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Multi-Cell Current Source Inverter Topology for Modular Machine Drives

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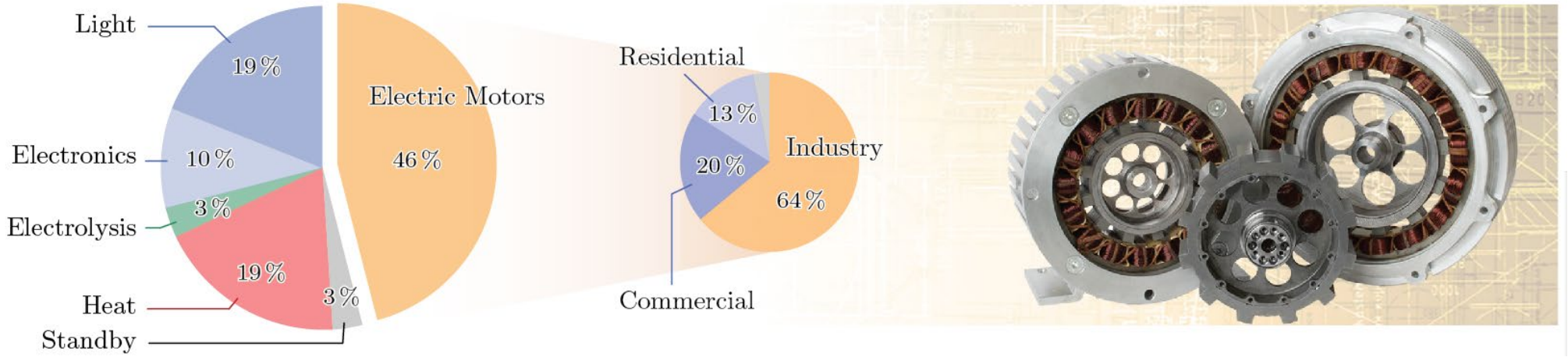
ASML US LP
Wilton, Connecticut, USA

October 29, 2025
14:30 – 14:50
Session F43
Room F4.06

Energy Impact and Future Outlook of Drive Systems

- Drive systems consume account for around 45% of global energy use
- Motivation: make drive systems as efficient as possible → large impact on the energy consumed



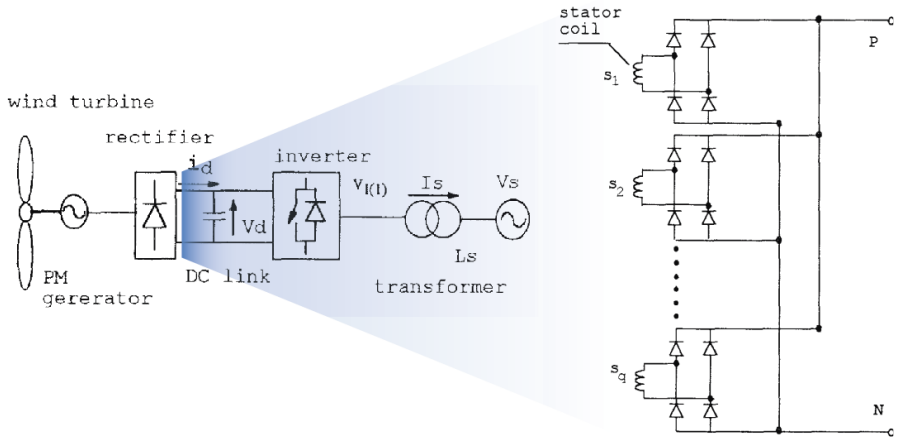
Eestimated share of global electricity demand by end-use

- Efficiency gains in drive inverters directly translate to lower CO_2 and renewable energy savings.
- Future systems: modular, scalable, fault-tolerant, and efficient. → "Modular machine drives" combine segmented machines with distributed converters.

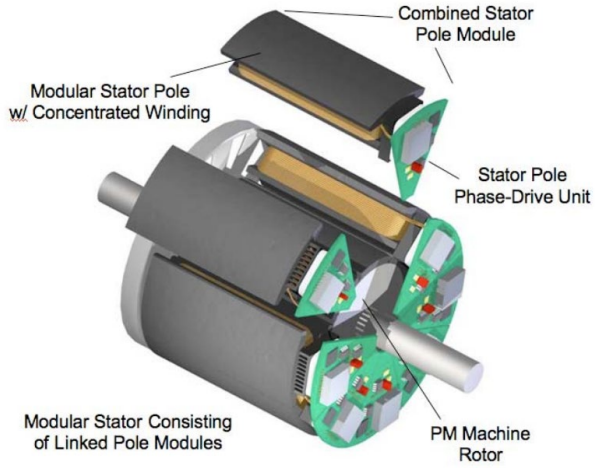
Source: P.Waide, C. U. Brunner, "*Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*", International Energy Agency, 2011

Modular Drive System Concept

- Modular Drive Systems combine modular machines and modular converters, both divided into multiple segments
- The concept originated in the 1990s, enabling scalable machine ratings for wind turbine generator



Modular Concept Wind Turbine Generator[1*]



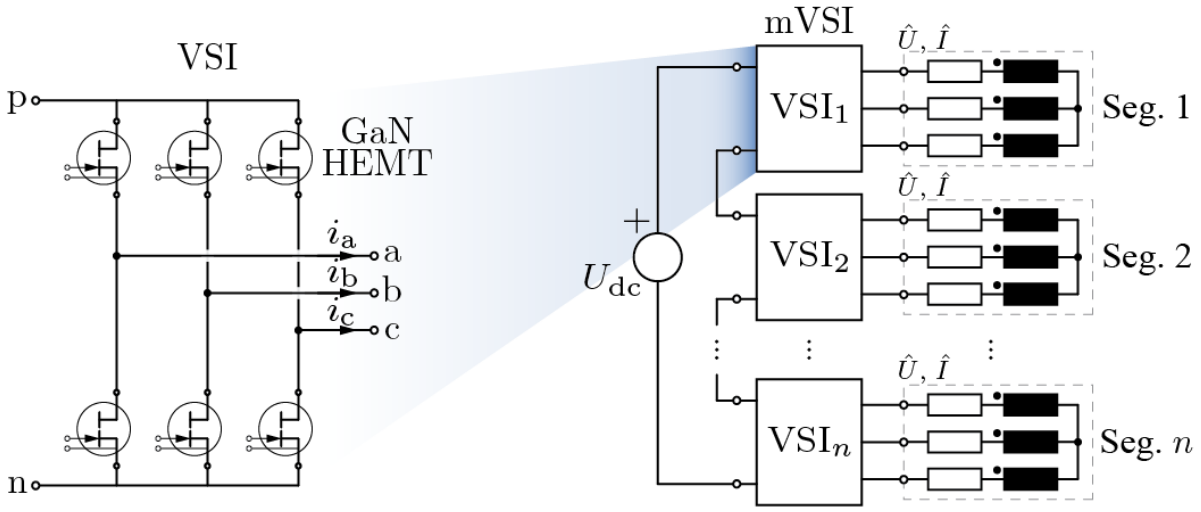
Concept of Integrated Modular Drive System [2*]

