Modern Current Source Inverter Drives: Modulation, Control, Topologies

Power Electronics for Energy Transition Symposium @SAL

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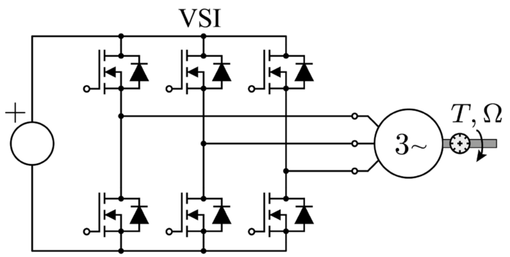
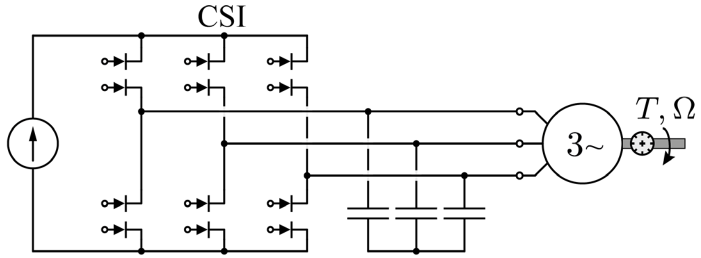
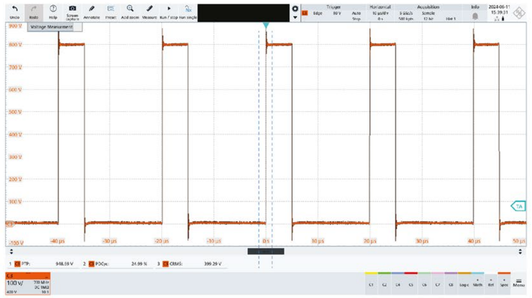
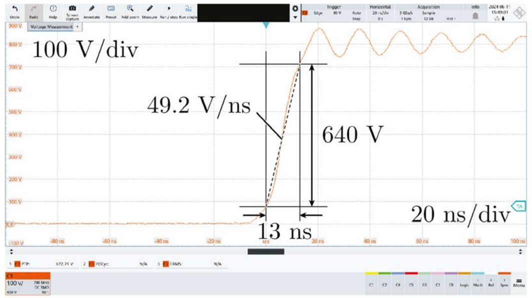
Introduction: VSI and CSI for Drive Systems

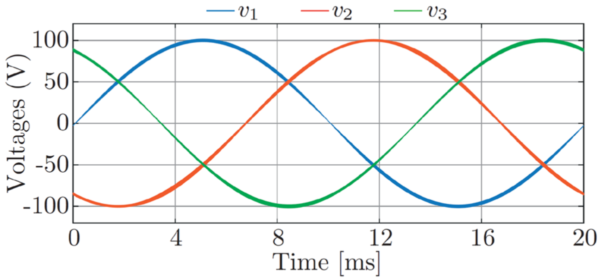
- Voltage Source Inverter (VSI) drive system → typically direct connection of the motor terminals to the switch node
- VSI generates pulsed voltage over motor windings → interturn overvoltage / harmonic losses / bearing currents / EMI / insulation aging







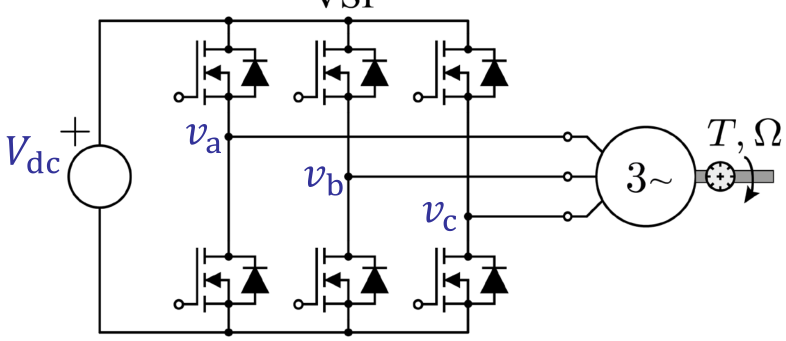




- Current Source Inverter (CSI) drive system → provides ‘smooth’ line voltages over the motor windings due to output filter capacitors
- Therefore, CSI ‘could’ potentially solve high-frequency issues typical for the VSI drive systems
- Blocking of voltage and current in both directions for CSI → Monolithic Bidirectional Power Transistors

Introduction: Modulation VSI and CSI?

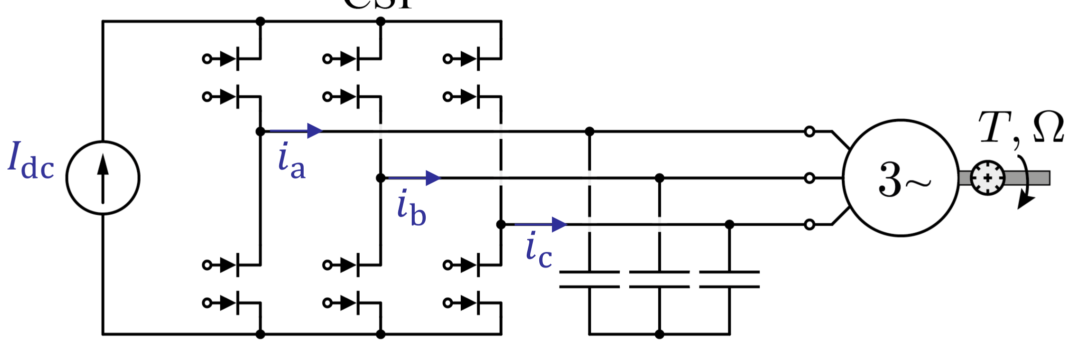
- Pulse width modulation (PWM) is well established and mainly used for VSIs
- Duty cycles are calculated directly from the voltage reference



$$d_a = \frac{\langle v_a \rangle}{V_{dc}} \quad d_b = \frac{\langle v_b \rangle}{V_{dc}} \quad d_c = \frac{\langle v_c \rangle}{V_{dc}}$$

- PWM for VSIs is done per half-bridge
- For more then 3 phases, the same principle applies: voltage reference divide by the DC link voltage
- To get more voltage amplitude → zero voltage component

- For CSIs the best established modulation method is SVM
- There are some PWM approaches for CSI, but it is not so straightforward like with VSIs



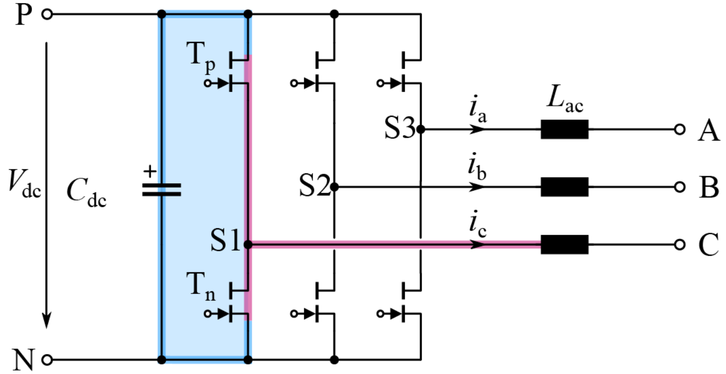
$$\cancel{d_a = \frac{i_a}{I_{dc}}} \quad \cancel{d_b = \frac{i_b}{I_{dc}}} \quad \cancel{d_c = \frac{i_c}{I_{dc}}}$$

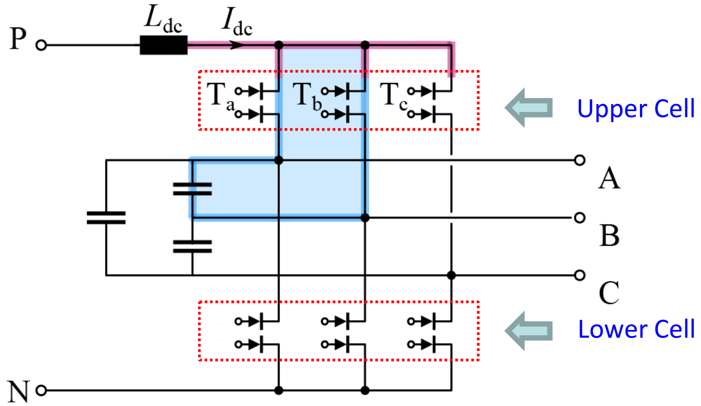
- Duty cycles for CSI can not be calculated directly from the current reference like for VSIs, or can they?
- There is no general modulation method for CSIs that works for any number of phases, is there a way to do it?

Content

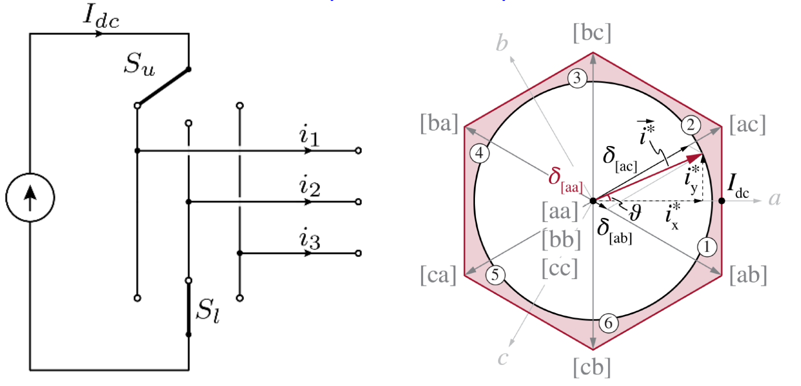
CSI Commutation: per Cell

- Current source inverter modulation process is not straightforward as for the voltage source inverters (VSIs)
- For VSIs, duty cycles can be calculated by simply dividing the desired voltage per phase with the DC link voltage
- For CSIs, such direct approach as for VSIs is not possible since we have to actually always ensure the ‘flow’ of DC link current
- For CSIs there has to be always one and only one of the upper switches on, and one and only one of the lower switches on





Conventionally, SVM is mostly used for CSI modulation

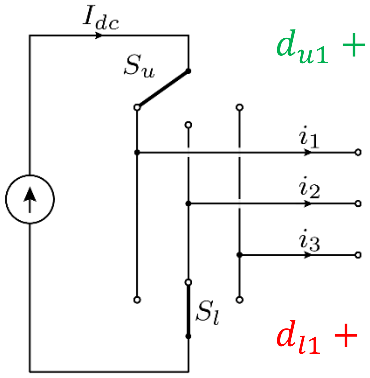


- VSI commutation loop → half bridge
- CSI commutation loop → cell

Picture source: Nain, N., Kovacevic-Badstuebner, I., Huber, J., Grossner, U., & Kolar, J. W. (2022, October). Design aspects of three-phase current-source converter commutation cells with monolithic bidirectional GaN transistors. In 2022 IEEE Energy Conversion Congress and Exposition (ECCE) (pp. 1-8). IEEE.

