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Current Source Inverter-Fed Variable Reluctance Motor Drive with DC-Machine-Like Control Characteristics

Spasoje Mirić | Predrag Pejović | Takanobu Ohno | Michael Haider

University of Innsbruck, Institute for Mechatronics
Innsbruck Drives and Energy Systems Laboratory (iDES)
Technikerstraße 13a, Floor 1, Office 128
https://www.uibk.ac.at/mechatronik/ides/

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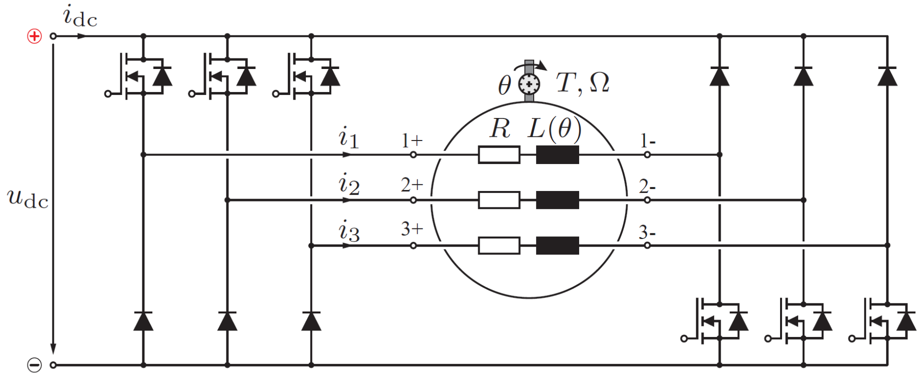
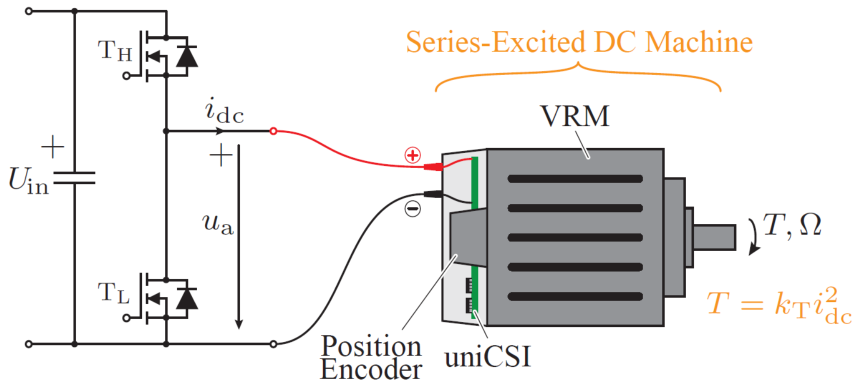
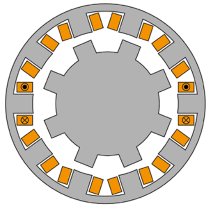
Motivation: Make Reluctance Motor Behave Like a DC Machine for the User

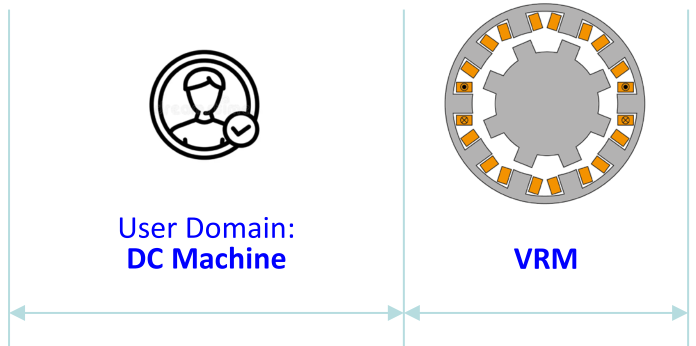
- Variable reluctance machine (VRM) operation → challenge with controlling the currents especially at high speeds
- Non standard inverter topology due to unipolar currents → there are many inverter topology options for VRMs