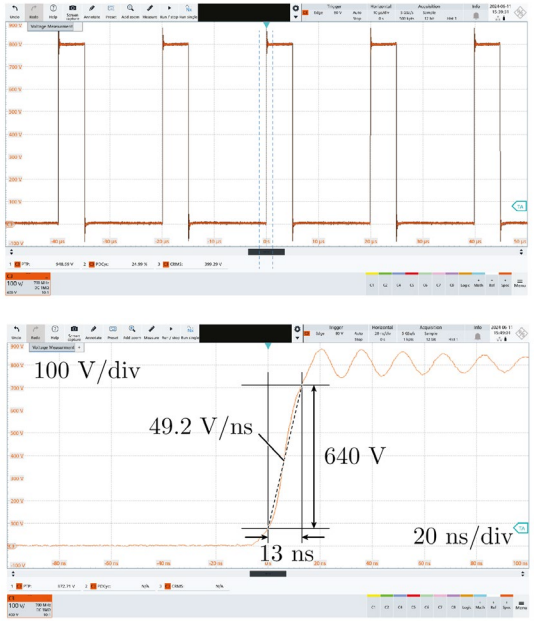
- Advantages: flexibility, maintainability, scalable design, distributed integration, and fault tolerance

[1*] Z. Chen, and E. Spooner, „A Modular, Permanent-Magnet Generator for Variable Speed Wind Turbines“, *Proc. of the International Conference on Electrical Machines and Drives*, 1995.
[2*] N.R.Brown, et.al, „ Power Converter Design for an Integrated Modular Motor Drive“, *Proc. of the IEEE Industry Applications Annual Meeting*, 2007.

VSI-based Multi-Segment Modular Drive System

- Each machine segment is driven by a Voltage Source Inverter (VSI)
- Series stacking of VSIs allows operation at high voltage and power while keeping each segment at a lower voltage



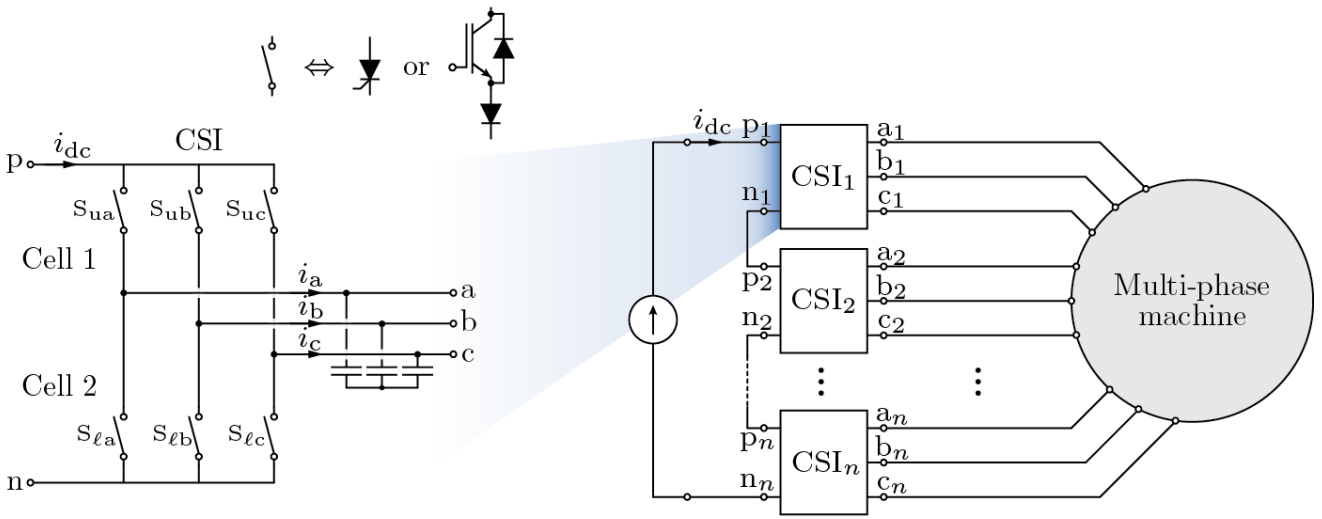


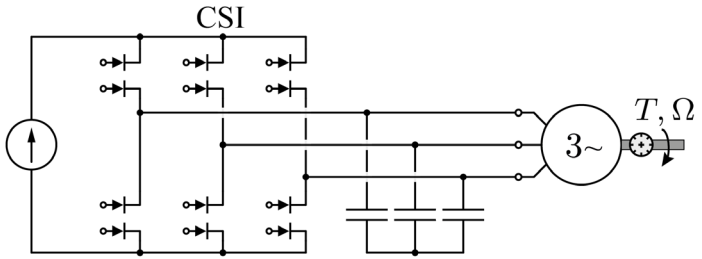
High dv/dt of phase voltages

- VSI stacking requires precise DC-link voltage balancing among segments
- Each segment must employ current measurement, requiring multiple current sensors
- High dv/dt pulsed voltage stress machine insulation, requiring additional filter

CSI-based Multi-Segment Drive System

- Each machine segment is driven by a Current Source Inverter (CSI)
- DC-link current is shared among all segments, ensuring consistent current flow