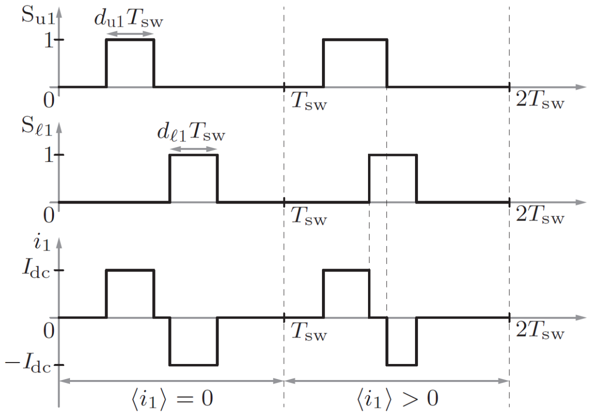
CSI Modulation: Requirements

- 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



$$d_{u1} + d_{u2} + d_{u3} = 1$$

$$d_{l1} + d_{l2} + d_{l3} = 1$$



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

$$\langle i_1 \rangle = I_{dc}(d_{u1} - d_{l1})$$

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

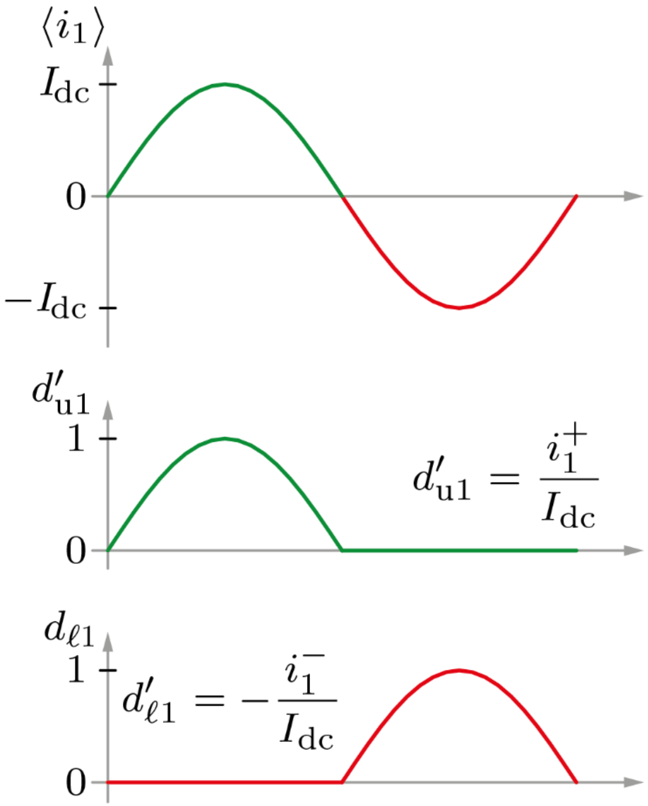
1. Average value of the phase current: $\langle i_1 \rangle = I_{dc}(d_{u1} - d_{l1})$
2. Continuity of the DC link current: $d_{u1} + d_{u2} + d_{u3} = 1$ and $d_{l1} + d_{l2} + d_{l3} = 1$

CSI Modulation: 1st Requirement – Phase Current Average Value

- CSI needs to provide to the AC load desired averaged phase current value $\langle i_1 \rangle$
- The phase current is 'algebraically' obtained from the duty cycles and the DC link current value, and it is equal to the difference of the upper and lower duty cycles:

$$\langle i_1 \rangle = I_{dc}(d_{u1} - d_{l1})$$

- We can have an extremely simple approach to obtain the phase current:
  - for $\langle i_1 \rangle > 0$ → put $d'_{l1} = 0$
  - for $\langle i_1 \rangle < 0$ → put $d'_{u1} = 0$

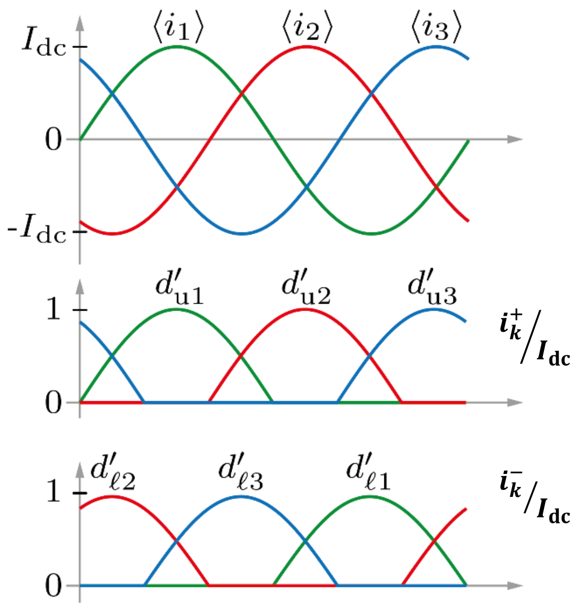


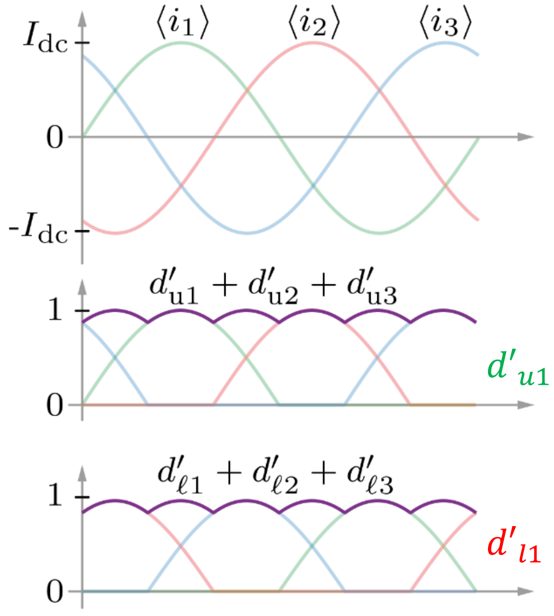
$$\langle i_1 \rangle = I_{dc}(d'_{u1} - d'_{l1})$$

$$\langle i_1 \rangle = I_{dc}(d'_{u1} - d'_{l1})$$

CSI Modulation: 2nd Requirement – Continuity of DC Link Current

- To provide the flow of the DC link current → the upper duty cycles need to sum up to unity: $\sum d_u = 1$
- To provide the flow of the DC link current → the lower duty cycles need to sum up to unity: $\sum d_l = 1$
- But, by just calculating duty cycles from the ratio i_k^+/I_{dc} of i_k^-/I_{dc}, they do not add up to unity!



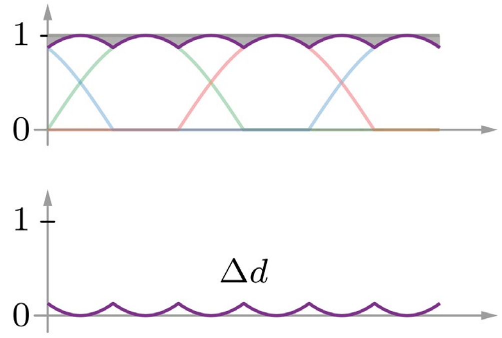


$d'_{u1} + d'_{u2} + d'_{u3} \neq 1$

$d'_{l1} + d'_{l2} + d'_{l3} \neq 1$

Excess duty cycle

$\Delta d = 1 - (d'_1 + d'_2 + d'_3)$



- The 'leftover' duty cycle, i.e., the difference of the duty cycle sum to 1 → excess duty cycle Δd

CSI Modulation: Excess Duty Cycle - Δd

- What would happen if we distribute Δd equally between the phases → we solve the continuity of the DC link current requirement!

$$d_{u1} = d'_{u1} + \frac{\Delta d}{3}$$
$$d_{u2} = d'_{u2} + \frac{\Delta d}{3}$$
$$d_{u3} = d'_{u3} + \frac{\Delta d}{3}$$

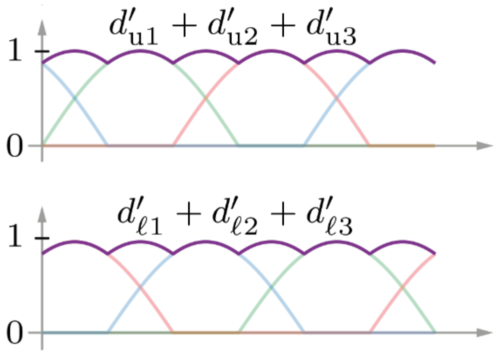
$\Rightarrow$ $d_{u1} + d_{u2} + d_{u3} = 1$

$$d_{l1} = d'_{l1} + \frac{\Delta d}{3}$$
$$d_{l2} = d'_{l2} + \frac{\Delta d}{3}$$
$$d_{l3} = d'_{l3} + \frac{\Delta d}{3}$$

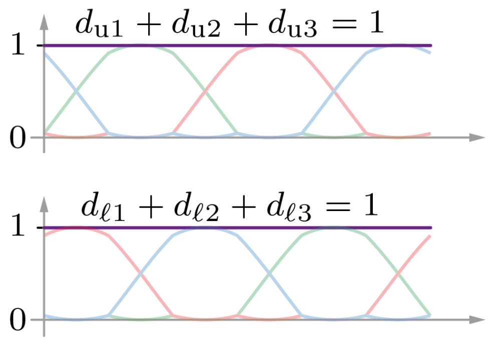
$\Rightarrow$ $d_{l1} + d_{l2} + d_{l3} = 1$

Excess duty cycle

$$\Delta d = 1 - (d'_1 + d'_2 + d'_3)$$



$+\frac{\Delta d}{3}$ $\Rightarrow$



CSI Modulation: Excess Duty Cycle - Δd

- **Adding excess duty cycles solve the issue of the DC link current continuity (1st req.), but did it mess up our averaged phase current (2nd req.)**

$$d_{u1} = d'_{u1} + \frac{\Delta d}{3}$$
$$d_{u2} = d'_{u2} + \frac{\Delta d}{3}$$
$$d_{u3} = d'_{u3} + \frac{\Delta d}{3}$$

$$\Rightarrow \quad d_{u1} + d_{u2} + d_{u3} = 1$$

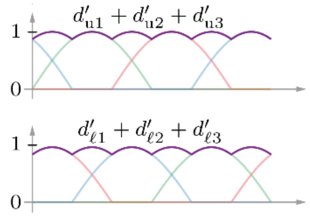
$$d_{l1} = d'_{l1} + \frac{\Delta d}{3}$$
$$d_{l2} = d'_{l2} + \frac{\Delta d}{3}$$
$$d_{l3} = d'_{l3} + \frac{\Delta d}{3}$$

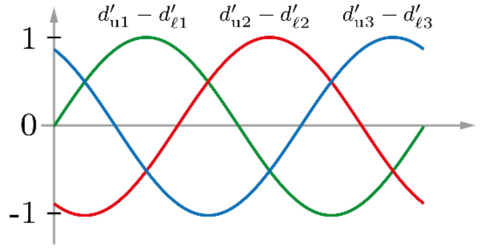
$$\Rightarrow \quad d_{l1} + d_{l2} + d_{l3} = 1$$

$$d'_{u1} - d'_{l1} = \left(d'_{u1} + \frac{\Delta d}{3}\right) - \left(d'_{l1} + \frac{\Delta d}{3}\right) = d_{u1} - d_{l1} \qquad \langle i_1 \rangle = I_{dc}(d_{u1} - d_{l1})$$

$$d'_{u2} - d'_{l2} = \left(d'_{u2} + \frac{\Delta d}{3}\right) - \left(d'_{l2} + \frac{\Delta d}{3}\right) = d_{u2} - d_{l2} \qquad \langle i_2 \rangle = I_{dc}(d_{u2} - d_{l2})$$

$$d'_{u3} - d'_{l3} = \left(d'_{u3} + \frac{\Delta d}{3}\right) - \left(d'_{l3} + \frac{\Delta d}{3}\right) = d_{u3} - d_{l3} \qquad \langle i_3 \rangle = I_{dc}(d_{u3} - d_{l3})$$





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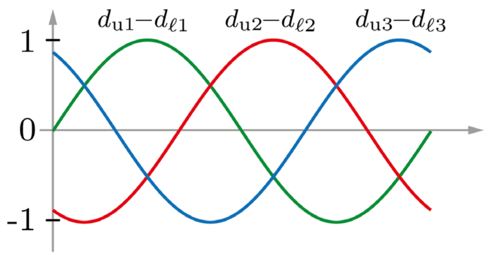
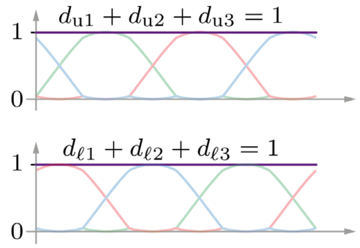
1st Req.



