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A Switch-per-Phase PWM Current Source Converter Topology for Variable Reluctance Motor Drive

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October 08, 2025

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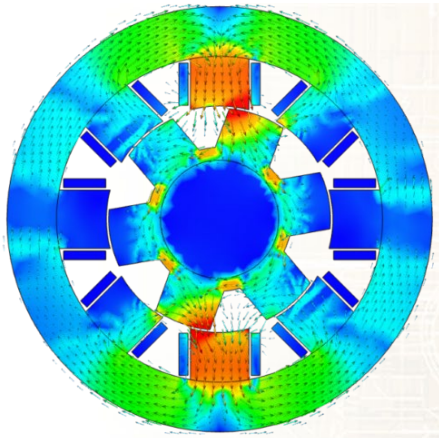
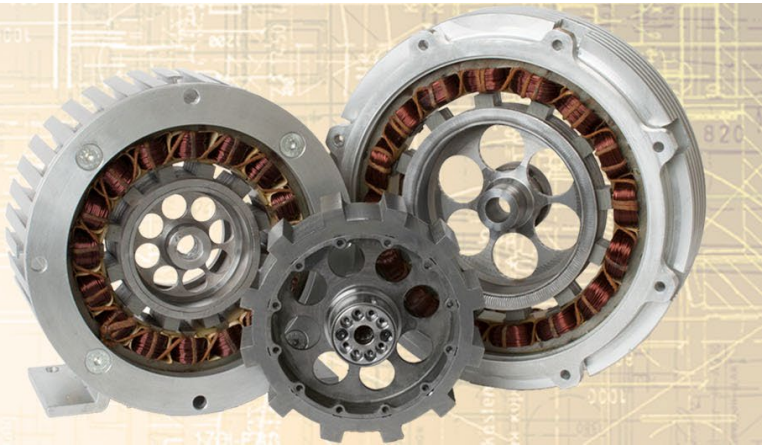
Introduction: Switched Reluctance Machine

- Rotor: simple laminated steel, no winding, no magnets
- Stator: concentrated windings, easy to manufacture



Torque Generation of SRM[1*]



Stator and Rotor [2*]

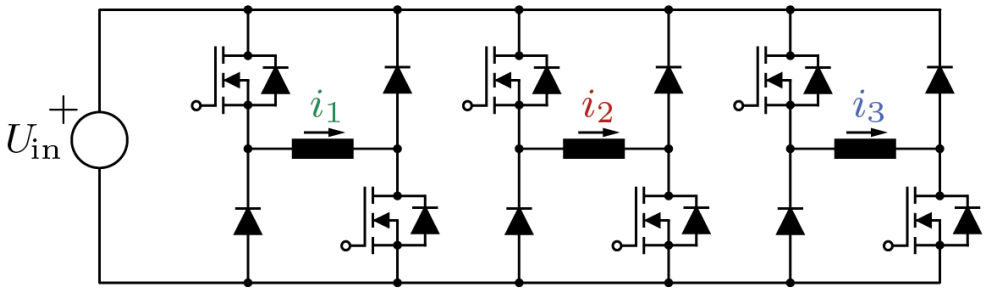
- Magnet-free machine → low cost, no rare-earth dependency, high mechanical and thermal robustness
- Torque production relies on rotor position and phase excitation

[1*] © **Simscale**, https://www.simscale.com/blog/switched-reluctance-motor-srm/, 2025

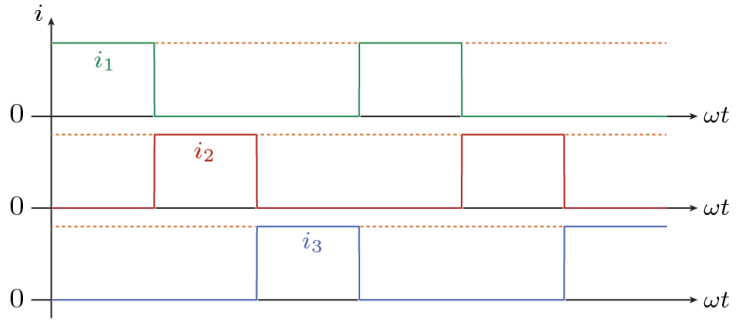
[2*] © **KASKOD-MTRONIX OÜ**, https://kaskod.ee/ 2025

Introduction: Conventional SRM Drive – Asymmetric H-Bridge

- Asymmetrical H-Bridge generates pulsed phase currents due to switched excitation
- Requires fast current control bandwidth to achieve efficient torque regulation