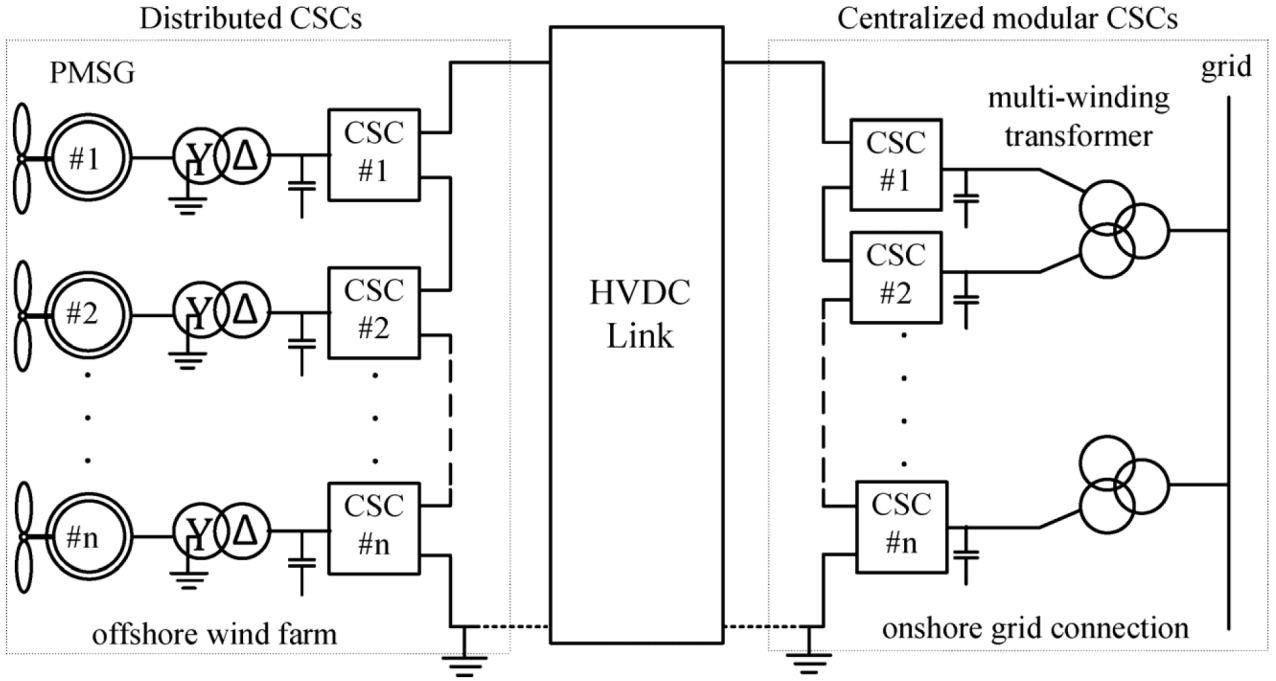


'Smooth' phase voltages

- Maintaining voltage balance without dedicated control, current sensors
- Providing smooth phase voltage, identical gate signals can be applied across all segments
- Each CSI switch must handle bidirectional current, requiring a MOSFET + Diode or bidirectional switch (BDS) per switching arm
- Requiring $6 \times$ Number of Segments BDS in totall

Offshore Wind Farms Using Cascaded Current Source Converters

- Wind turbines operate under varying wind speeds → unequal power generation
- Unequal turbine power causes dc-link current imbalance challenges

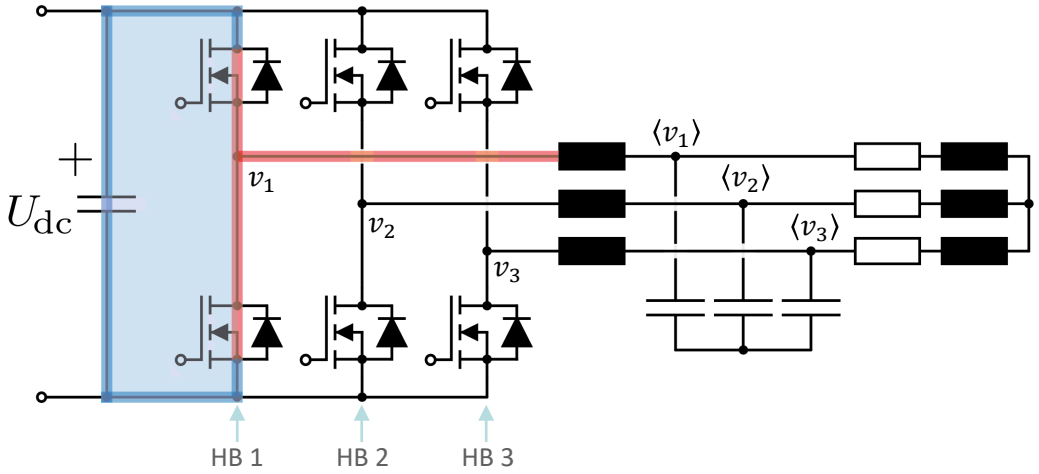


- Cascaded PWM-CSCs avoid large offshore converter platforms
- Coordinated dc-link current control ensures stable operation

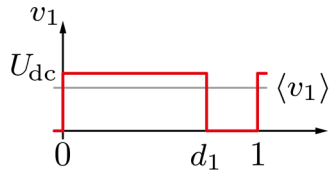
[1] Popat, M., Wu, B., Liu, F. and Zargari, N., 2012. Coordinated control of cascaded current-source converter based offshore wind farm. IEEE Transactions on Sustainable Energy, 3(3), pp.557-565.

Control and Modulation: Per-Phase to Per-Cell Operation

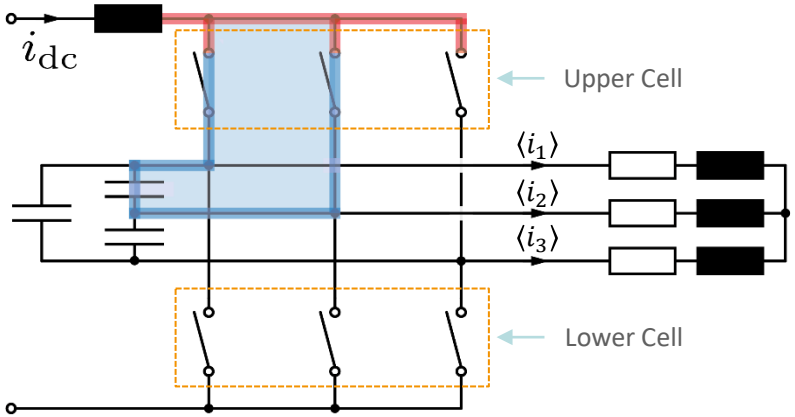
- In a VSI, each half-bridge controls one phase → duty cycles d_1, d_2 , d_3 directly define the phase voltages.
- Commutation loops are closed within each half-bridge, enabling straightforward per-phase PWM control.



$$d_1 = \frac{\langle v_1 \rangle}{U_{dc}} \quad d_2 = \frac{\langle v_2 \rangle}{U_{dc}} \quad d_3 = \frac{\langle v_3 \rangle}{U_{dc}}$$



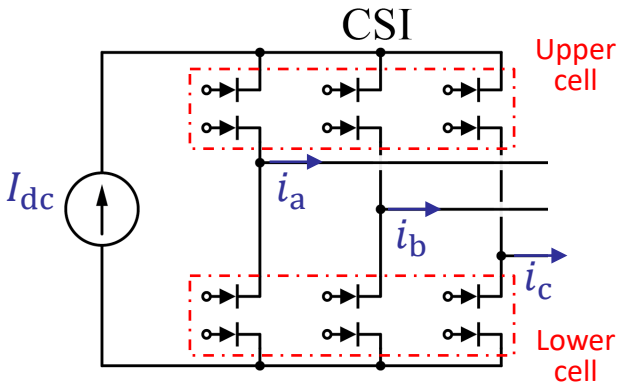
- In a CSI, the DC current is shared among all phases → modulation occurs per converter cell instead of per phase.
- The commutation loops are contained within the switching cells, as indicated → requiring coordinated multi-cell modulation.