2nd Req.

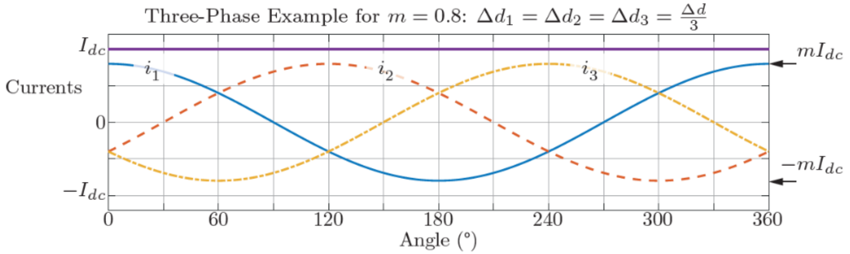


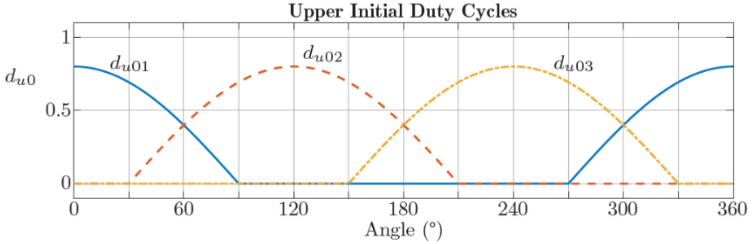
- **Adding excess duty cycle does not mess up our 2nd requirement for the averaged phase current!**

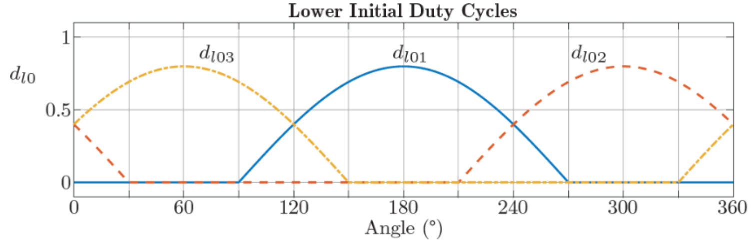
CSI Modulation: 4 Simple Steps

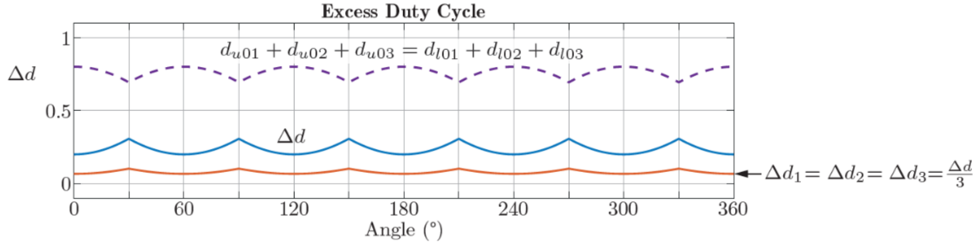
- **Split calculation of the CSI duty cycle into simple steps:**

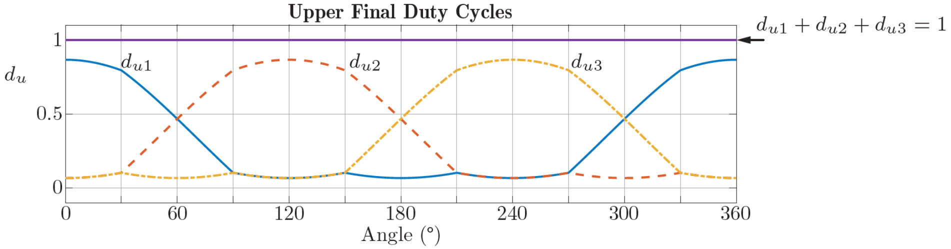
  1. Calculate the initial duty cycles as: $d_{u0k} = \frac{i_k^+}{I_{dc}}$, $d_{l0k} = \frac{i_k^-}{I_{dc}}$ where $k \in \{1,2,3\}$
  2. Calculate excess duty cycle: $\Delta d = 1 - (d_{u01} + d_{u02} + d_{u03}) = 1 - (d_{l01} + d_{l02} + d_{l03})$
  3. Distribute excess duty cycle: $\Delta d_1 = \Delta d_2 = \Delta d_3 = \frac{\Delta d}{3}$
  4. Calculate final duty cycles: $d_{u1} = d_{u01} + \Delta d_1$, $d_{u2} = d_{u02} + \Delta d_2$, $d_{u3} = d_{u03} + \Delta d_3$
     $d_{l1} = d_{l01} + \Delta d_1$, $d_{l2} = d_{l02} + \Delta d_2$, $d_{l3} = d_{l01} + \Delta d_3$

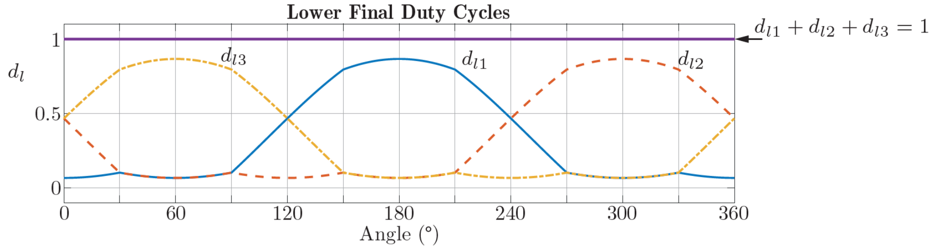












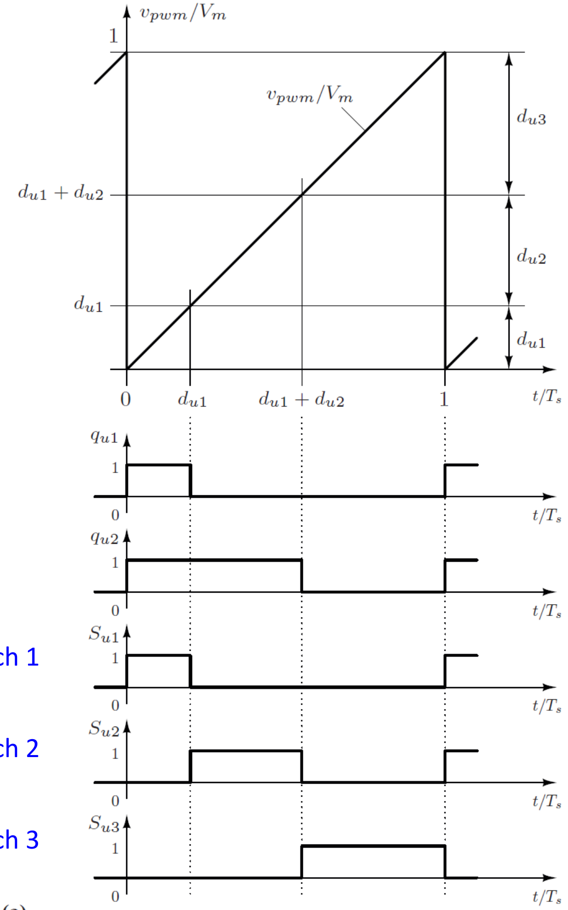
Multiple Threshold Modulator (MTM)

- **The calculated average duty cycles are supplied to the 'multiple-threshold modulator' to generate gate signals for switches**

Gate signal for the upper switch 1

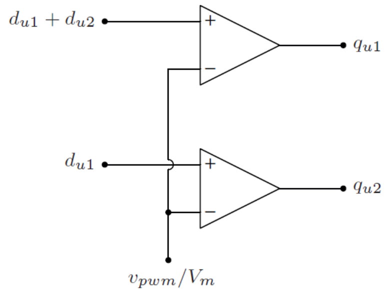
Gate signal for the upper switch 2

Gate signal for the upper switch 3

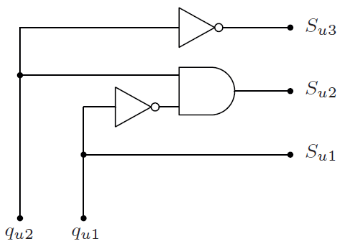


(a)

Gate signals organized like 'relay race'.



(b)