Asymmetric H-Bridge Circuit

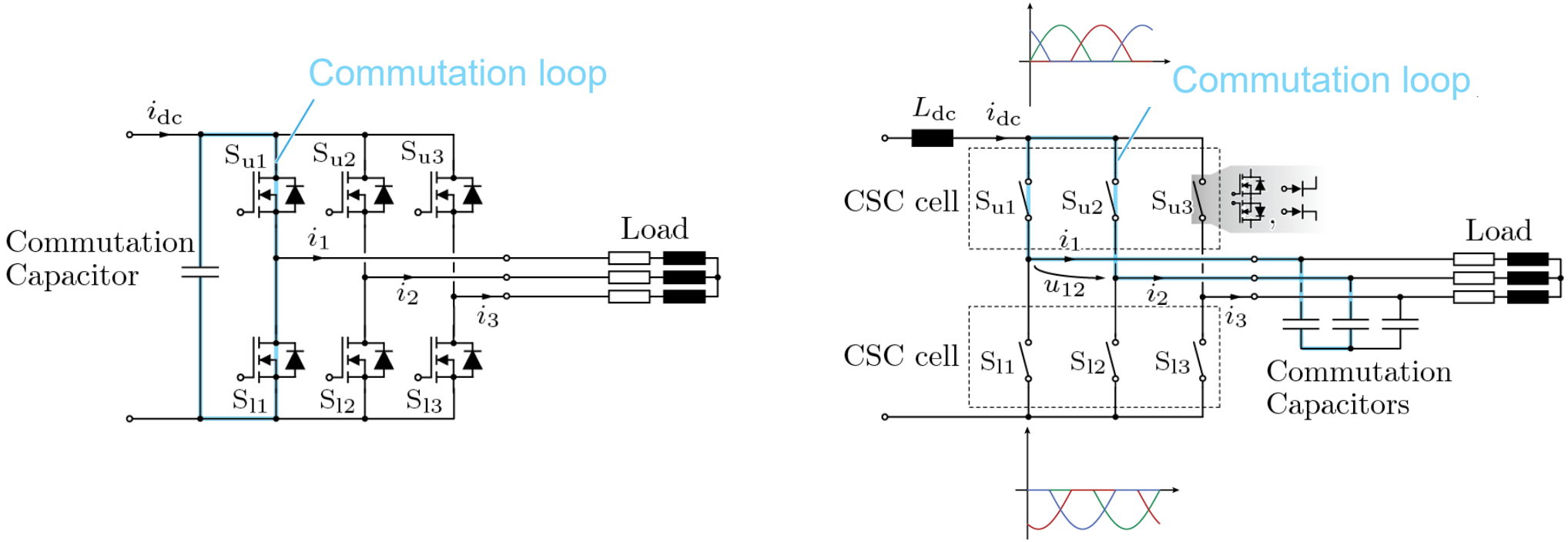


Ideal Pulsewise Curents

- Modern drive systems employ WBG devices (SiC/GaN) for higher control bandwidth
- However, high dv/dt causes insulation stress, EMI, and reliability concerns

Introduction: Voltage Source Inverter/Current Source Inverter

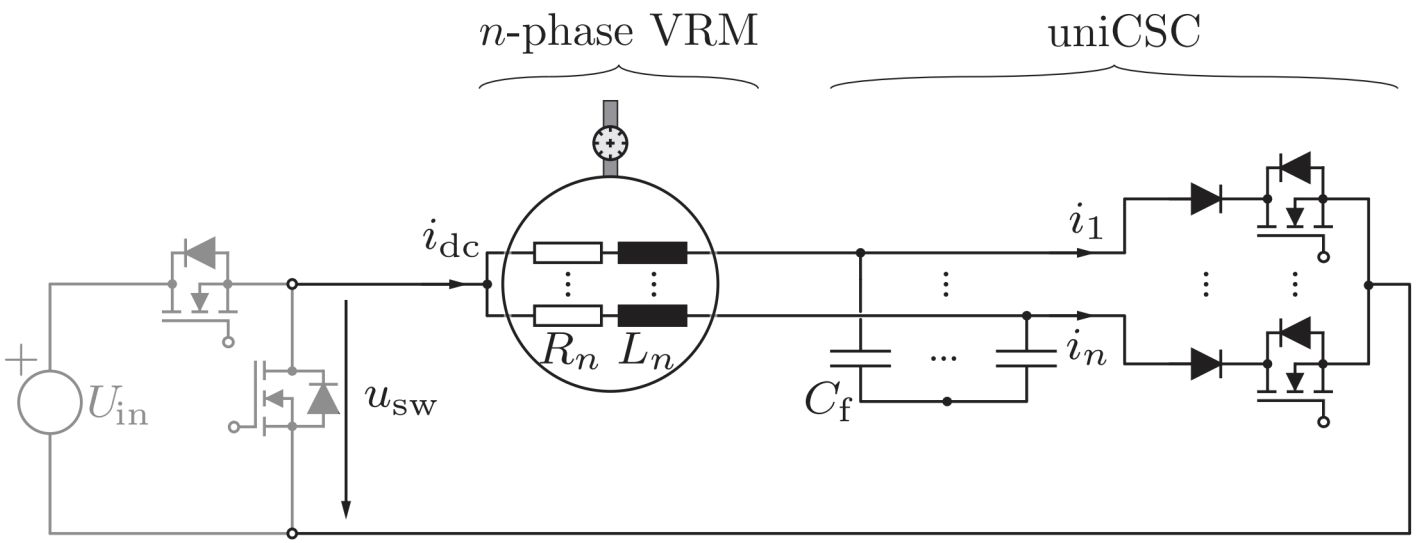
- CSI provides a smooth line voltage over motor windings → mitigates high dv/dt issues
- Output capacitors naturally filter → reduces EMI, insulation stress, bearing currents



- Operation unit is not a leg but arm-cell → each arm-cell inherently processes unipolar phase currents

Introduction: Proposed Converter – *uniCSI*

- Simple, Scalable, and Low-cost structure



- 1 switching device + 1 diode per phase
- No bulky input inductor
- All switches at the same potential → low-cost gate driver circuit design
- Compatible with carrier-based PWM → simple drive implementation