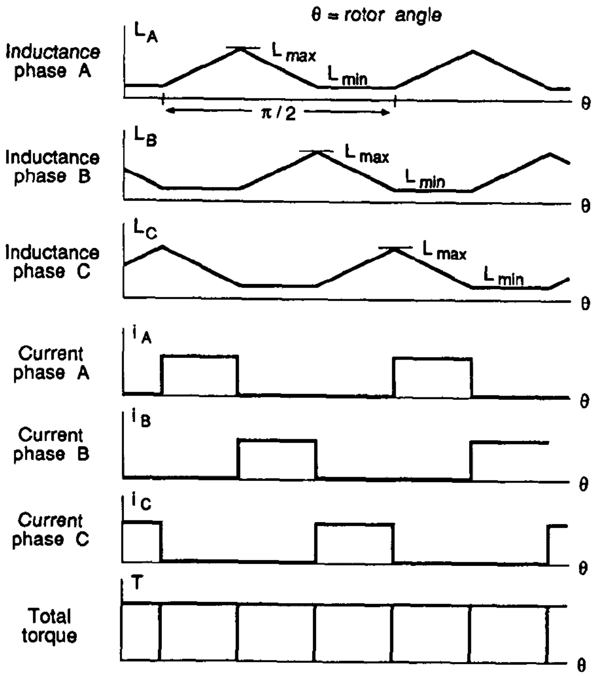
VRM
(Variable Reluctance Machine)



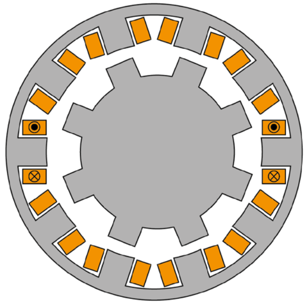
- Our goal is to make VRM simple as DC machine for the user →