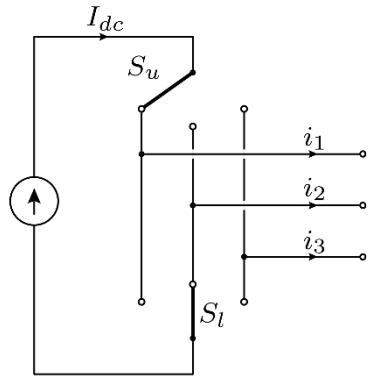


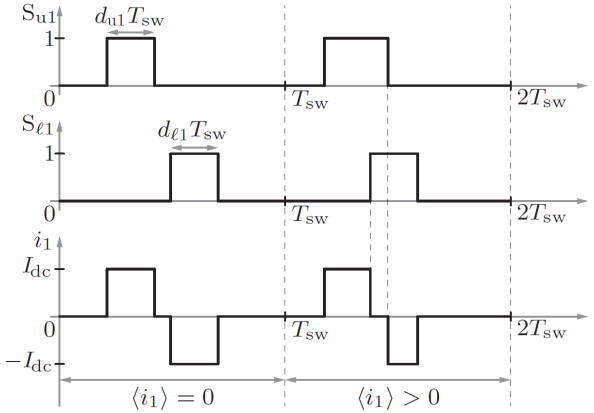
$$d_1 = \frac{\langle i_1 \rangle}{i_{dc}} \quad d_2 = \frac{\langle i_2 \rangle}{i_{dc}} \quad d_3 = \frac{\langle i_3 \rangle}{i_{dc}}$$

Modulation Principle of CSIs

- The task of the modulation is to ensure the desired value of the average phase current at the output
- Upper switch on → positive current pulse; lower switch on → negative current pulse; both switches on → zero current
- Every switching state must ensure the 'flow' of the DC link current







Average value of the current $\langle i_1\rangle$ is obtained by averaging the DC link current pulses.

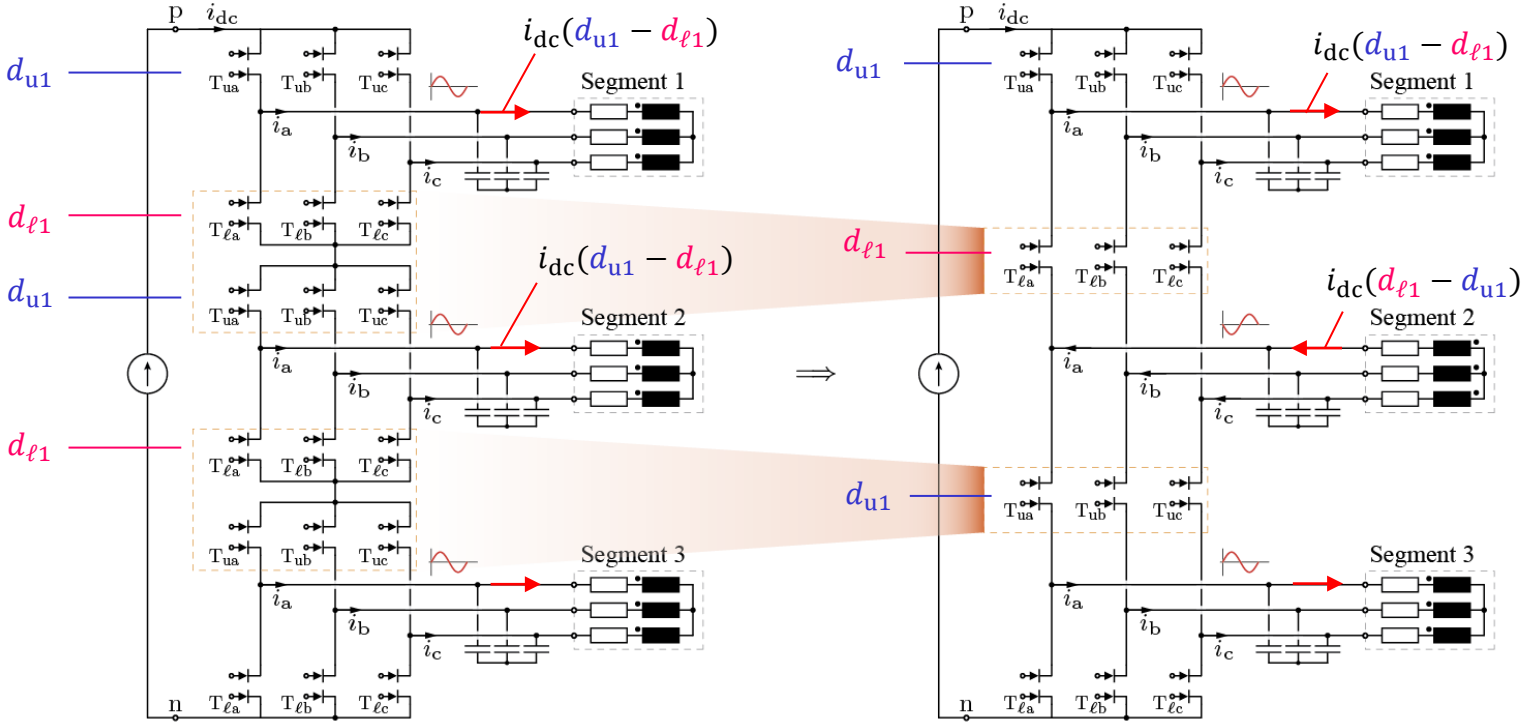
$$\langle i_1\rangle = I_{dc}(d_{u1} - d_{\ell 1})$$

- Current source inverter modulation process has to ensure the following two conditions:

1. Average value of the phase current: $\langle i_1\rangle = I_{dc}(d_{u1} - d_{l1})$
2. Continuity of the DC link current: $d_{u1} + d_{u2} + d_{u3} = 1$ and $d_{l1} + d_{l2} + d_{l3} = 1$