Content

- Topology Derivation
- Modulation Method
- Simulation Results
- Conclusions

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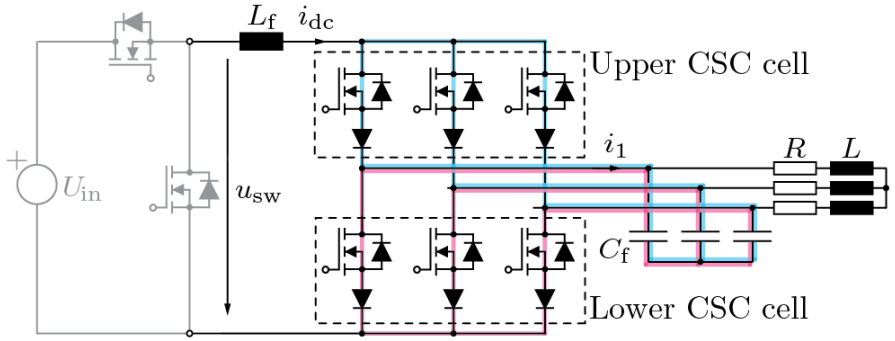
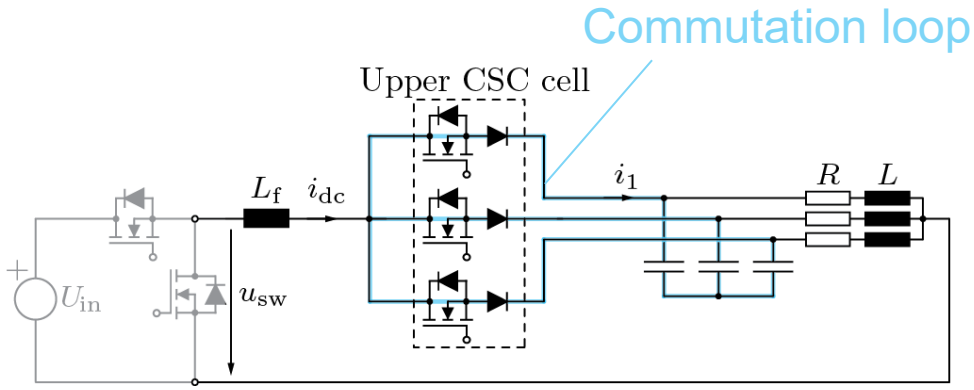
Topology Derivation

- Conventional CSI: both upper and lower devices in each CSC cell process AC-current

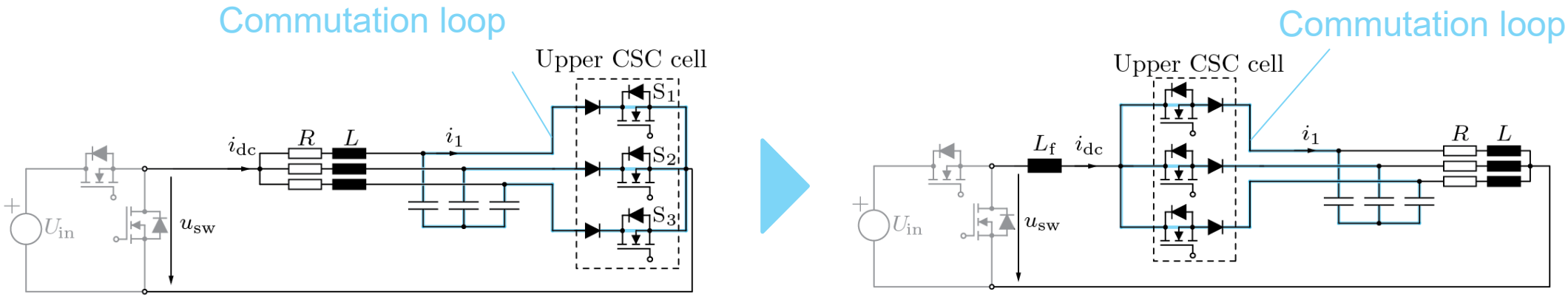




- Proposed simplification: remove lower devices
- Only high-side arm devices process positive phase currents
- Current returns through star-point → DC-bus

Topology Derivation

- **Exchange order of CSC cell and load connection**



- **DC-link inductor replaced by motor phase inductance**
- **All switching devices share the same source potential**
- **Completed proposed topology – simple, scalable, and low-cost**