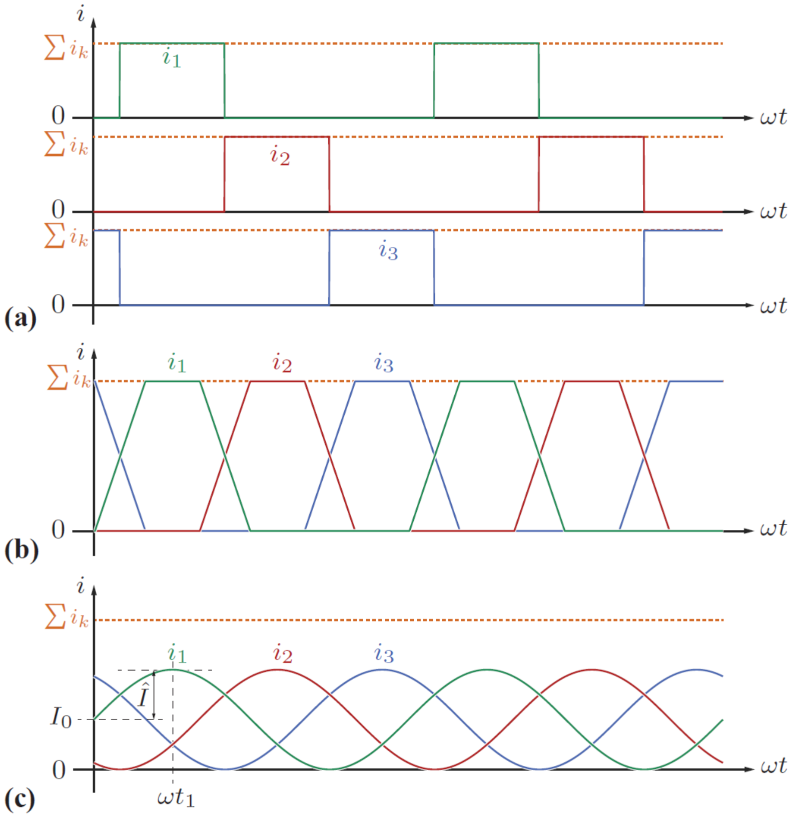
Reluctance Machine: Unipolar Currents

- 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



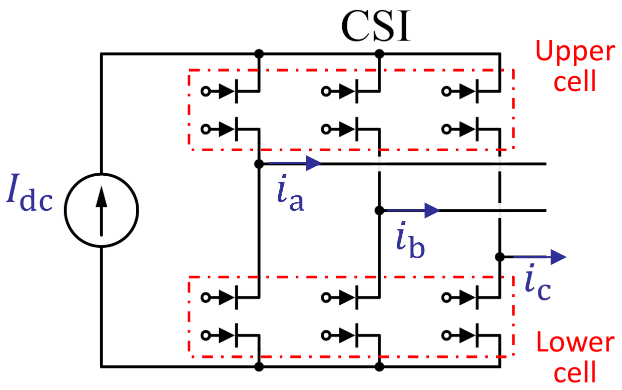
$$T \sim i^2 \frac{\partial L}{\partial \Theta}$$

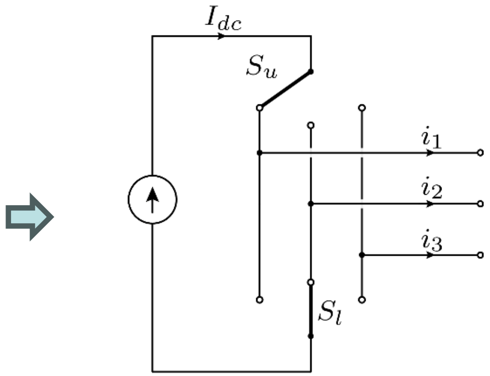


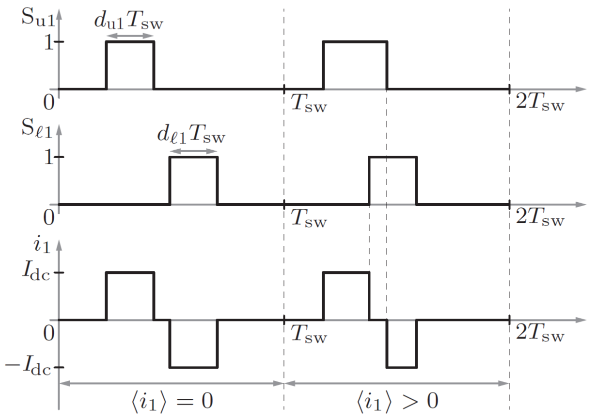


Current Source Inverter (CSI) Modulation

- 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.

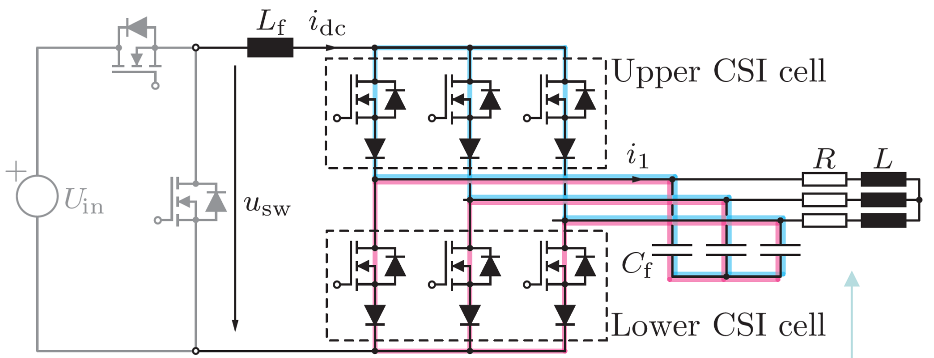
$$\langle i_1 \rangle = I_{dc}(d_{u1} - d_{l1})$$

