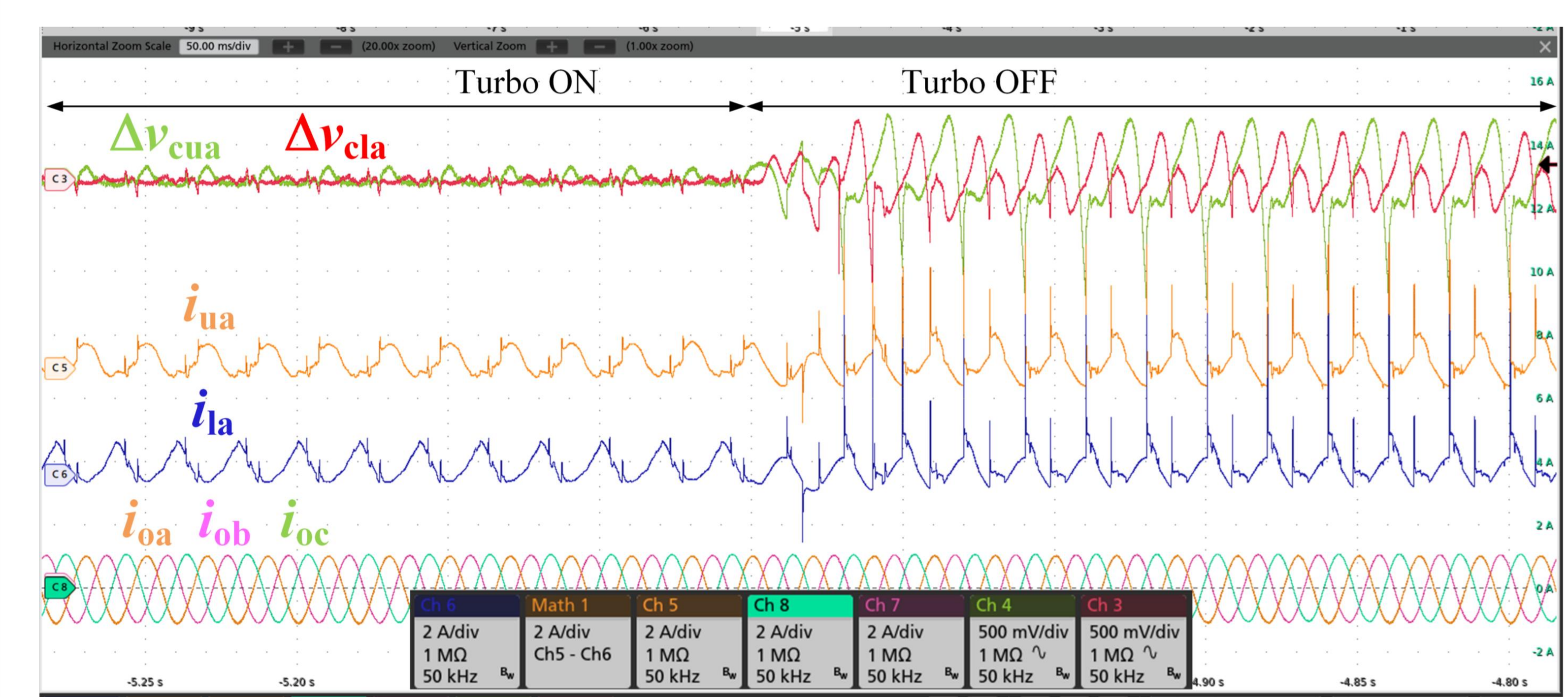


Fig. 10: Measured waveforms of the prototype Turbo-MMC with f_o = 50 Hz. High voltage ripple even causes arm inductor saturation without Turbo operation.

- Summary: Turbo-MMC operation for startup process can
  1. Reduce the submodule capacitor and arm inductor size.
  2. Reduce the voltage ripple in submodule capacitors for low frequency and high power operation;