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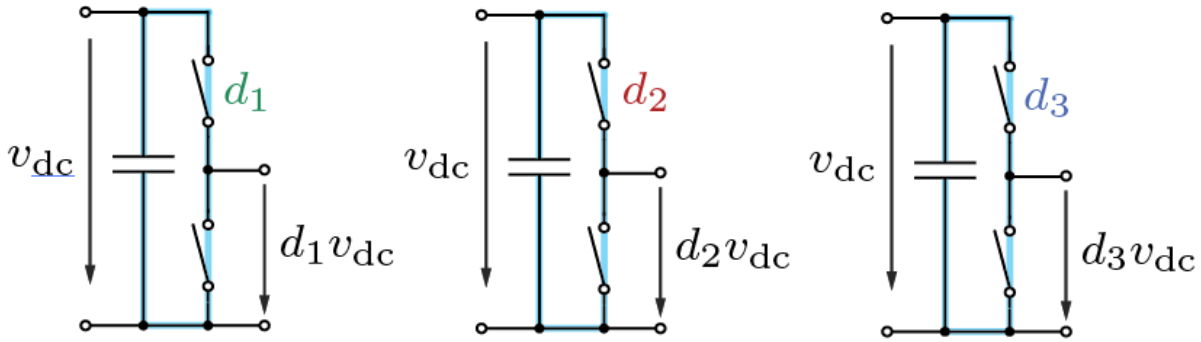
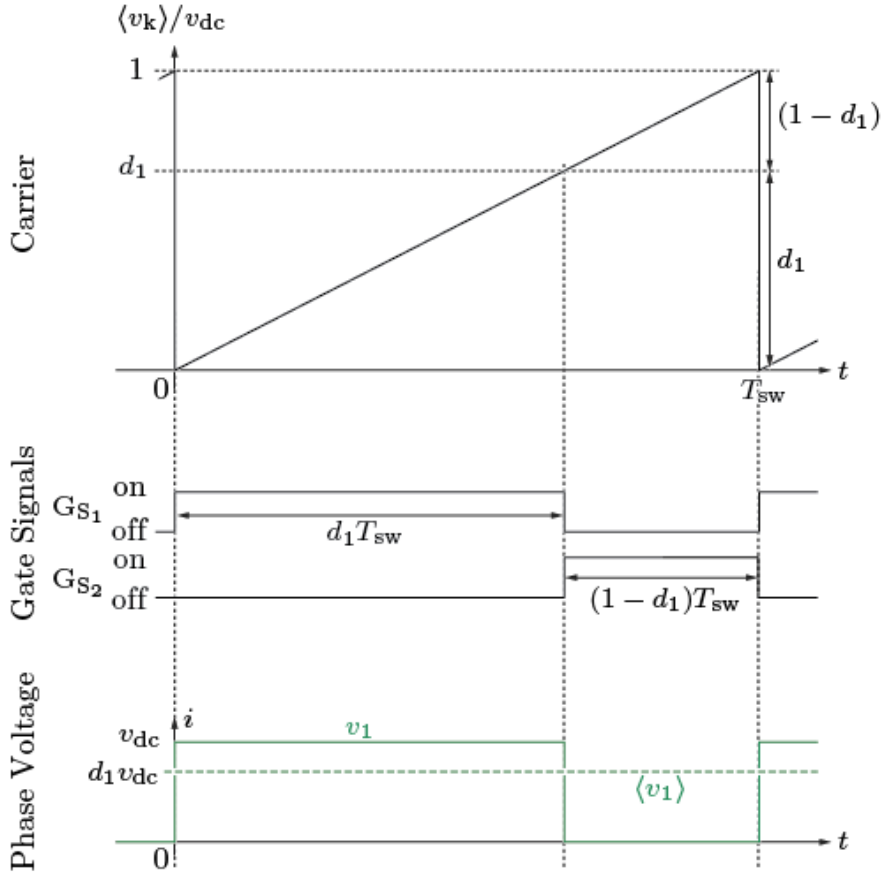
Carrier-Based Modulator for VSI

- Commutation occurs between DC-link capacitor and switching leg

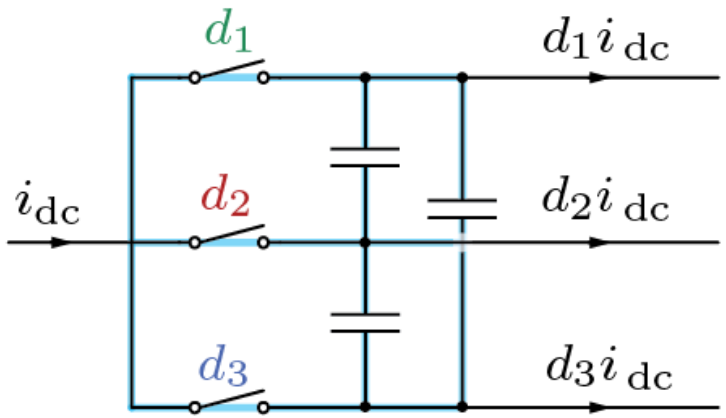


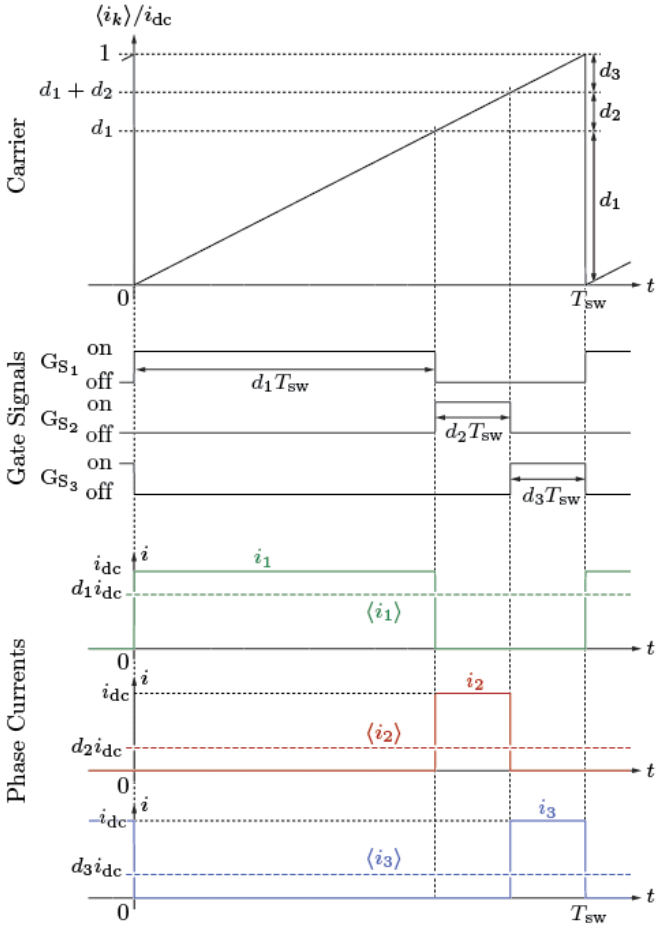


- Each phase is independent from the others in terms of commutation
- Output average voltage is controlled by duty ratio relative to the carrier
- Enables simple carrier-based PWM for sinusoidal voltage synthesis