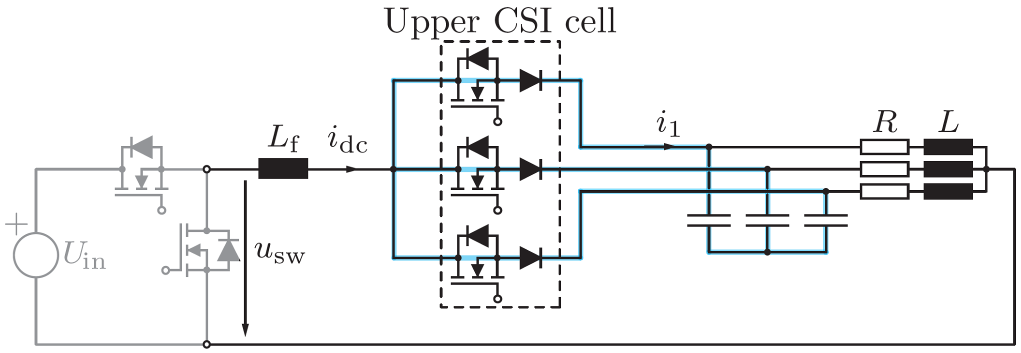
- Current source inverter modulation process has to ensure the following two conditions:
  1. Average value of the phase current: $\langle i_1 \rangle = I_{dc}(d_{u1} - d_{l1})$
  2. Continuity of the DC link current: $d_{u1} + d_{u2} + d_{u3} = 1$ and $d_{l1} + d_{l2} + d_{l3} = 1$

uniCSI: Current Source Inverter for Unipolar Currents (1)

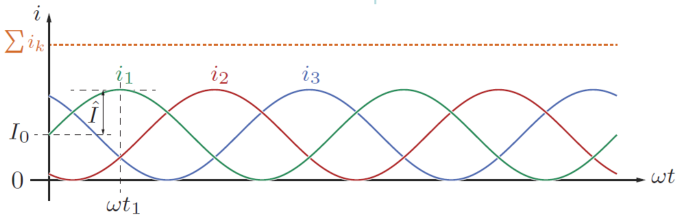
- The average phase current is proportional to the duty cycle difference of the upper and lower CSI cells
- CSI needs a DC link inductor (L_f) so we can build a DC link current source!
- If we need positive only current → we can realize it with the upper cell only!
- The RL load (represents VRM) need positive only phase currents!