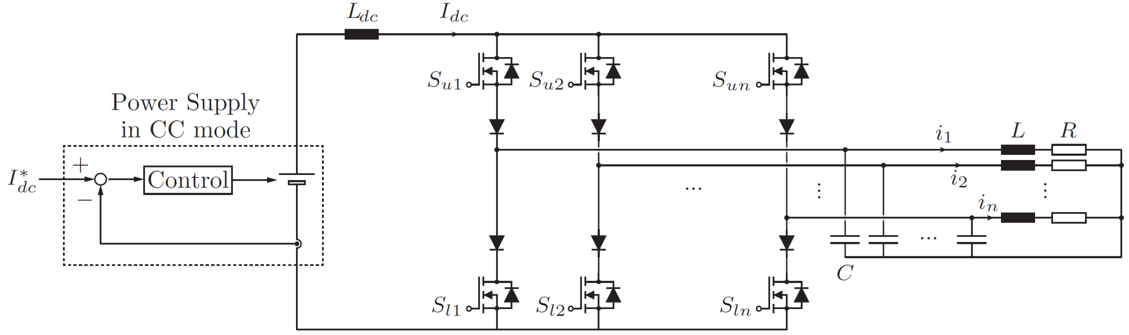


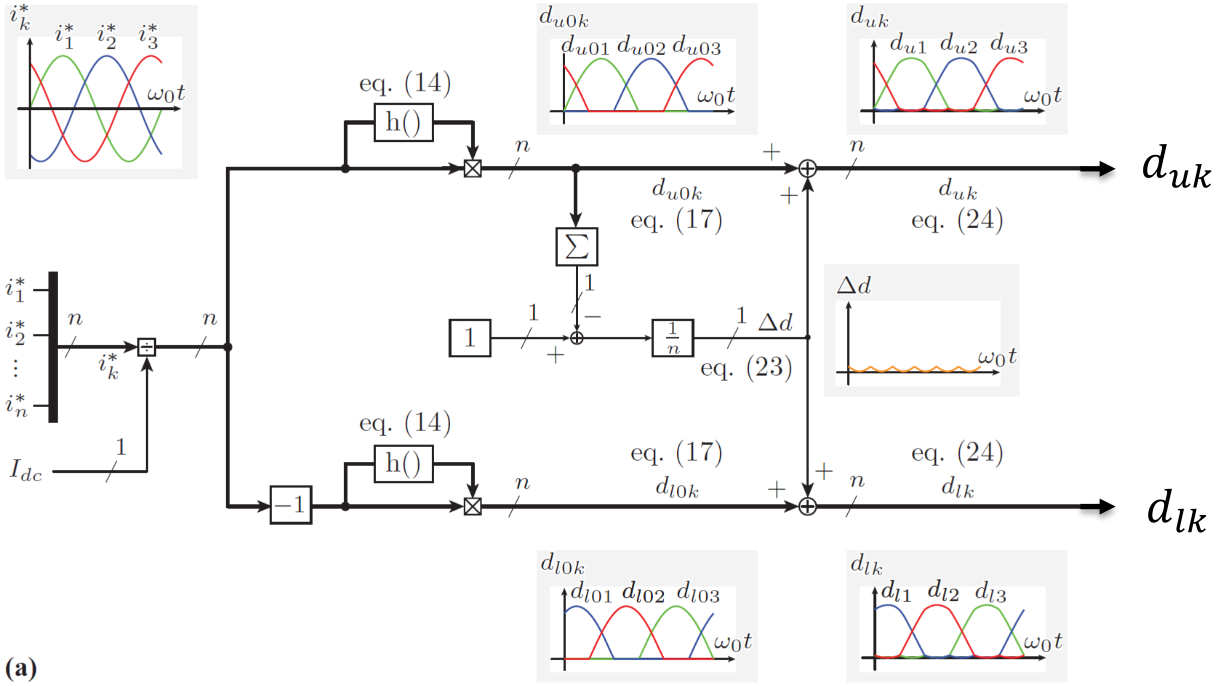
(c)

(b) and (c) are digital circuits ensuring gate signals happen one after the other ('relay race')

n-Phase CSI: the 4 Simple Steps

- **These modulation steps can be generalized for n-phase CSI**
  1. Calculate the initial duty cycles as: $d_{u0k} = \frac{i_k^+}{I_{dc}}$, $d_{l0k} = \frac{i_k^-}{I_{dc}}$ where $k \in \{1, \ldots, n\}$
  2. Calculate excess duty cycle: $\Delta d = 1 - \sum_{k=1}^{k=n} d_{u0k} = 1 - \sum_{k=1}^{k=n} d_{l0k}$
  3. Distribute excess duty cycle: $\Delta d_1 = \cdots = \Delta d_n = \frac{\Delta d}{n}$
  4. Calculate final duty cycles: $d_{uk} = d_{u0k} + \Delta d_k$
     $d_{lk} = d_{l0k} + \Delta d_k$

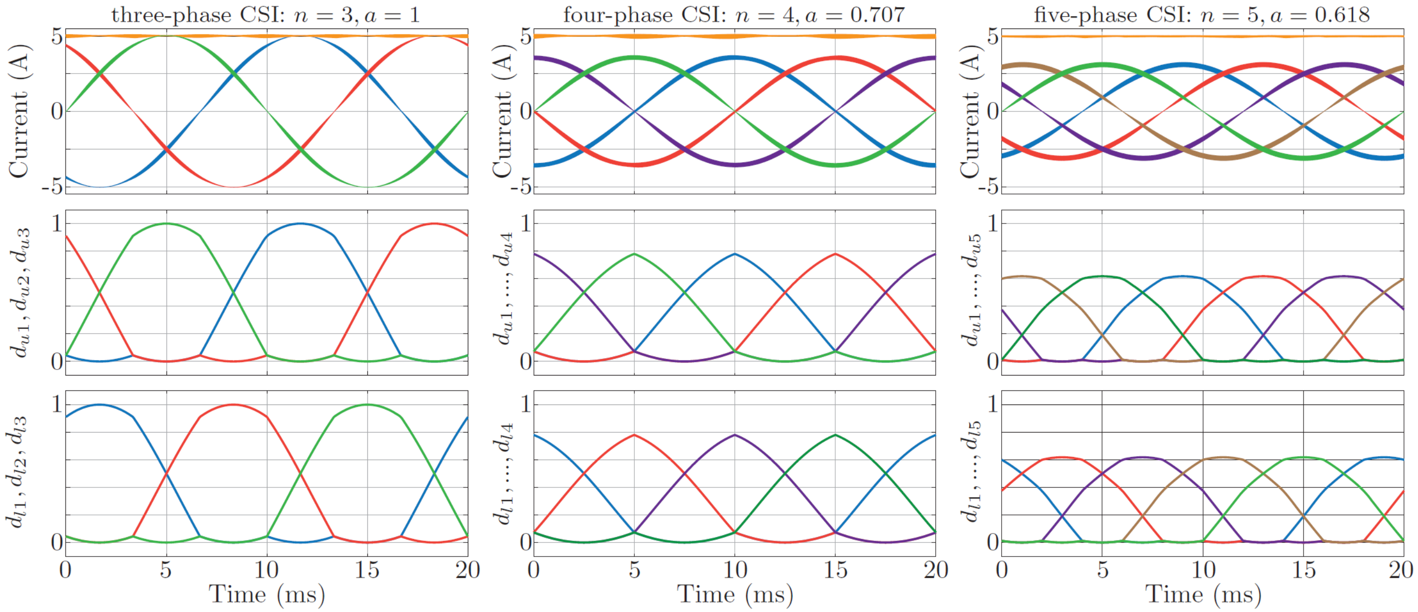


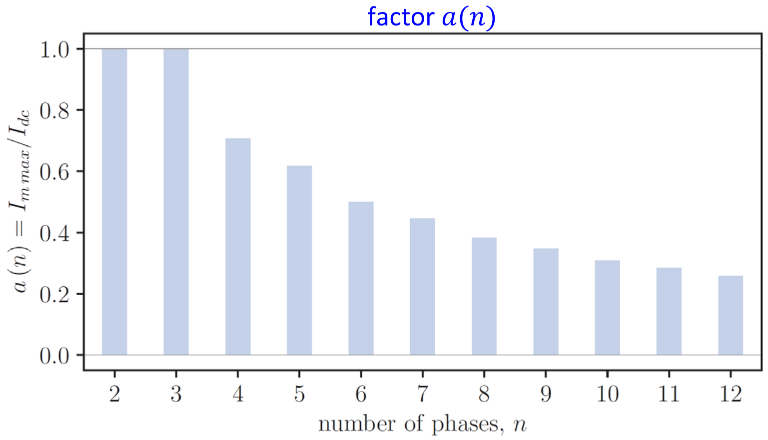


(a)

n-Phase CSI: the 4 Simple Steps

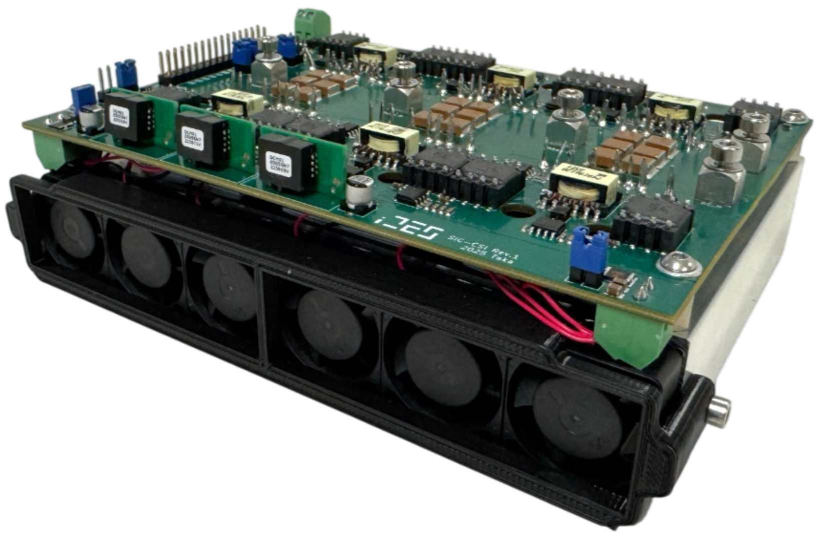
- 3-, 4-, and 5-phase examples
- Phase reduction when number of phases is larger then 3 → factor a



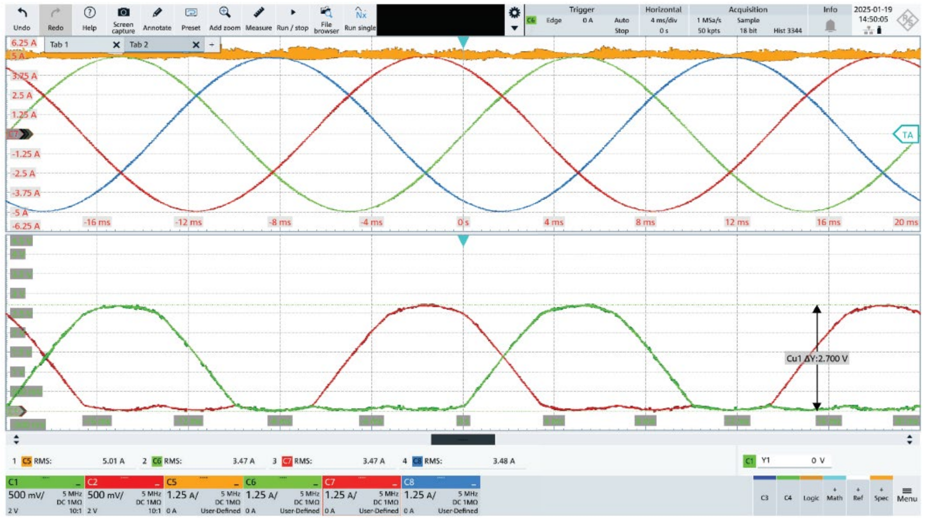


CSI Modulation: Experimental Verification

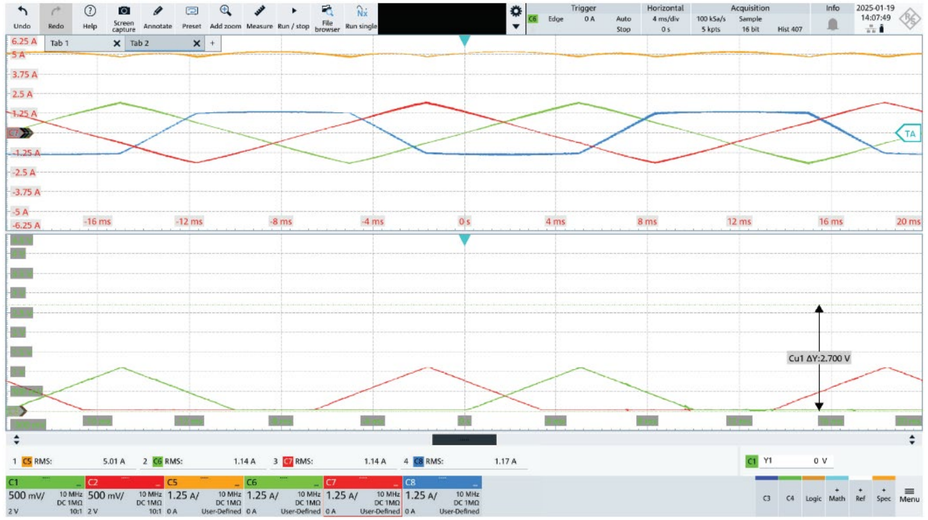
- CSI realized using 650V SiC MOSFETs



Sinusoidal reference



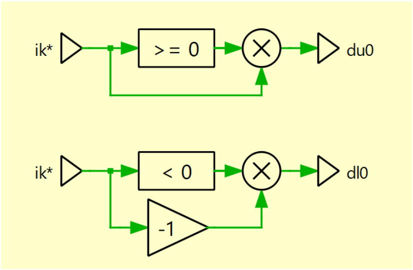
Arbitrary waveform



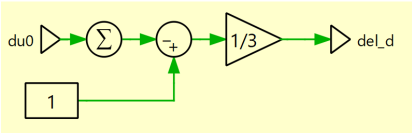
CSI Modulation: PLECS

- Reaction from PLECS for the proposed method: '…you can realize CSI modulation without C-script block? Incredible!…'