Carrier-Based Modulator for CSC

- Commutation occurs through output capacitors → phases are coupled
- Duty cycle must satisfy $\Sigma d = 1$ → phase current cannot be controllerd independently

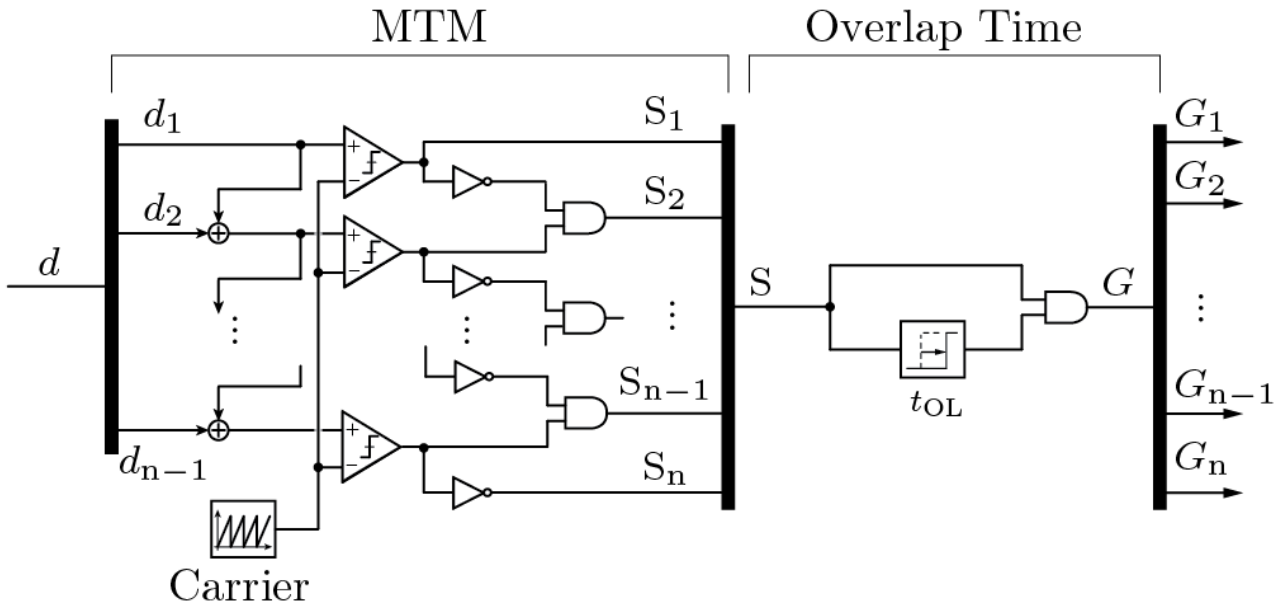




- Developed Multi-threshold Carrier-based Modulator (MTM)
  -- Splits carrier into thresholds to allocate duty among phases
  -- Achieves simple carrier-based PWM for CSC

Carrier-Based Modulator for CSC: Multi-Threshold-Modulator (MTM)

- Modular structure – identical cell repeated for each cell
- Duty allocation achieved by multi-threshold comparison with a single carrier



- Naturally scalable to arbitrary number of phases
- Enables carrier-based PWM for CSC with simple digital implementation