Proposed Multi-Cell Current Source Inverter (mCSI) Topology

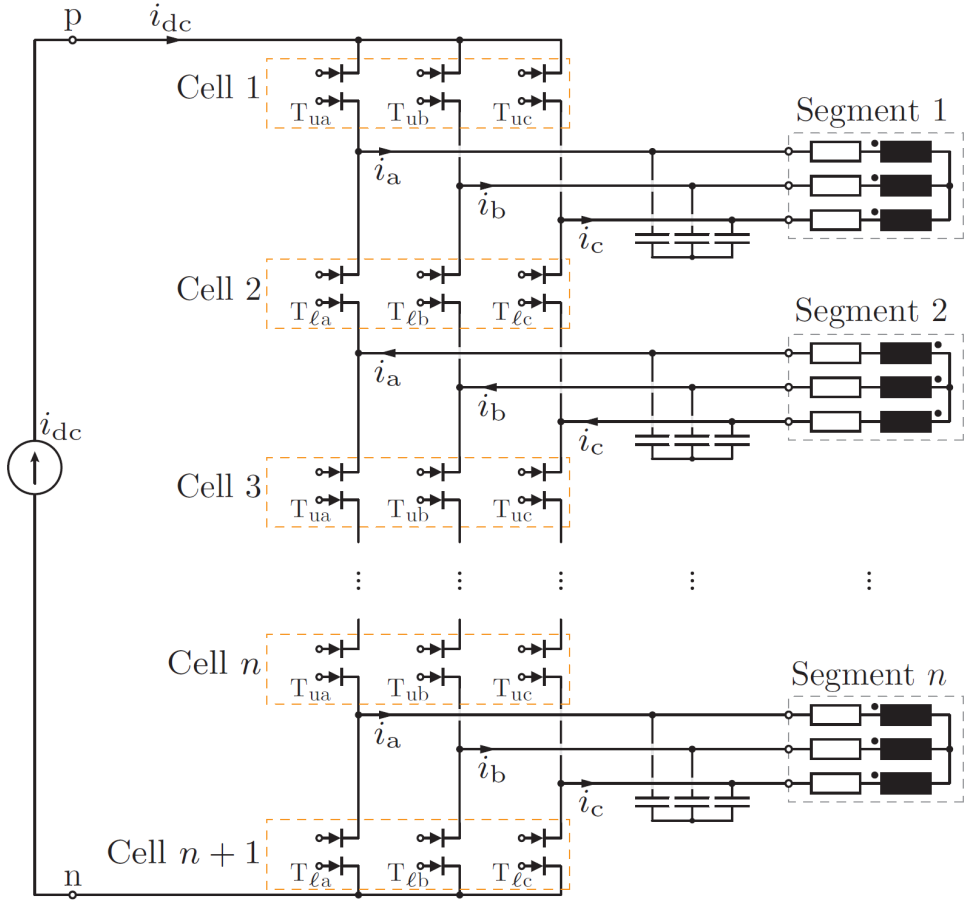
- Key idea: Reuse and re-arrange duty cycles among segments, combining the middle cell
- Each segment applies swapped upper/lower duty-cycle combinations, resulting in reversed current direction
- The reversed current can be compensated by flipping the winding polarity.

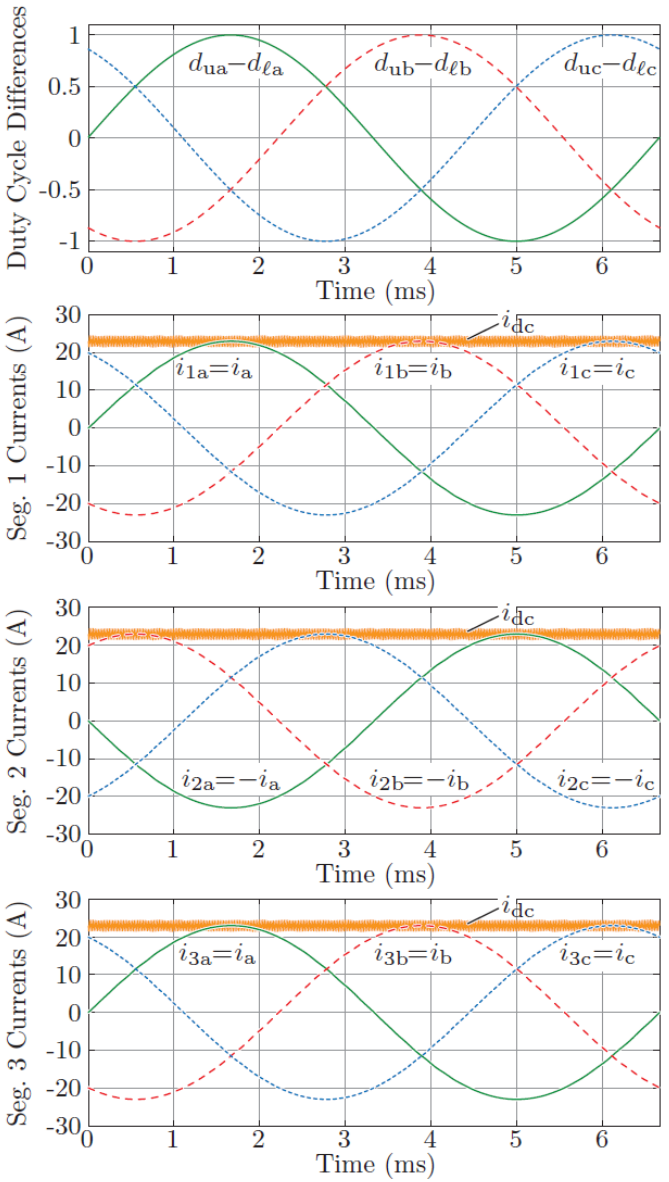


Conventional stacked CSI **Proposed mCSI**

mCSI: n Segments Require $n + 1$ CSI Cells

- The modular CSI (mCSI) topology extends directly to any number of motor segments.





Currents alternate direction from segment to segment simply by duty cycle differences.