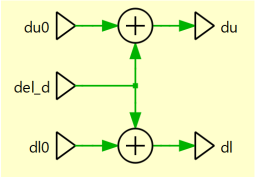
Step 1



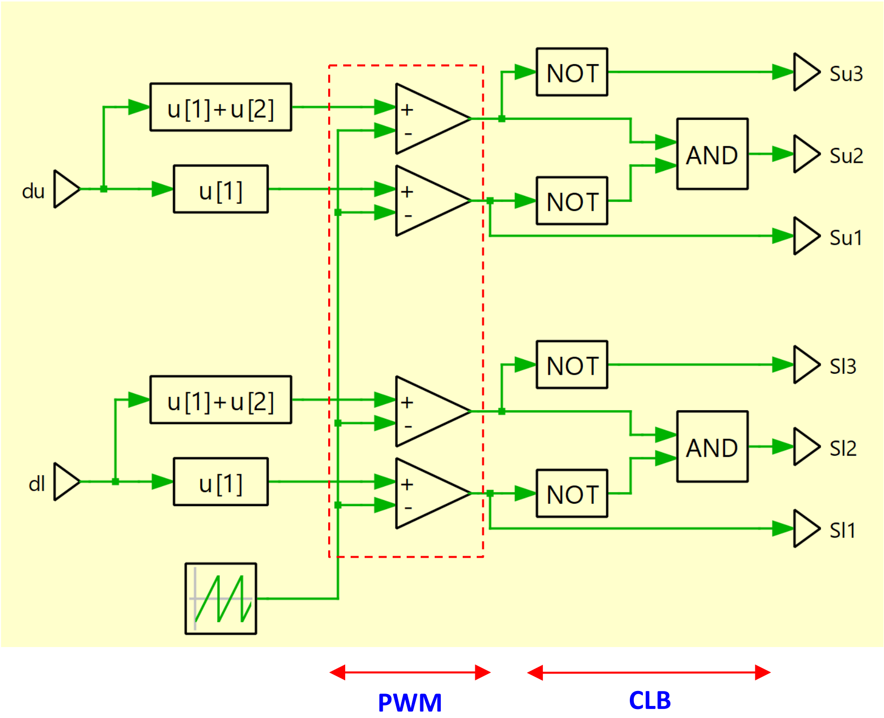
Step 2,3



Step 4



Works for any number of phases!



- Implementation: PWM registers + CLB (Configurable Logic Block)
- FPGA
- Infineon PSoC (old), Microchip PIC16F13145, TI F28P55x

CSI Modulation: PLECS

- **The proposed CSI modulation method will be in PLECS library in the new version 5.**

PLECS

DEMO MODEL

Multi-Phase Current Source Inverter

Last updated in PLECS 5.0.1

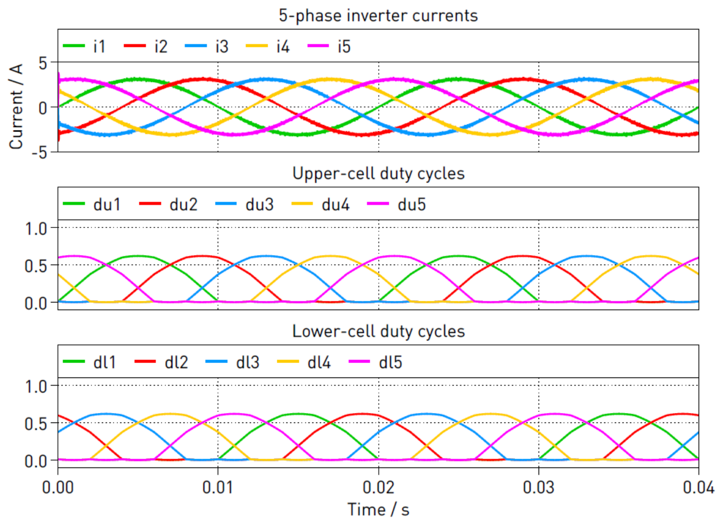


Figure 8: Simulation results for 5-phase CSI

4 Conclusion

This demo aims at showcasing a novel modulation technique for current source inverters with an arbitrary number of phases.

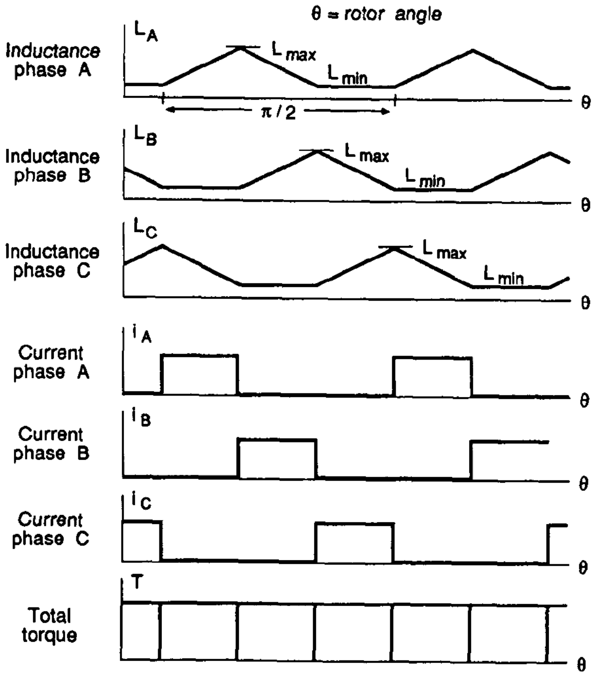
References

[1] Pejović, P., Ohno, T., Borović, U. and Mirić S., "Pulse width modulation for current source inverters with arbitrary number of phases," in *Scientific Reports* 15, 8744 (2025). Available: https://doi.org/10.1038/s41598-025-92388-9. [Accessed: Aug. 28, 2025].

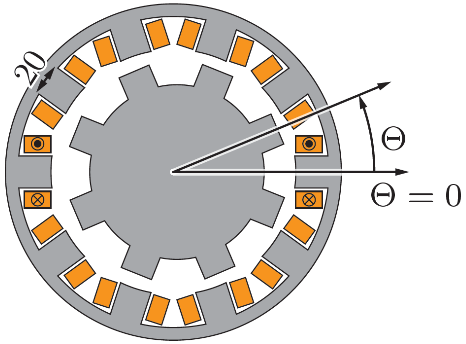
Content

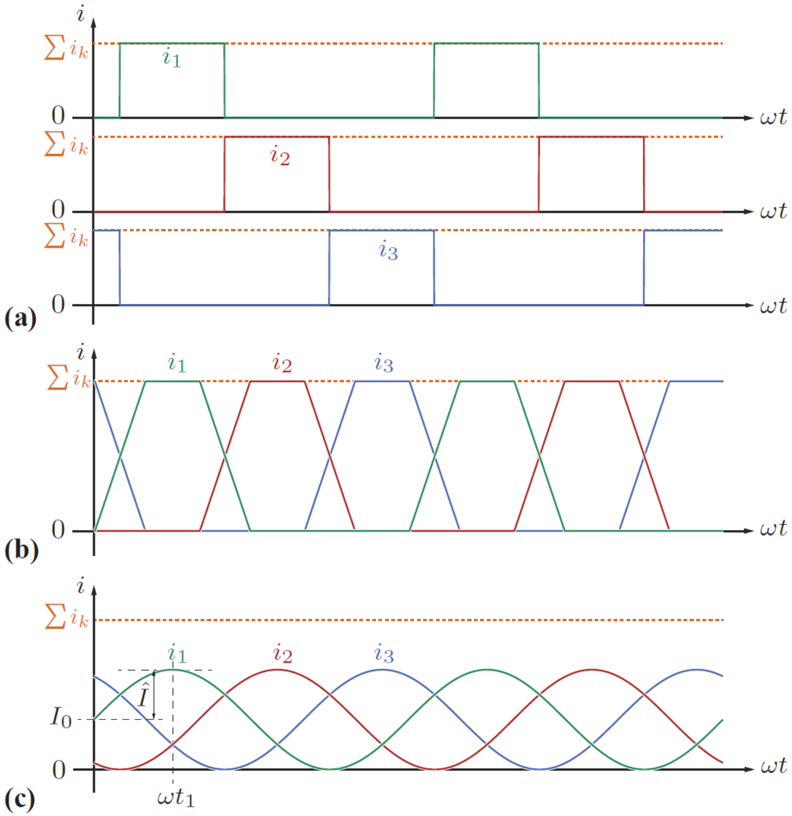
Reluctance Machine: Unipolar Currents

- Built from iron and copper → no permanent magnets; good ratio of the torque and the moment of inertia → good acceleration
- Torque is proportional to the inductance change and the square of the current → unipolar phase currents



$$T \sim i^2 \frac{\partial L}{\partial \Theta}$$



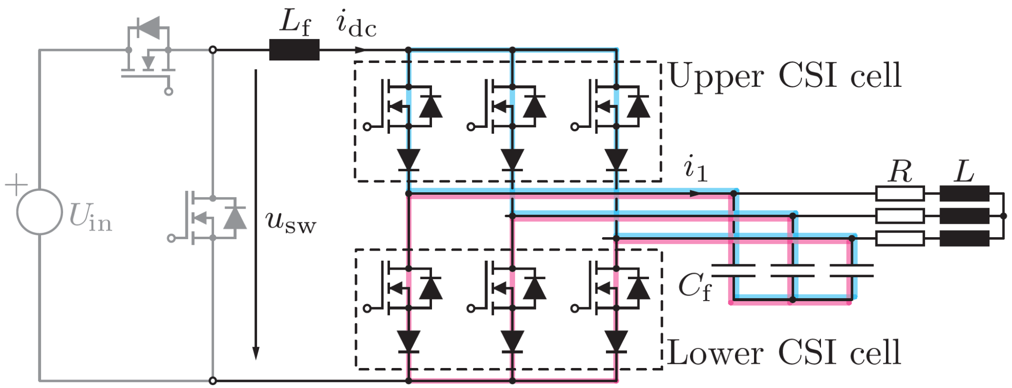


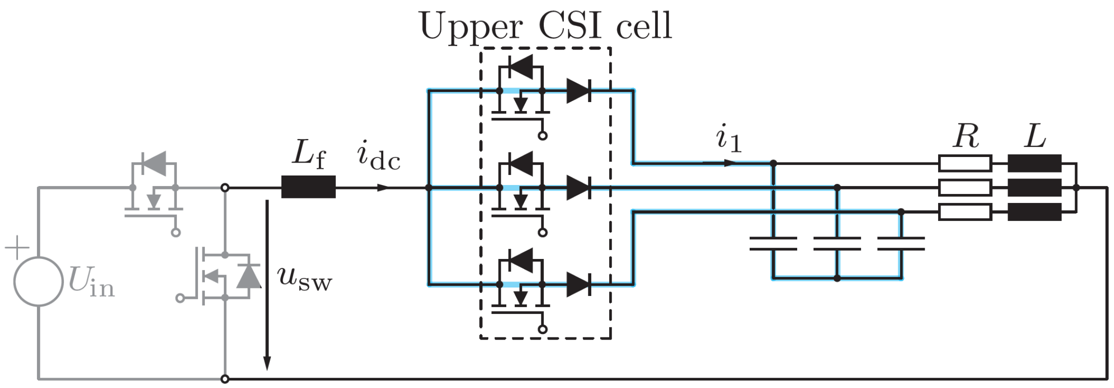
Unipolar phase currents

CSI for Unipolar Currents (uniCSI): Topology Derivation (1)