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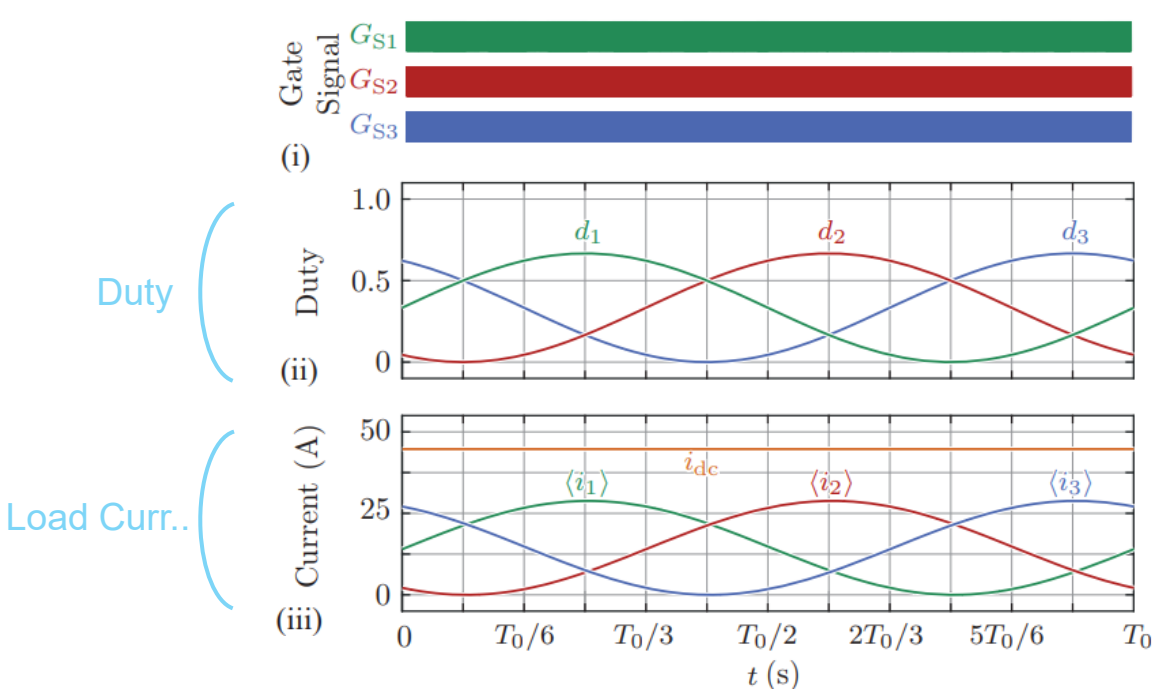
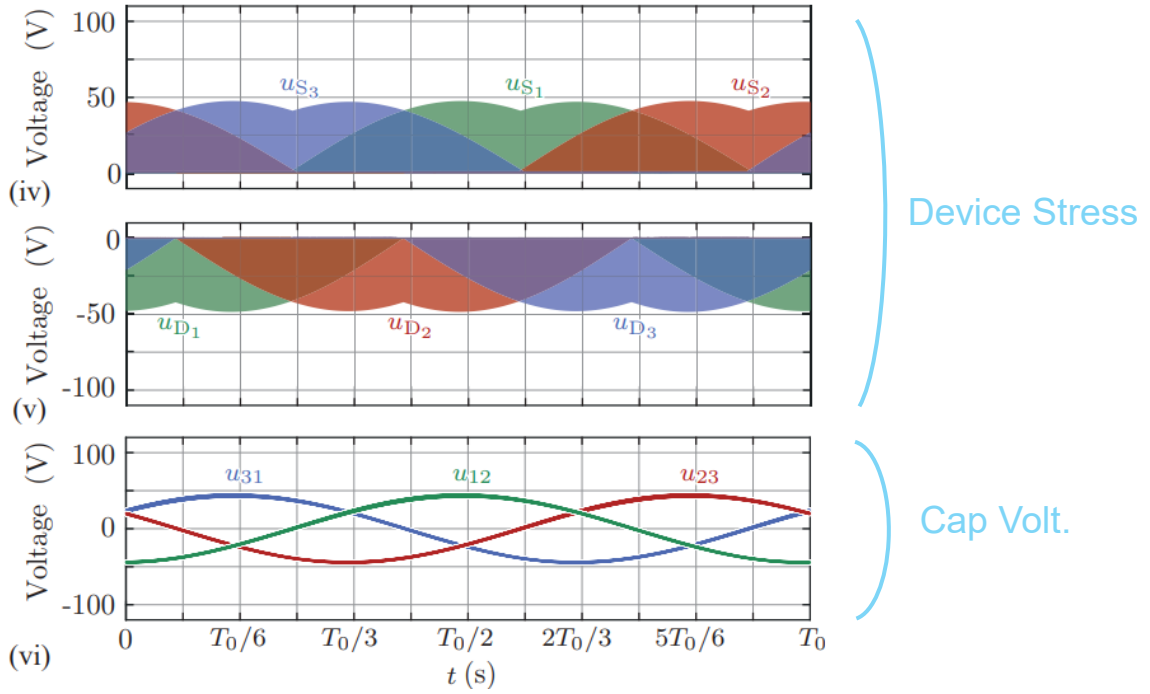
Parameter	Symbol	Value
Input current	i_{dc}	40 A
Output capacitance	C_{f}	4.7 µF
Load resistance	R	1 Ω
Load inductance	L	3.5 mH
Switching frequency	f_{sw}	200 kHz
Fundamental frequency	$f_0 = 1/T_0$	50 Hz

TABLE I: Simulation Parameters.

Simulation Result: Sinusoidal Operation

- Phase current amplitude proportional to duty cycle → confirms CS operation
- Device voltage stress appears as line-to-line voltage across output capacitors

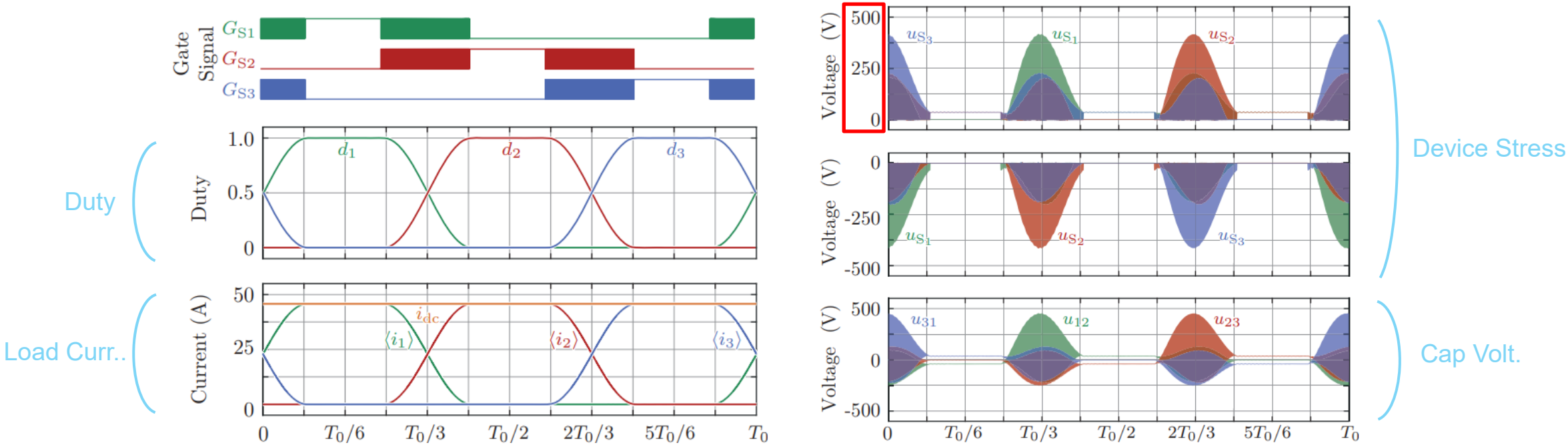




- Stress level depends on load conditions inherited CSI characteristic
- Simulation validates feasibility of the proposed MTM-based CSC modulation