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





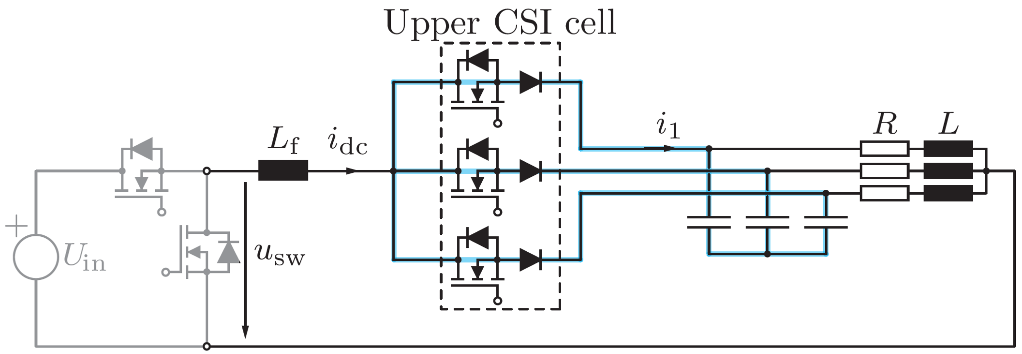
Unipolar positive currents

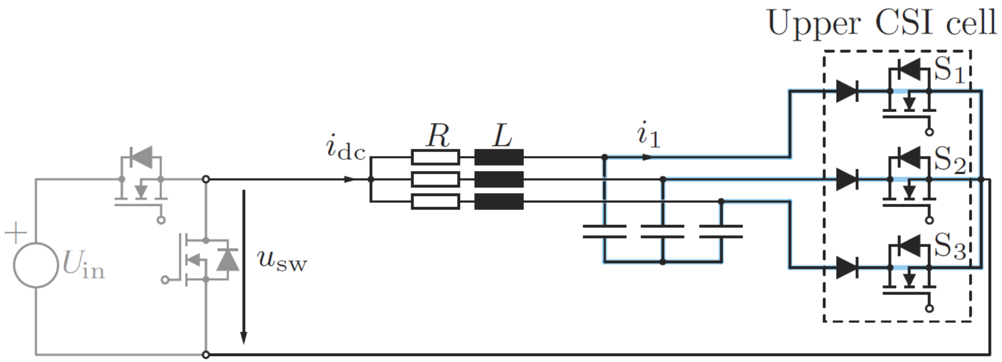


How to further improve this topology? →

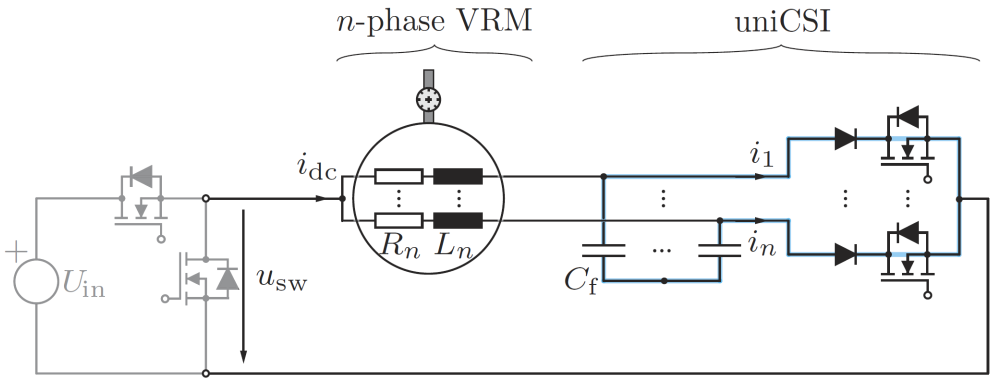
uniCSI: Current Source Inverter for Unipolar Currents (2)

- Reluctance machine has open end windings due to unipolar currents → remove the DC link inductor as machine common-mode inductance acts as L_f
- Series connection of the upper CSI cell and the RL load → relocate them so that MOSFETs are connected to the GND (no gate driver isolation needed)





- uniCSI topology for reluctance machines → ‚switch per phase‘

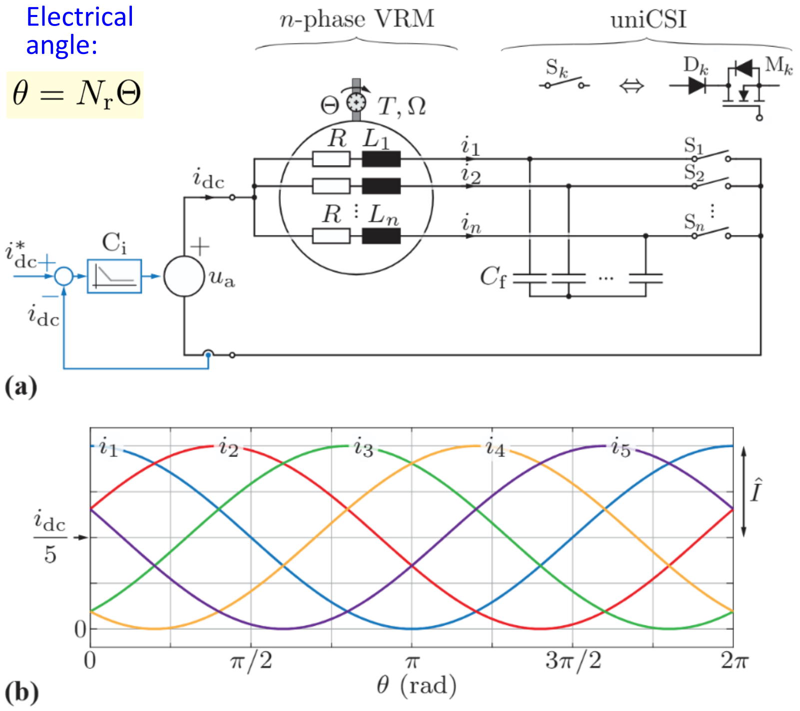


Variable Reluctance Machine (VRM) Drive with uniCSI

- Switch per phase uniCSI topology to supply VRM → switch is series connection of a diode and a MOSFET (or bidirectional switch)
- For VRM, the phase currents sum up to the DC link current value → for 5-phase example: $i_1 + i_2 + i_3 + i_4 + i_5 = i_{\mathrm{dc}}$
- We assume sinusoidal currents, but other waveforms like trapezoidal are possible