- The average phase current is proportional to the duty cycle difference of the upper and lower CSI cells
- If we need positive only current → we can realize it with the upper cell only!

$$\langle i_1 \rangle = i_{dc}(d_{u1} - d_{l1})$$

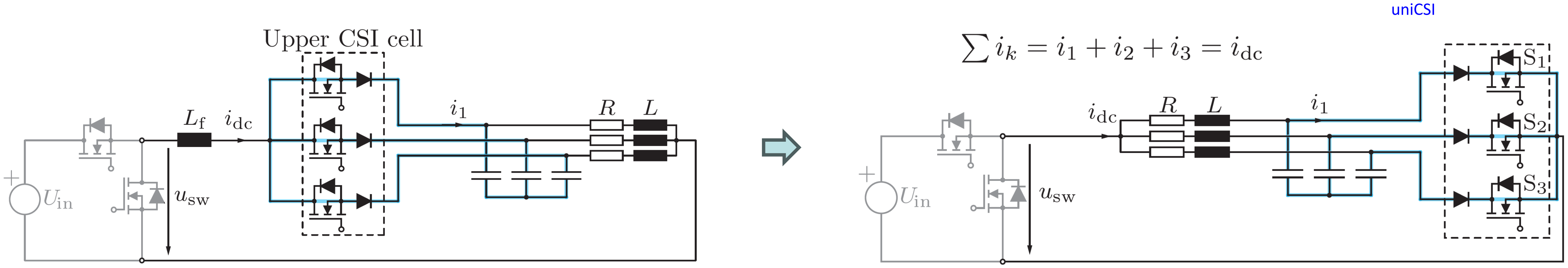




- RL load represents a reluctance machine that needs positive only phase currents!
- How can we further develop this topology?

CSI for Unipolar Currents (uniCSI): Topology Derivation (2)

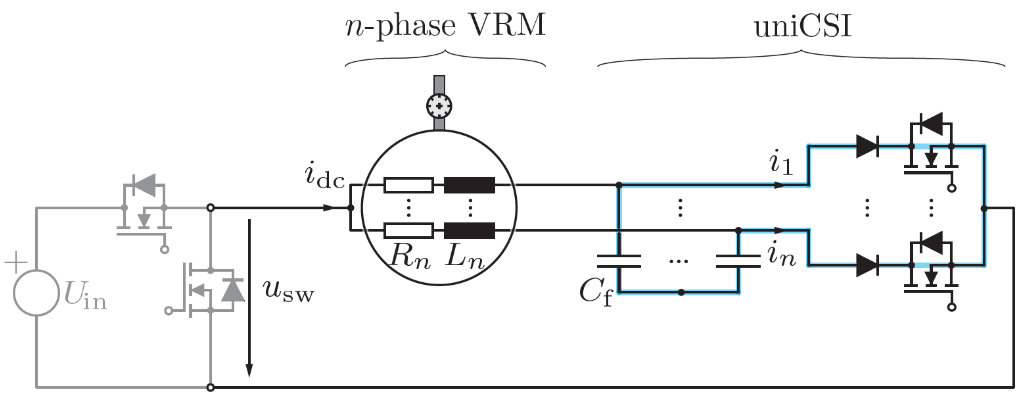
- To improve the topology on the left, we can do the following:
  1. Swap the position of the CSI cell and the RL load → this allows us to have MOSFETS sitting on the GND – simple gate driver design
  2. We can remove the DC link inductor, since the RL load's inductance is 'seen' on the DC side and can support the CSI opration



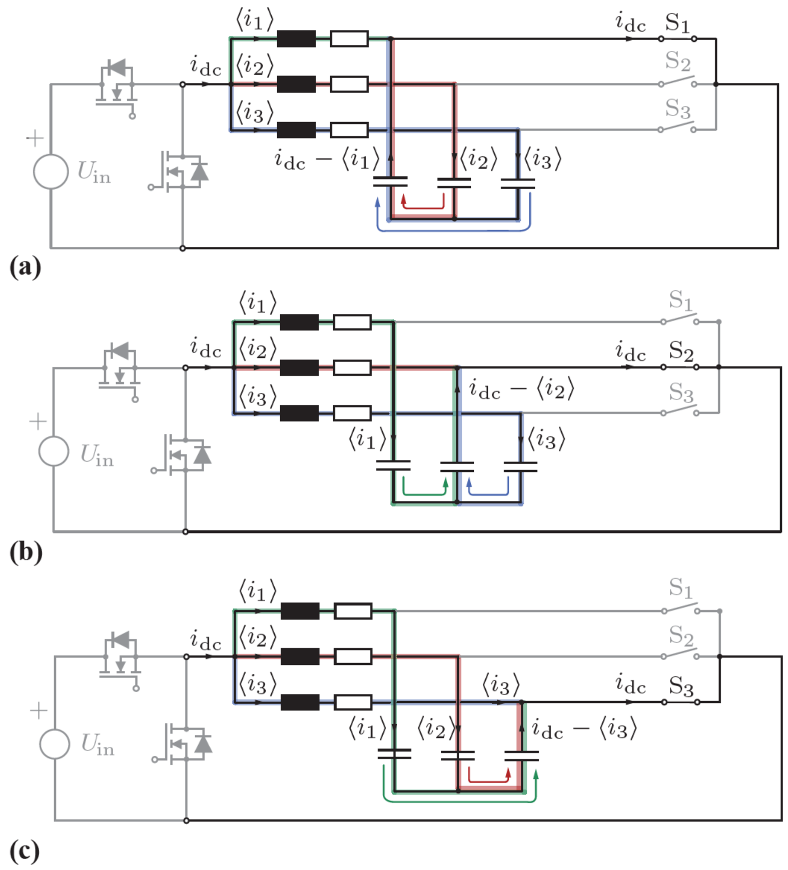
- In uniCSI topology the sum of phase currents is equal to the DC link current.
- Open end winding of the reluctance motor → enables us to remove the DC link inductor!

uniCSI: Switch per Phase

- In case of n-phase Variable Reluctance Machine (VRM), we need n-MOSFETs → switch per phase
- High-frequency operation of the switches → 'distributing' the DC link current among phases



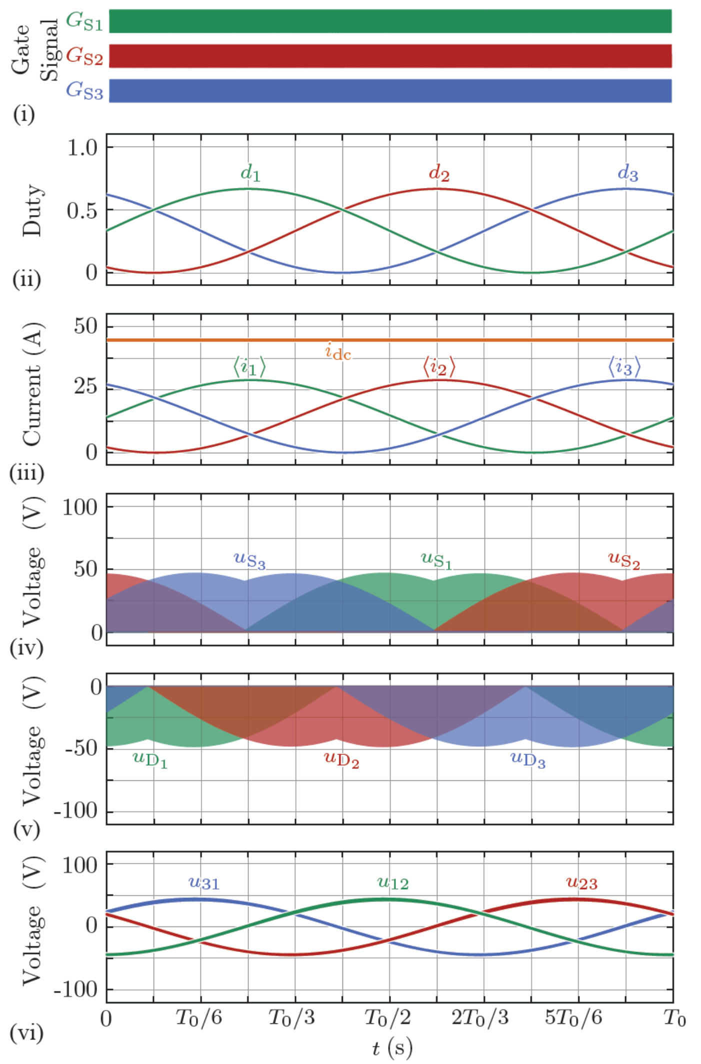
- Line to line voltages are 'moving' currents between phases →