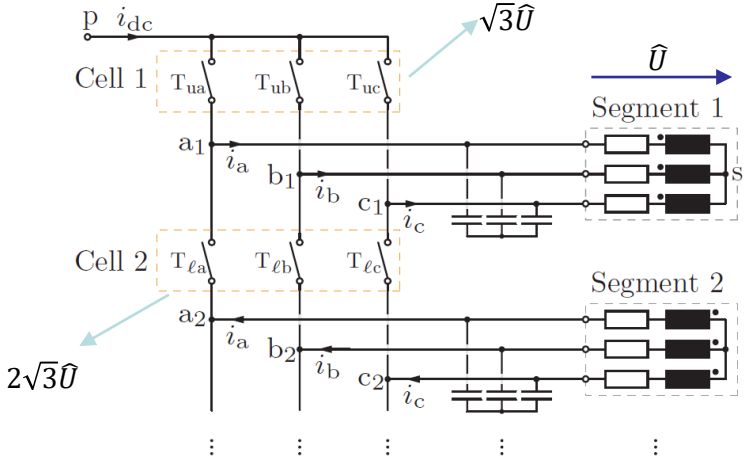
Segment 1

Segment 2

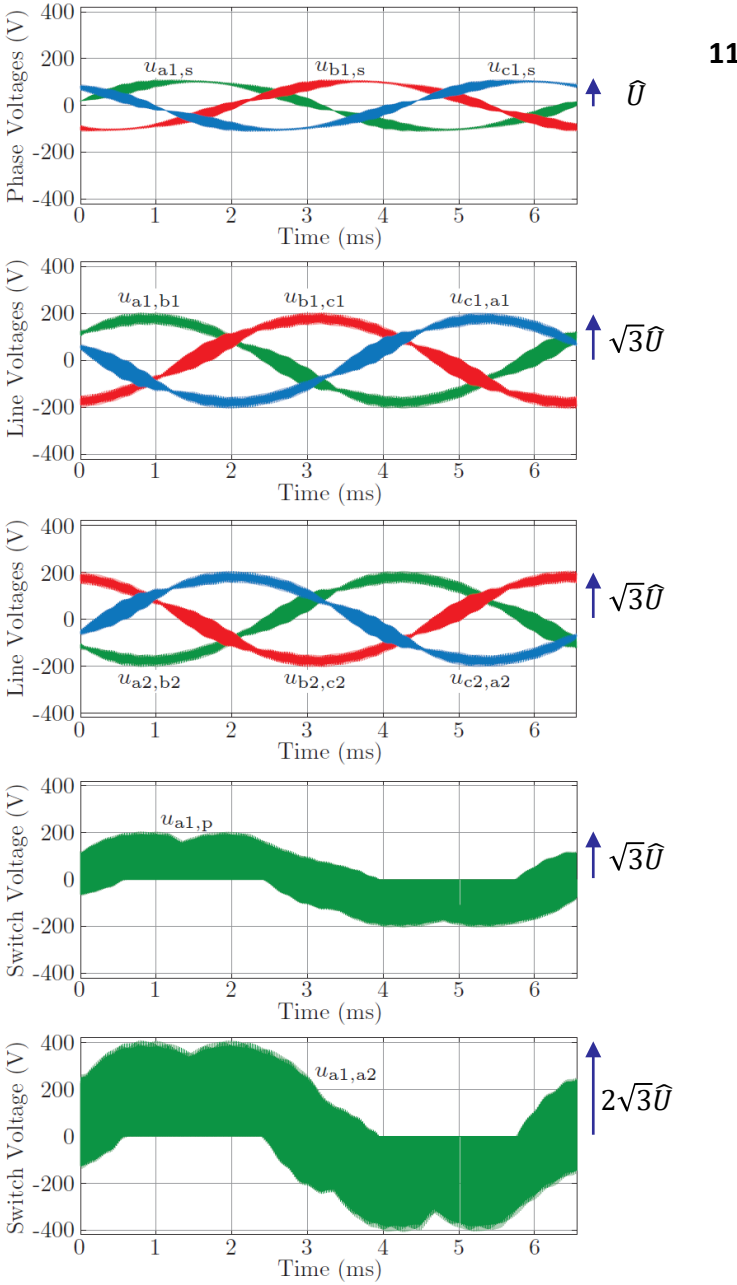
Segment 3

mCSI: Switch Blocking Voltages

- In the modular CSI, switches experience different blocking voltages
- End switches (top and bottom cells) must block up to $\sqrt{3}\hat{U}$, where $\hat{U}$ is the peak phase voltage of one segment.
- Mid switches must block up to $2\sqrt{3}\hat{U}$ due to the cumulative segment voltages.



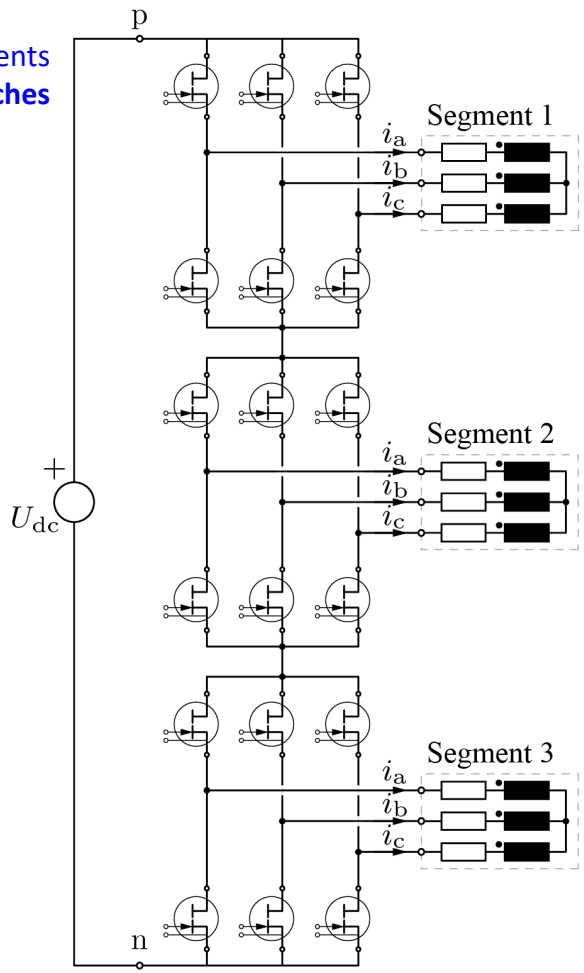
- Compared to modular VSI (mVSI), where all switches block $2\hat{U}$, the mCSI maintains comparable voltage stress



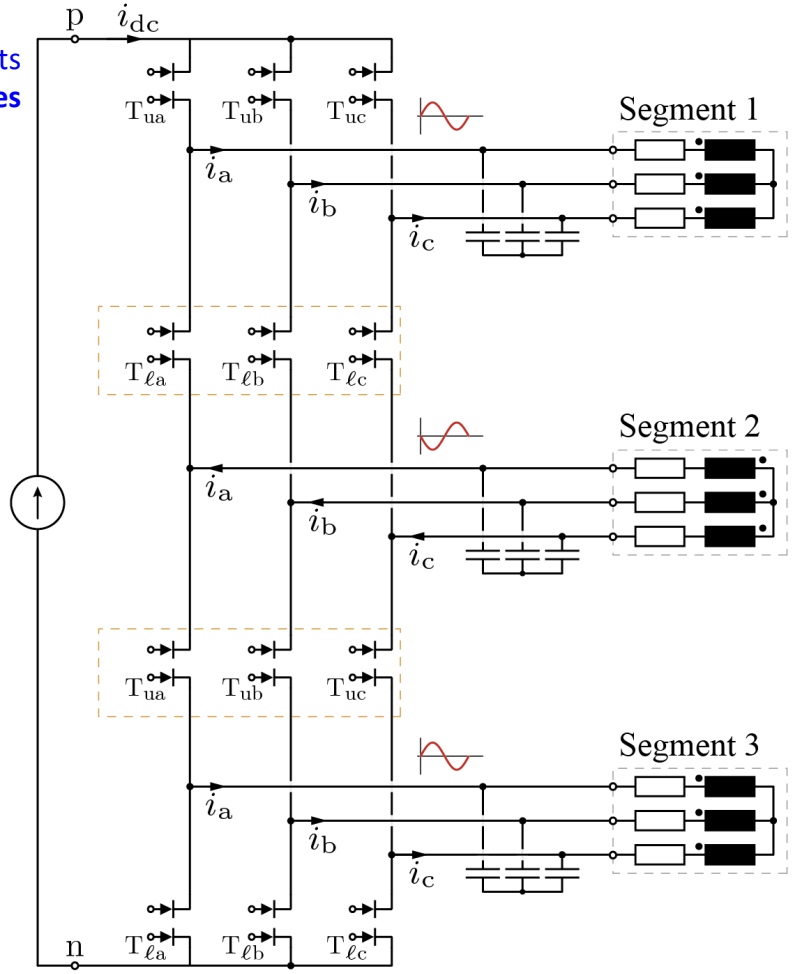
Comparison of mVSIs and mCSIs

- Series-stacked VSIs are a known approach, but they suffer from voltage balancing problems and require phase current sensing for each segment.
- Series-stacked CSIs **avoid voltage balancing issues** and naturally share current **without per-phase sensors**, making them attractive for segmented linear motors.

mVSI for 3 segments
18 switches



mCSI for 3 segments
12 switches



Efficiency Comparison: mVSI vs. mCSI (3-Segment Motor)

- Both converters supply the same 3-segment motor with $\hat{U} = 100\text{V}$ and $P_{\text{el}} = 10\text{kW}$.
- The mCSI hard-switches AC segment voltages → lower losses at high switching frequencies.