Electrical angle:

$$\theta = N_{\mathrm{r}}\Theta$$



$$i_k = d_k\, i_{\mathrm{dc}}$$

$$\sum_{k=1}^{5} i_k = i_{\mathrm{dc}}$$

uniCSI duty cycles:

$$d_k = \frac{i_k}{i_{\mathrm{dc}}} = \frac{m}{n}\cos\left(\theta + \theta_i - (k-1)\frac{2\pi}{n}\right) + \frac{1}{n}$$

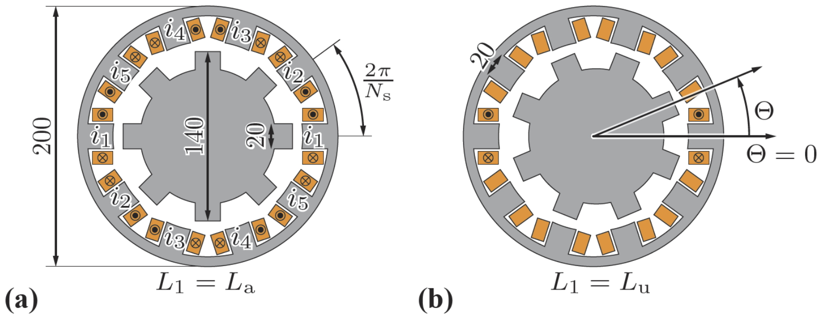
$$\sum_{k=1}^{n} d_k = 1$$

Phase currents:

$$i_k = m\frac{i_{\mathrm{dc}}}{n}\cos\left(\theta + \theta_i - (k-1)\frac{2\pi}{n}\right) + \frac{i_{\mathrm{dc}}}{n}$$

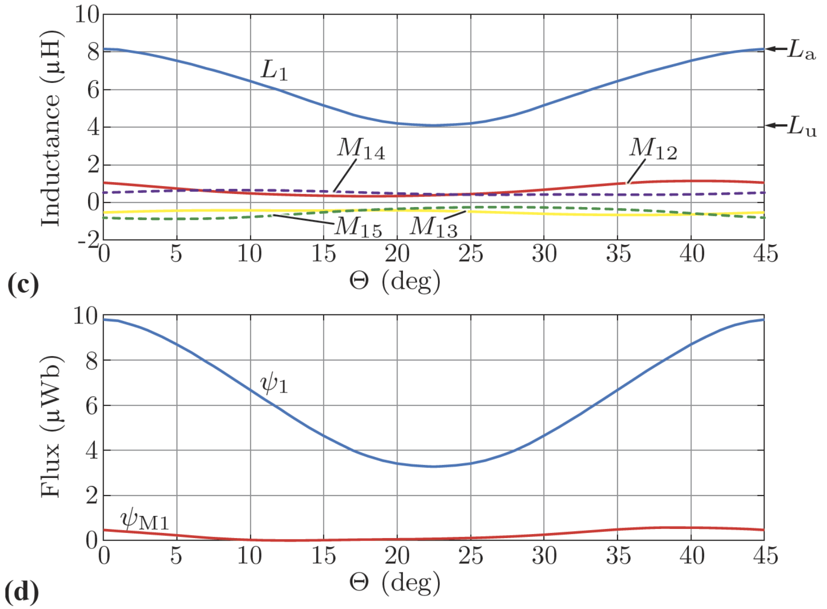
Variable Reluctance Machine Model

- We assume only self-inductance to be contributing to the flux linkage, which is justified by FEM simulations where the flux due to mutual inductances is negligible.
- In this example $N_\mathrm{r} = 8$



Electrical angle:

$$\theta = N_\mathrm{r}\Theta$$



- Sinusoidal inductance (used also in PLECS):

$$L_k(\theta) = L_\mathrm{u} + (L_\mathrm{a} - L_\mathrm{u})\, f_k(\theta)$$

$$f_k(\theta) = \frac{1}{2} + \frac{1}{2}\cos\left(\theta + (k-1)\,\frac{2\pi}{n}\right)$$