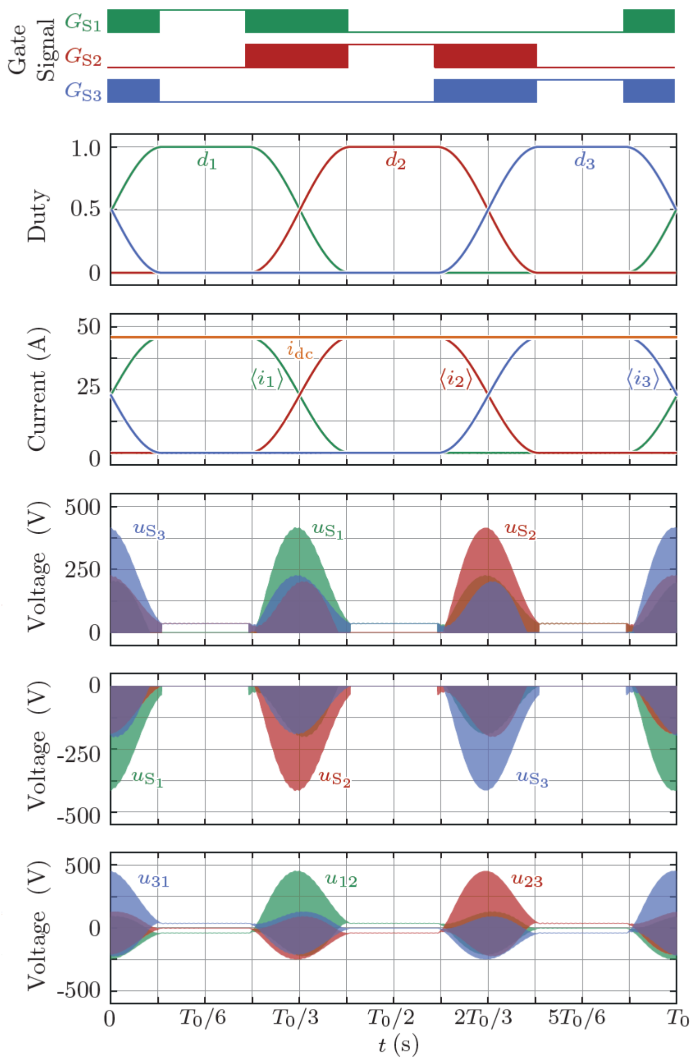


uniCSI: Simulation Results

- We can see that the line-to-line voltage are ‘responsible’ for moving the currents from phase to phase

Sinusoidal currents



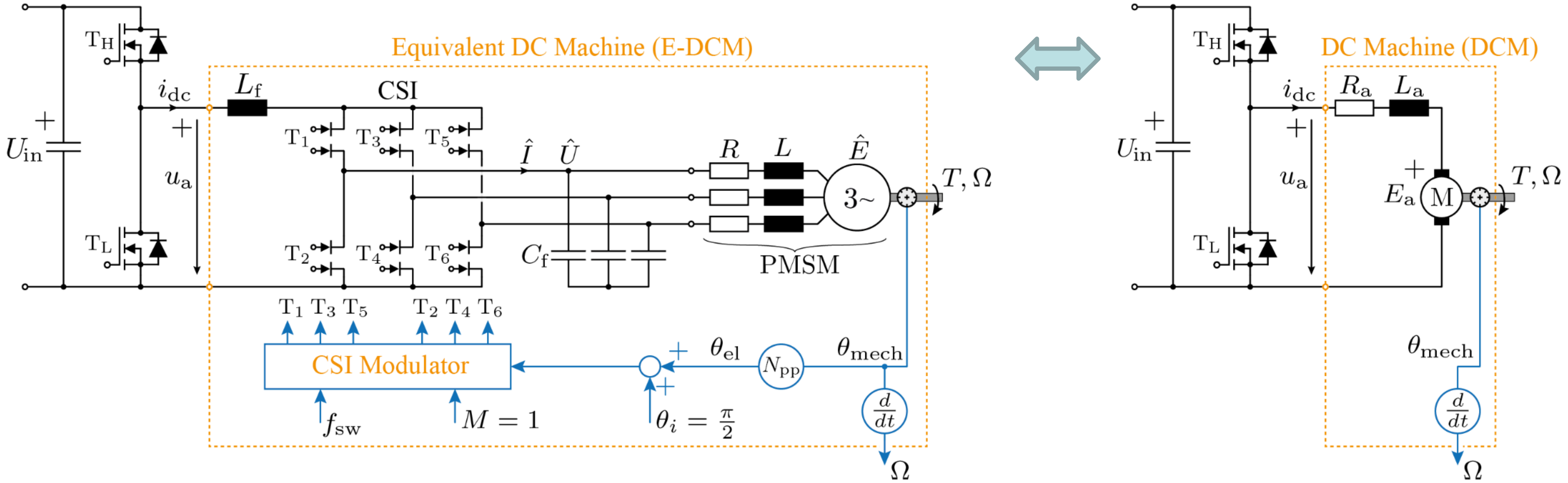


Trapezoidal currents

Content

DC Industry: CSI PMSM Drive Equivalent to DC Machine

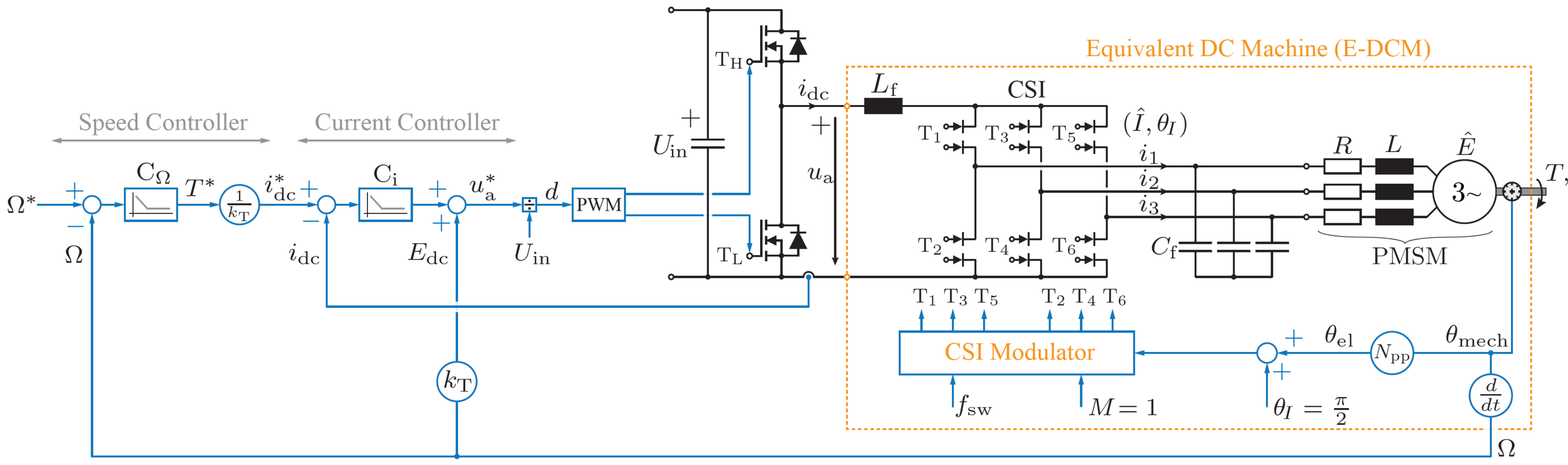
- **Simplify the control of the CSI drive → mimics the CSI operation by fixing the modulation index of the CSI to $M = 1$**
- **'CSI Modulator' block alternates the phase currents according to the angle information provided by the encoder**



- **Fixed modulation index of the CSI → DC side of the CSI is equivalent to the DC machine armature**
- **The torque on the PMSM shaft → directly proportional to the DC link current**
- **This arrangement allows us to manage the torque&speed control with the input DC-DC converter, like for a DC machine**
- **The user does not have to 'deal with' the CSI → enabling faster spread of CSIs in drive systems**

E-DCM Speed Control Drive System

- With E-DCM concept → torque on the PMSM shaft managed by the DC link current
- Cascaded control system structure → Outer speed controller loop (0.8kHz), and inner current controller loop (4kHz)



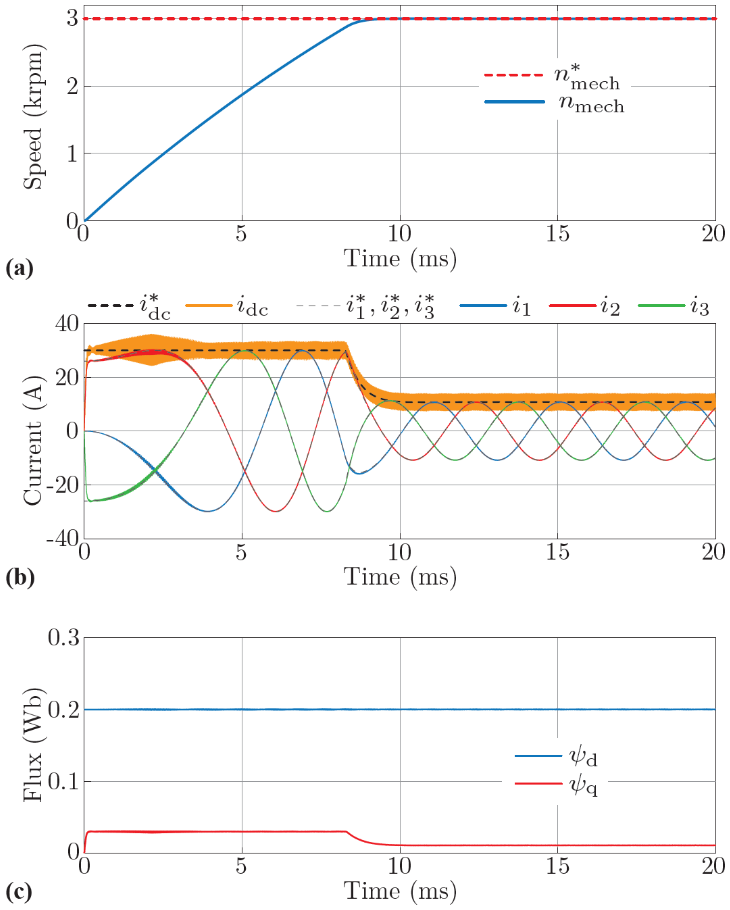
- The DC link current reference directly calculated from the speed controller torque reference: $i_{\mathrm{dc}}^{*} = \frac{T^{*}}{k_{\mathrm{T}}}$
- For tuning the current controller, the sum of the DC link inductance L_{f} and the DC-side equivalent inductance L_{dc} are considered: $L_{\mathrm{f}} + L_{\mathrm{dc}}$
- The user has manage only the 'DC-side' like for a DC machine

$$L_{\mathrm{dc}} = \frac{3}{2}M^2L = \frac{3}{2}L$$

Simulation Results: E-DCM Speed Control

- Step speed reference of 3krpm → speed controller applies the maximum possible torque during the acceleration (max. i_{dc} current of 30A)
- CSI modulation index and current angle are constant $M = 1$ and $\theta_I = \frac{\pi}{2}$

$$n_{\mathrm{mech}} = \Omega\,\frac{30}{\pi}$$



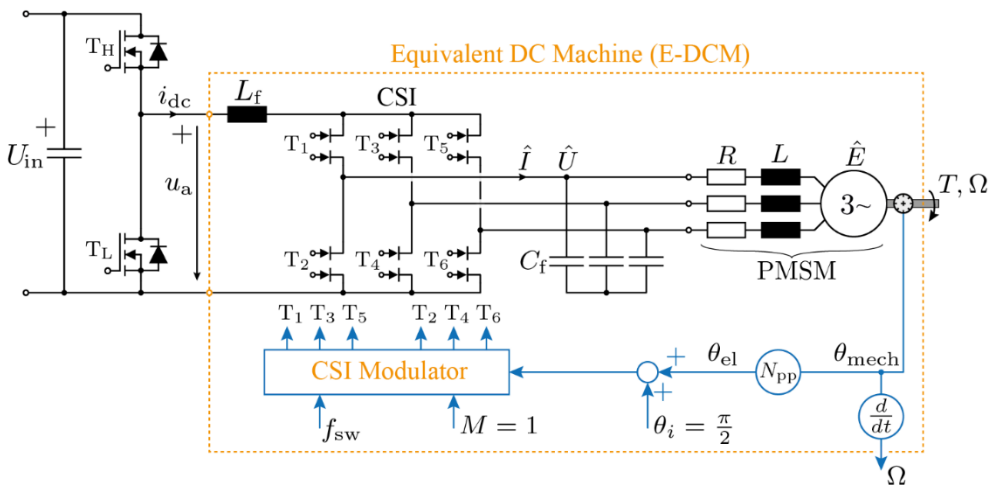
Parameter	Symbol	Value
Buck		
Input voltage	U_{in}	800 V
Switching frequency	$f_{\mathrm{sw,b}}$	80 kHz
CSI		
DC link inductance	L_{f}	450 µH
Output capacitance	C_{f}	0.1 µF
Switching frequency	f_{sw}	140 kHz
Max. DC link current	$I_{\mathrm{dc,max}}$	30 A
PMSM		
Phase resistance	R	0.2 Ω
Phase inductance	L	1 mH
Number of pole pairs	p	5
Flux linkage	$\hat{\Psi}$	0.2 Wb
Moment of inertia	J	0.001 kgm^2
Nominal mech. power	P_{mech}	5 kW
Nominal mech. speed	n_{mech}	3000 rpm
Controller gains		
C_{i} closed-loop bandwidth	f_{cc}	4 kHz
C_{i} proportional gain	K_{pc}	49 V/A
C_{i} integral gain	K_{ic}	10 000 V/(As)
C_{Ω} cross-over frequency	f_{cs}	0.8 kHz
C_{Ω} proportional gain	K_{ps}	3.3 sNm
C_{Ω} integral gain	K_{is}	3400 Nm