Key Quantities	mVSI	mCSI	
		end	mid
Device type	GaN HEMT	GaN MBDS	
Num. of segments (n)	3	3	
Num. of phases per seg.	3	3	
Num. of devices	$6n$	6	$3(n-1)$
Rated voltage (U_{rated})	$2\hat{U}$	$\sqrt{3}\hat{U}$	$2\sqrt{3}\hat{U}$
Dev. ON-state res. ($R_{\text{ds,on}}$)	R_{on}	R_{end}	R_{mid}

$$P_{\text{el}} = n\frac{3}{2}\hat{U}\hat{I} = 10\text{kW}$$

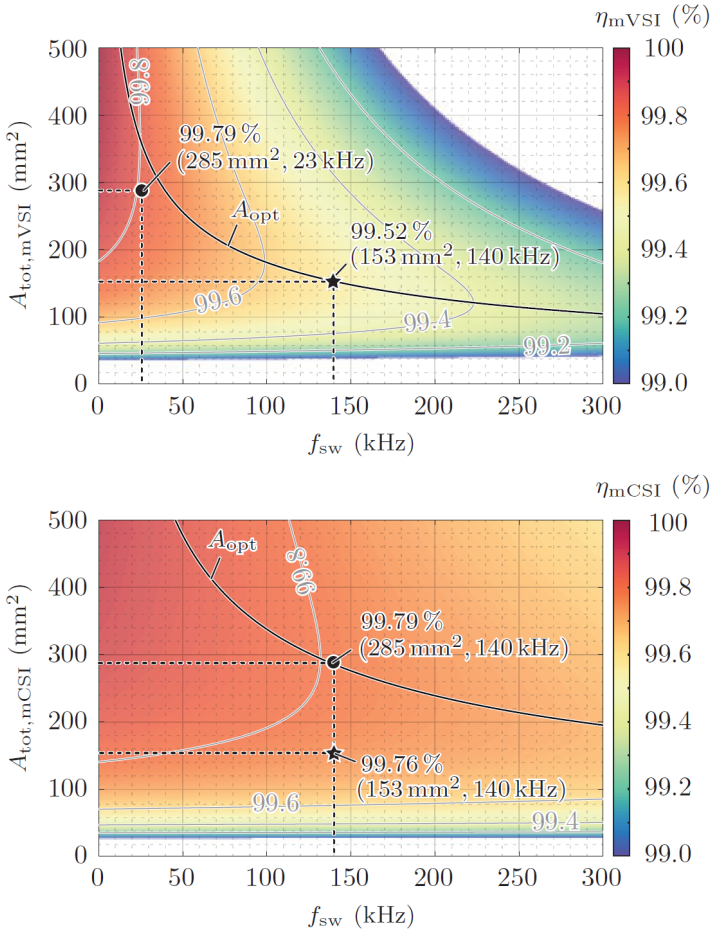
$$r(U_{\text{rated}}) = R_{\text{ds,on}}a_{\text{chip}} = \rho U_{\text{rated}}^{\gamma}$$

$$\rho = 0.26$$

$$\gamma = 1.1$$

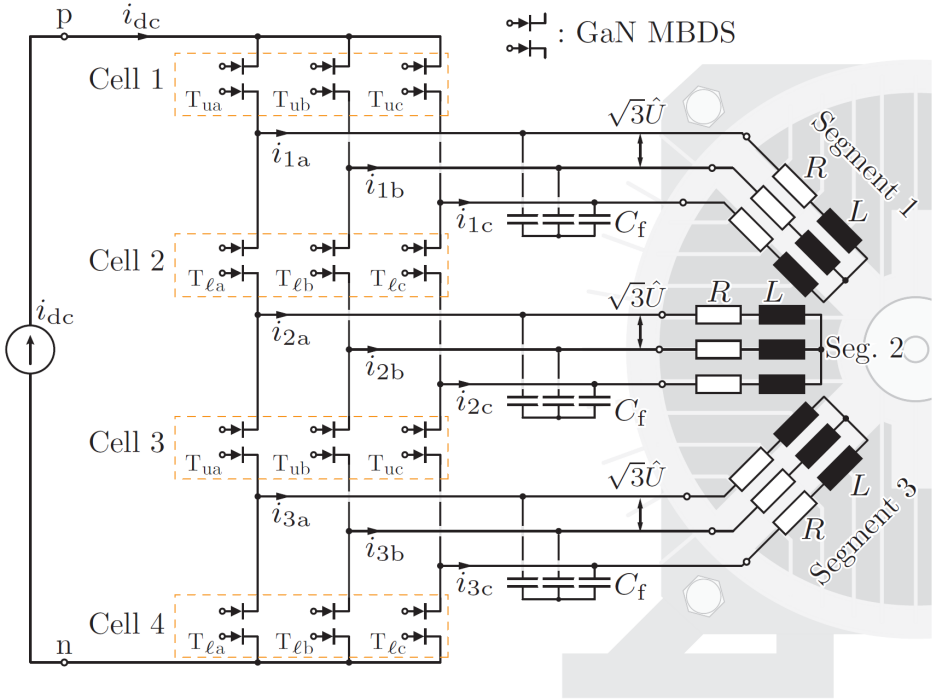
Values for GaN technology

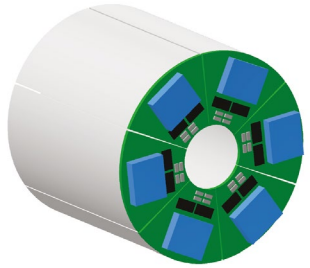
- For the same total semiconductor chip area, the mCSI achieves up to $+0.3\%$ higher efficiency than mVSI.



mCSI for Future Integrated Motor Drives (IMD)