Flux linkage: $\psi_k(\theta) = L_k(\theta)\, i_k(\theta)$

Voltage equation used for modeling: $u_k = R\, i_k + \frac{\mathrm{d}\psi_k}{\mathrm{d}t}$

DC-Side of the uniCSI

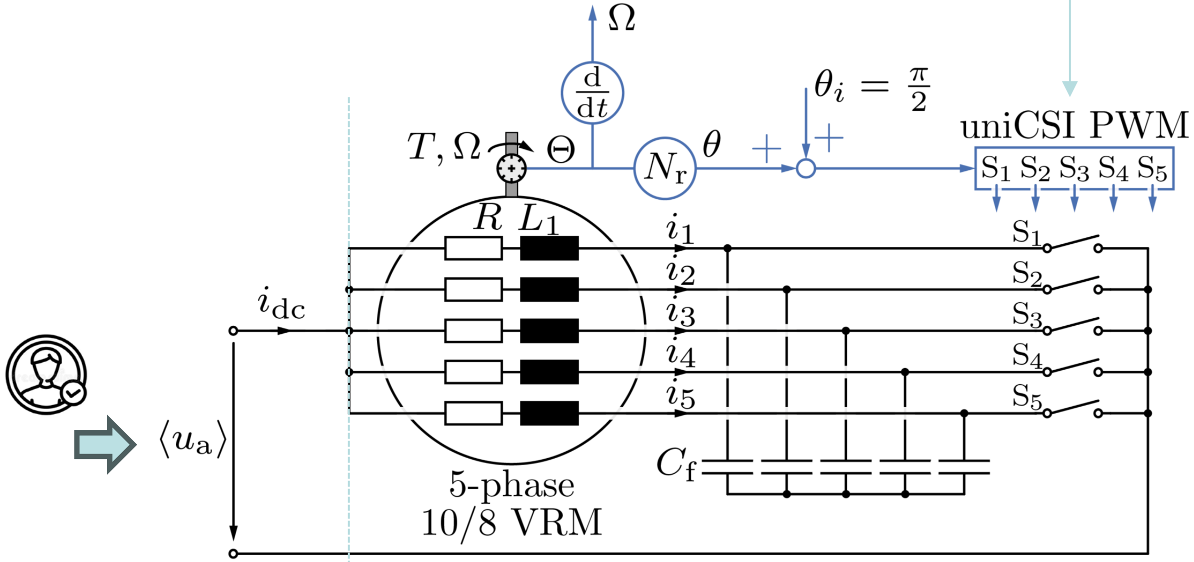
- Electrical angle given by the rotor position as: $\theta = N_\mathrm{r}\Theta$

$$d_k = \frac{i_k}{i_\mathrm{dc}} = \frac{m}{n}\cos\left(\theta + \theta_i - (k-1)\frac{2\pi}{n}\right) + \frac{1}{n}$$

$$u_k = R\,i_k + \frac{\mathrm{d}\psi_k}{\mathrm{d}t}$$

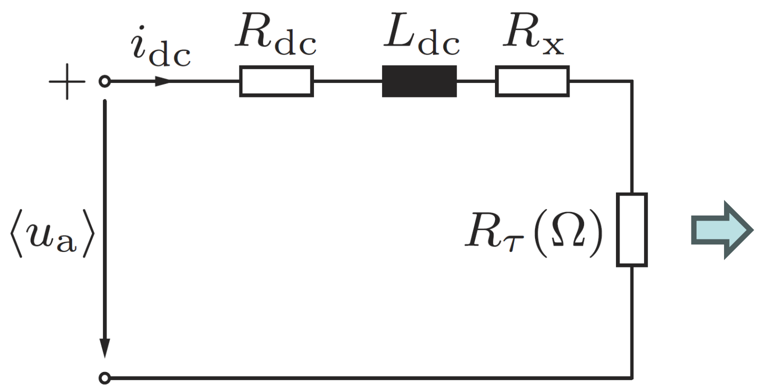
$$\langle u_\mathrm{a}\rangle\, i_\mathrm{dc} = R\sum_{k=1}^{5} i_k^2 = \underbrace{\frac{m^2+2}{10}R}_{=R_\mathrm{dc}}\, i_\mathrm{dc}^2$$