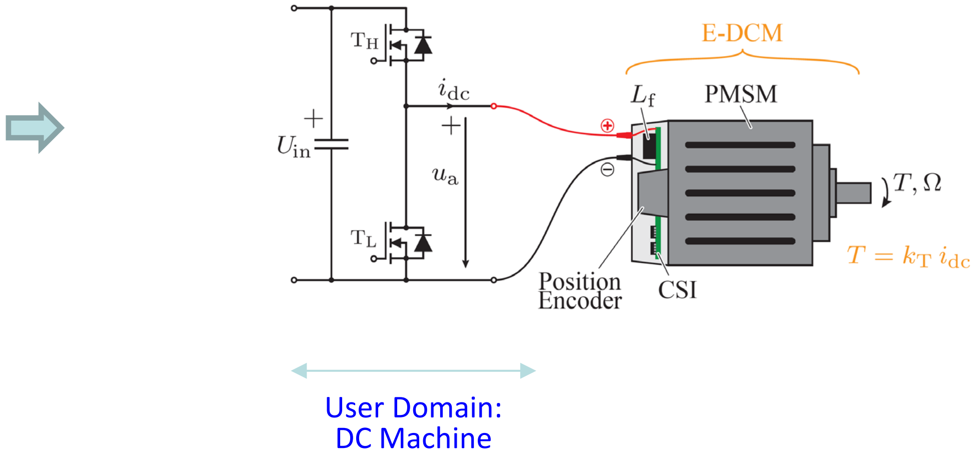
→ From PMSM flux linkage we can verify that the DC link current has the effect of the torque generating quadrature current, as it impacts only the ψ_q.

4 year PhD project funded by: FWF Austrian Science Fund

DC Industry: E-DCM for PMSM-Integrated CSI

- Integration of CSI together with encoder into the PMSM case → CSI can be run in open-loop to achieve E-DCM
- For the user the PMSM with integrated CSI appears like a DC machine if E-DCM is used



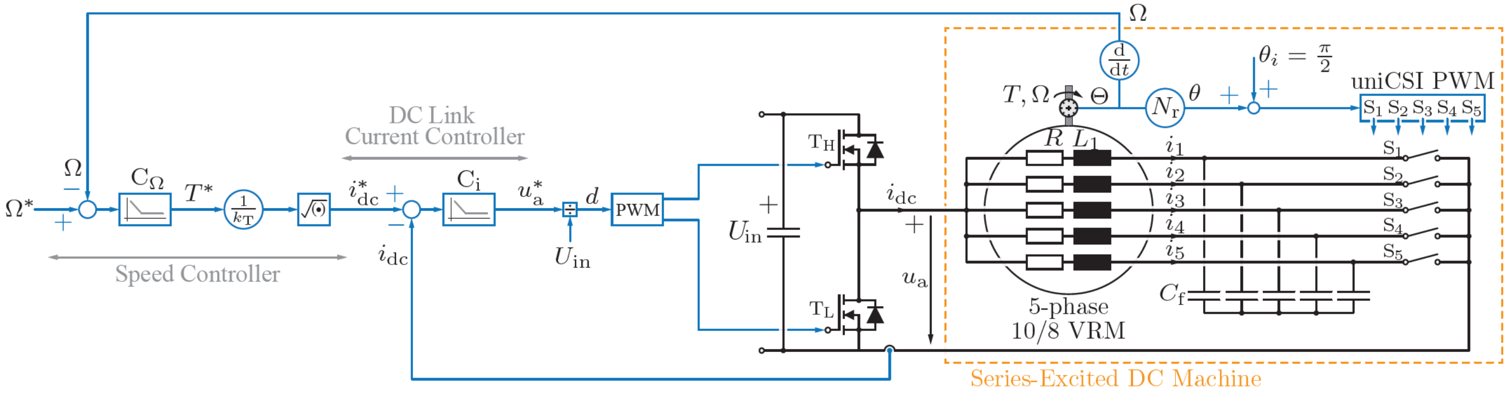


- An opportunity for 'plug-and-play' CSI drive system → enabling wide adoption of CSI drive systems into various applications!

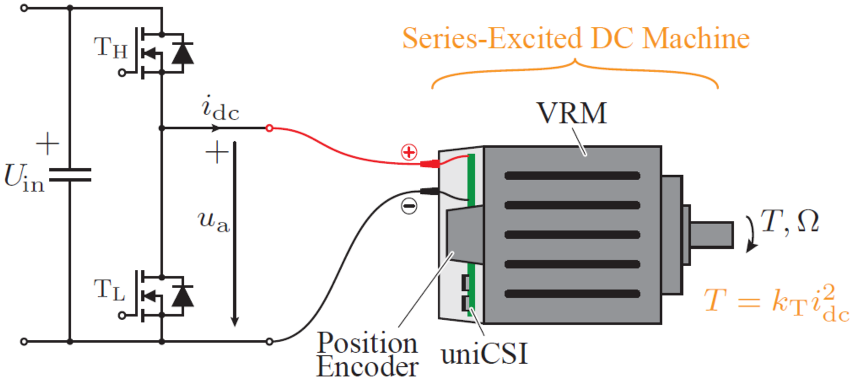
Content

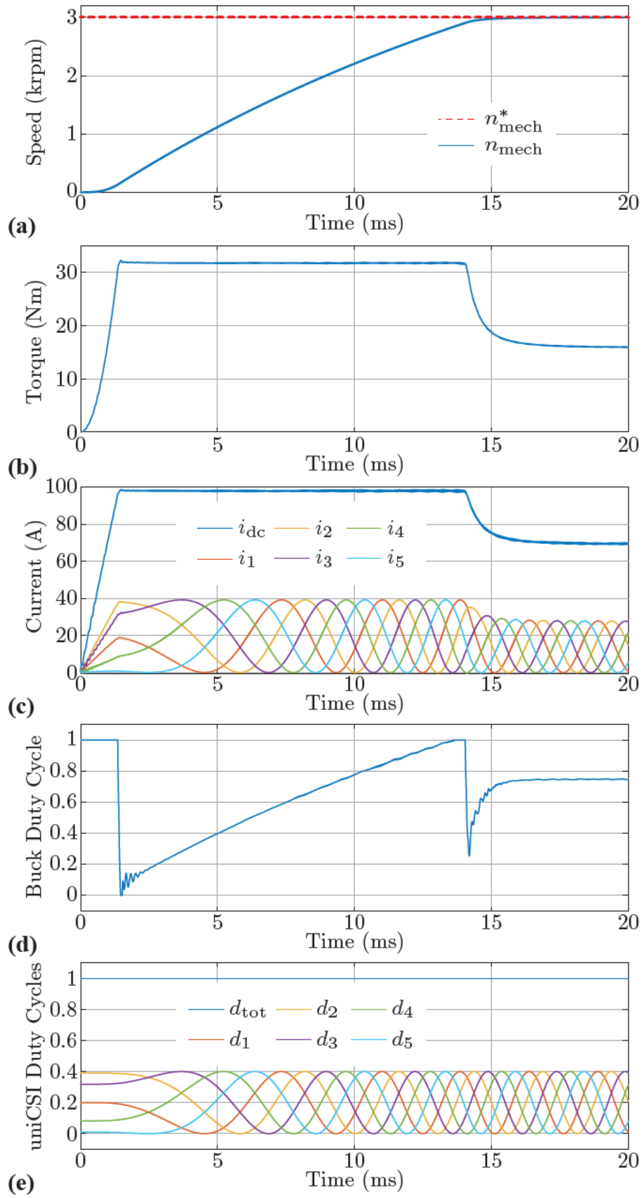
DC Industry: E-DCM for Reluctance Motors

- **uniCSI can make reluctance machine behave like a DC machine → E-DCM approach**



- **User is released of any interaction with the reluctance motor and uniCSI modulation:**

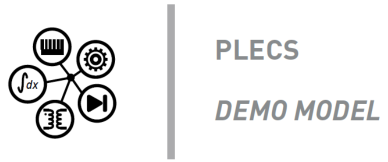




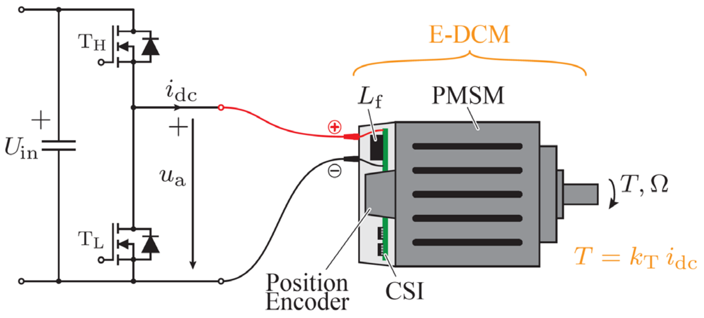
Content

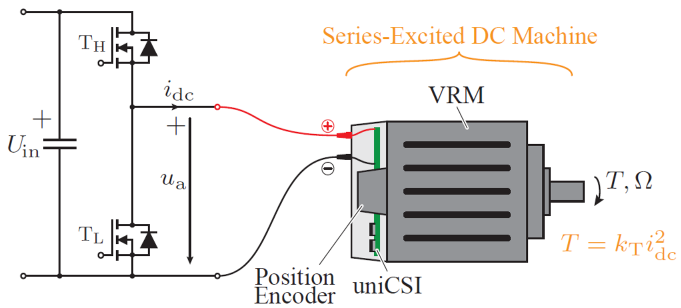
Conclusions

- **New CSI modulation method**
  - **- simple PWM**
  - **- works for any number of phases**
- **New CSI topology for reluctance machines – uniCSI**
- **Equivalent DC machines for DC industry – no AC machines in the future?**



Multi-Phase Current Source Inverter





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Thank you!