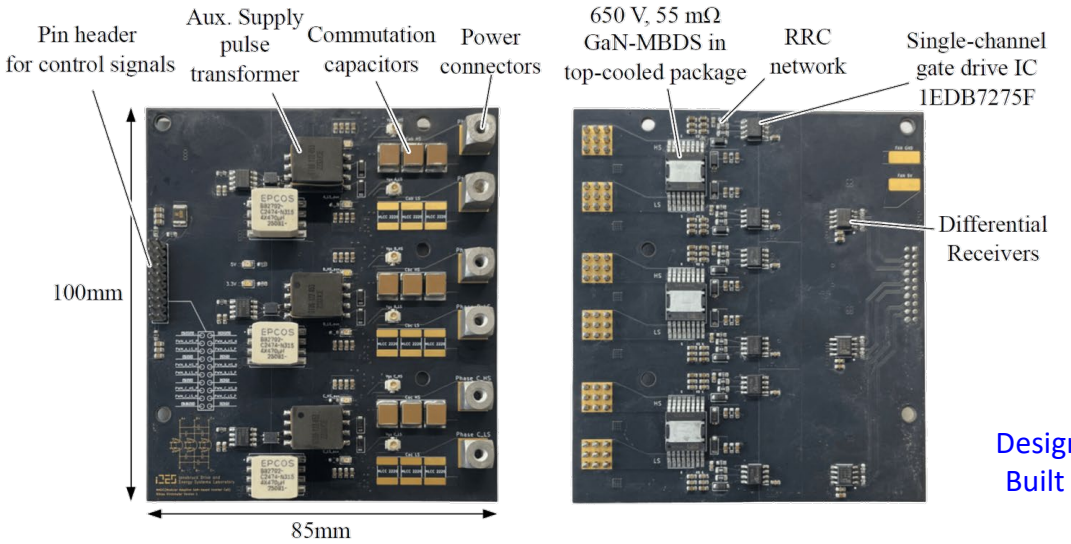
- The mCSI is not limited to linear motors → it can be naturally used for rotary multi-sector machines.
- With almost a switch-per-phase effort → an excellent candidate for Integrated Motor Drives (IMD).





mCSI: an excelent topology candidate for integration

Picture source: Bringezu, T., 2024. Concepts, Modelling, and Optimal Design of Integrated Motor Drives (Doctoral dissertation, ETH Zurich).

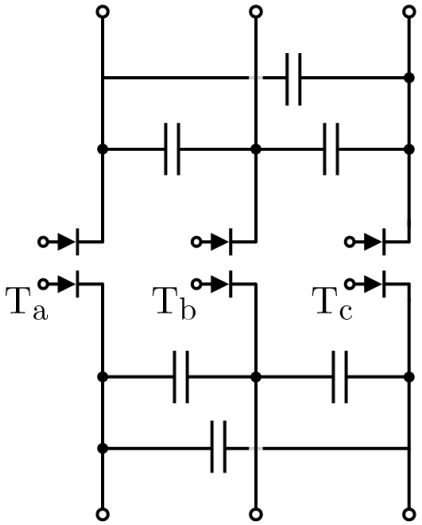


- We have designed and prototyped a single MBDS GaN mCSI cell at UIBK and will test it in the near future.

Designed and Built @UIBK

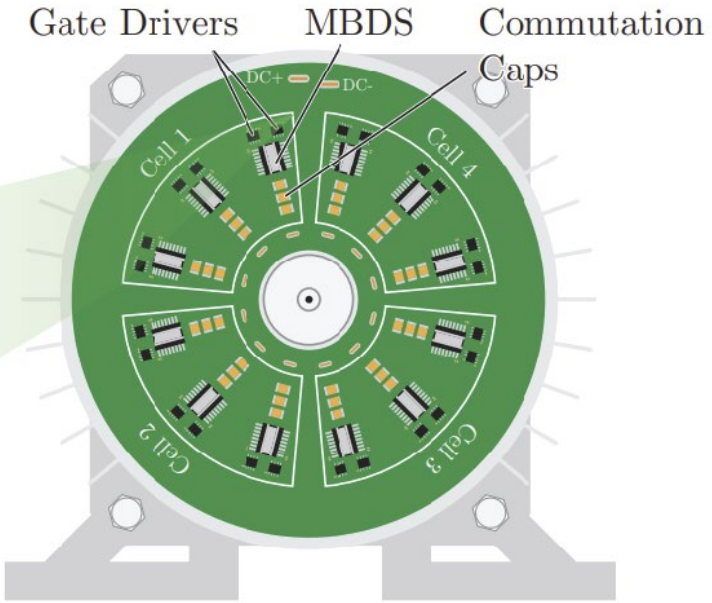
Integration: Building-Block Architecture of the mCSI

- The core element of the mCSI is the Current Source Converter Cell (CSC-Cell)
- Various CSI topologies can be realized through combinations of these cells → building-block design



Current Source Converter Cell

CSC Building Block

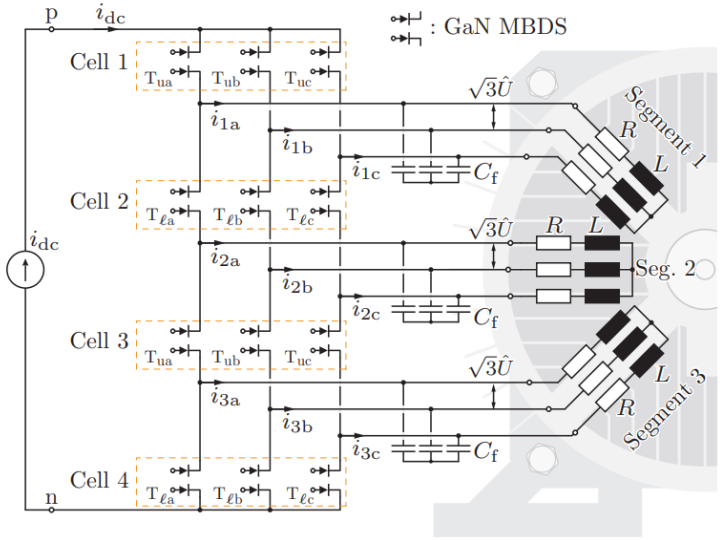


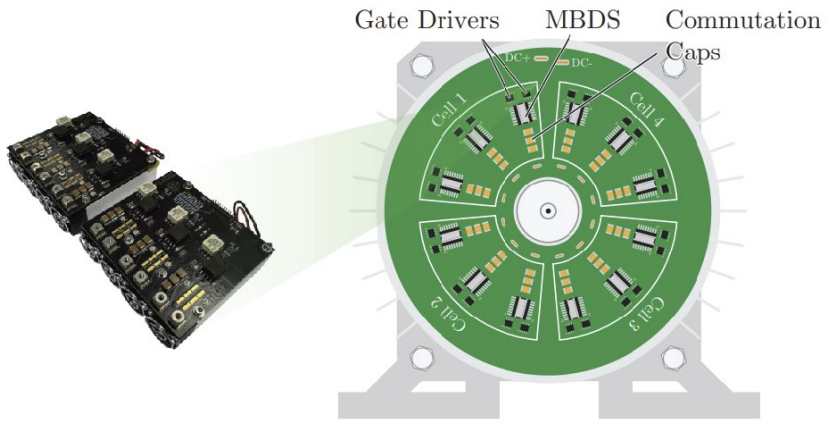
Integrated mCSI Drive System

- When integrated with the motor, the mCSI behaves as an *equivalent DC machine* from the external perspective

Conclusions

- A novel modular Current Source Inverter drive system, mCSI concept, has been proposed.
- By employing a shared intermediate switch configuration and a modified winding arrangement, a significant reduction in device count can be achieved.
- Owing to the shared gate-signal structure, only six gate-drive signals are required and can be repeated across all cells.
- Simulation results confirm the feasibility of a simple, equivalent DC-machine control scheme.
- Theoretical comparison indicates a forecasted improvement in both efficiency and power density compared to VSI-type modular drive systems.





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Thank you!