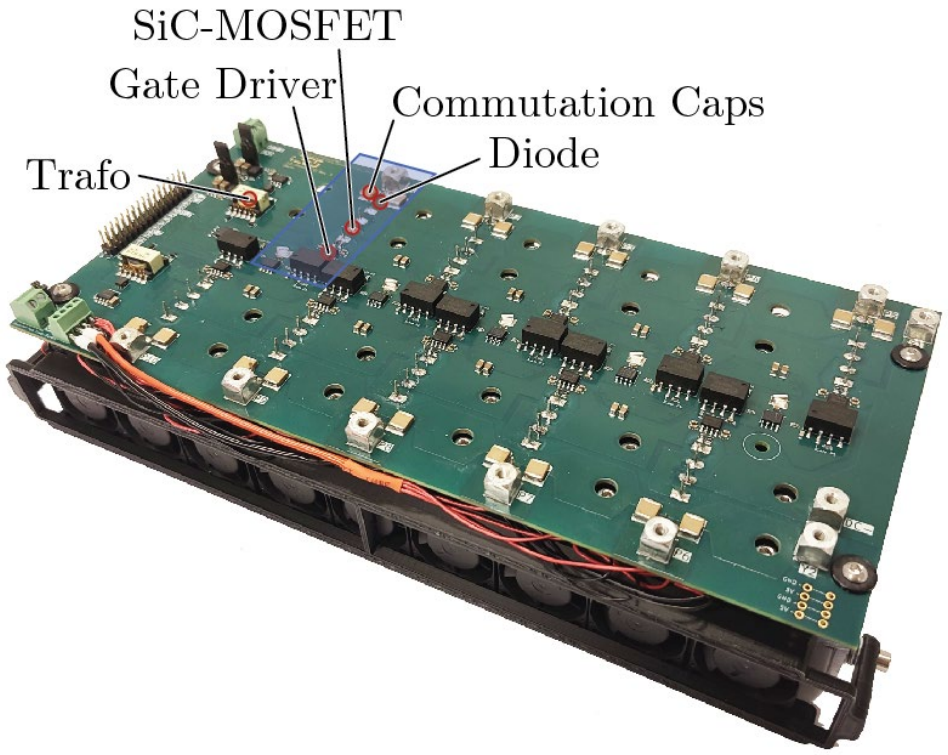
Simulation Result: Trapezoidal Operation

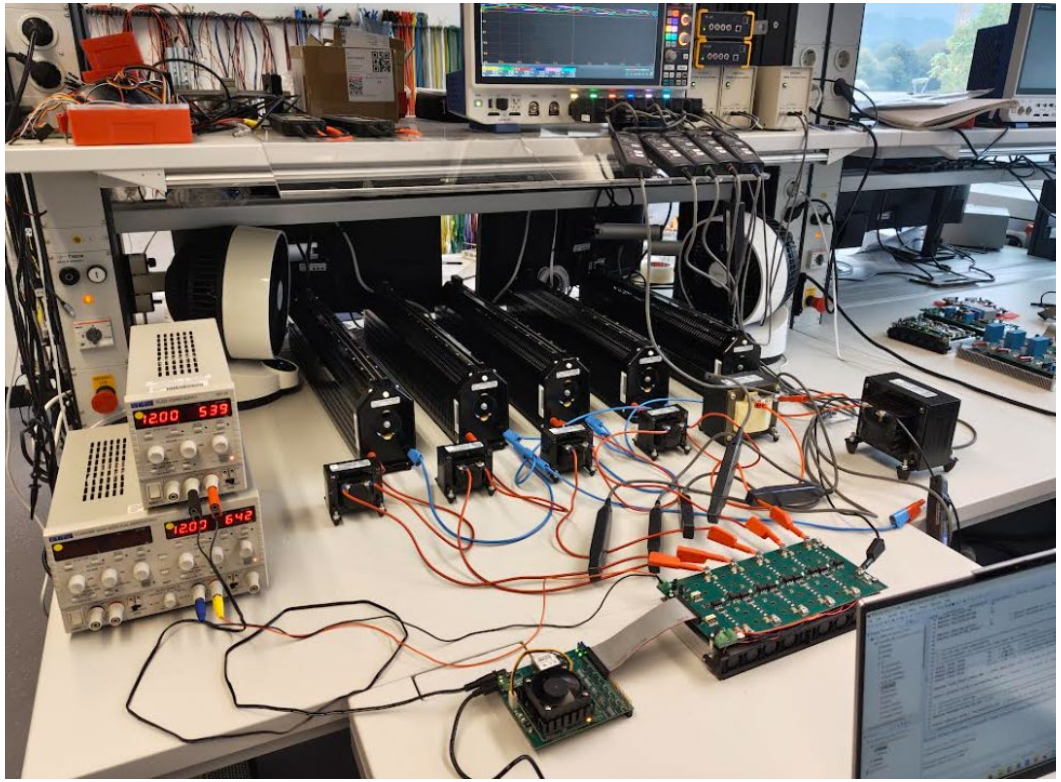
- Carrier-based method allows arbitrary current waveforms (e.g. trapezoidal)



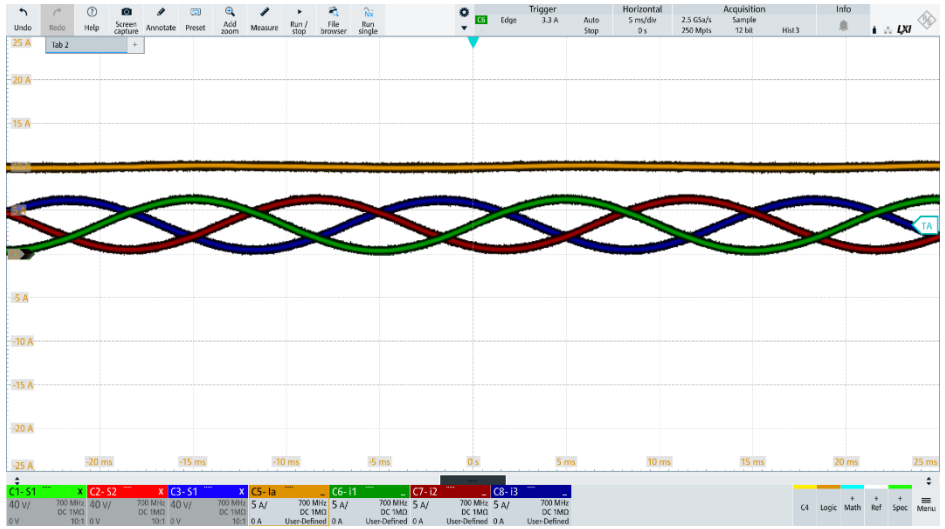
- Inductor energy is exchanged via capacitors → large voltage overshoot observed
- Overshoot magnitude depends on passive component and di/dt
- Further investigation required for reliable design and operation

Hardware Implementation: 10-phase uniCSI

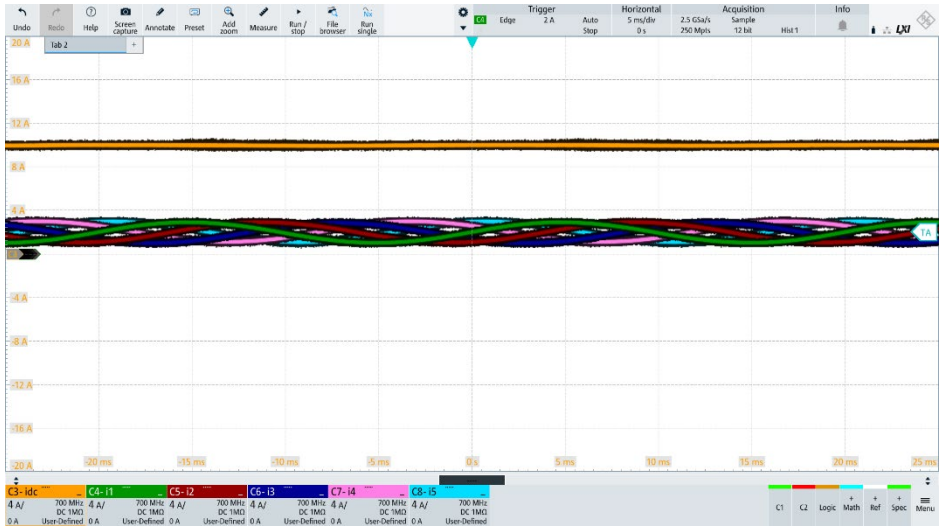




Hardware Implementation: 10-phase uniCSI



3-phase @ 10 A



5-phase @ 10 A

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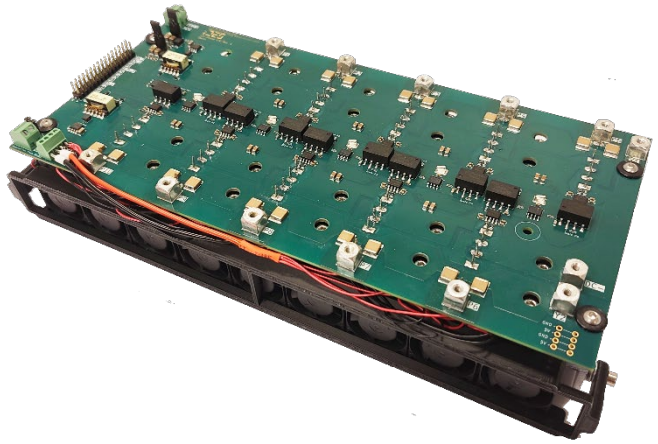
Conclusions

- Introduced a new CSI-based converter topology for VRM drives
- Achieves simple, scalable, and low-cost structure
  - -- Only one switch + one diode per phase
  - -- All switches share the same potential → reduced gate driver cost
- Developed modulation method using Multi-Threshold Moduator (MTM) → enables carrier-based PWM for CSC
- Simulation confirmed:
  - -- Phase current proportional to duty cycle (CSI operation)
  - -- Arbitrary waveforms drive (e.g. trapezoidal) feasible
- Observed capacitor voltage overshoot depends on passive components & di/dt
- Future work: voltage stress management, integrating the whole system



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Thank you!