$$\langle u_\mathrm{a}\rangle\, i_\mathrm{dc} = \sum_{k=1}^{5}\frac{\mathrm{d}\psi_k}{\mathrm{d}t}\, i_k = \left(L_\mathrm{dc}\frac{\mathrm{d}i_\mathrm{dc}}{\mathrm{d}t} + R_\mathrm{x}\, i_\mathrm{dc} + R_\tau\, i_\mathrm{dc}\right) i_\mathrm{dc}$$



Power balance: $\langle u_\mathrm{a}\rangle\, i_\mathrm{dc} = \sum_{k=1}^{5} u_k\, i_k$

- VRMs DC-side equivalent circuit:



Mechanical Power

Torque of the VRM Supplied by uniCSI

- Equivalent circuit, expressions of circuit elements:
- m – uniCSI modulation index
- θ_i – current phase shift with respect to the shaft electrical angle θ

$$L_\Sigma = L_a + L_u \quad L_\Delta = L_a - L_u$$

Equivalent DC inductance:

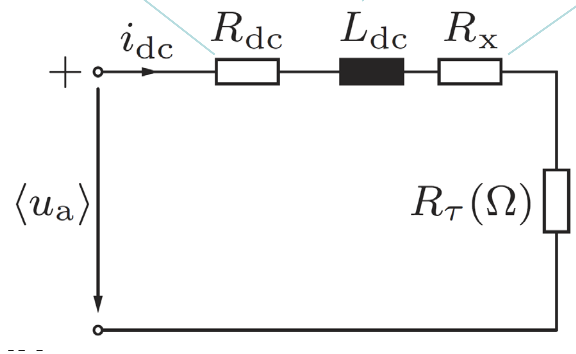
$$L_{dc} = \frac{(m^2+2)L_\Sigma + 2m\cos\theta_i\, L_\Delta}{20}$$

Equivalent DC resistance:

$$R_{dc} = \frac{(m^2+2)}{10} R$$

Dynamic resistance:

$$R_x = \frac{m\, L_\Sigma + \cos\theta_i\, L_\Delta}{20}\,\frac{dm}{dt}$$



Electromechanical torque resistance:

$$R_\tau(\Omega) = \frac{m\sin\theta_i\, L_\Delta}{20} N_r\Omega$$

- Torque expression derivation → power balance

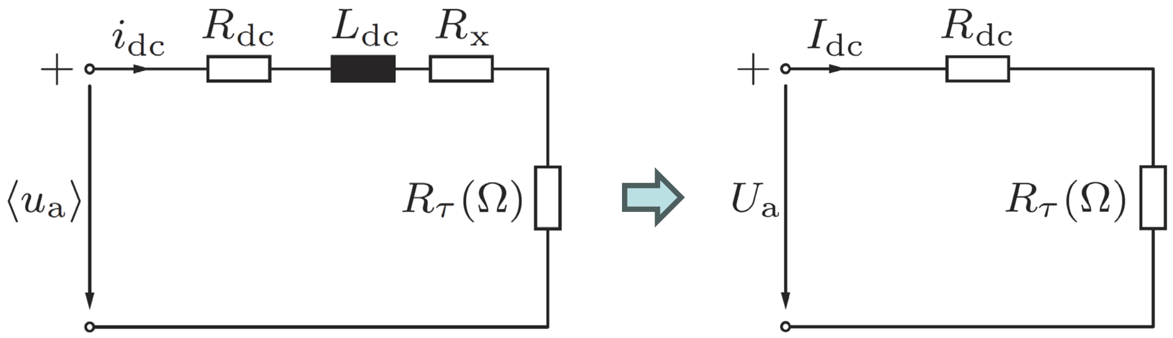
$$R_\tau\, i_{dc}^2 = T\,\Omega = T\,\frac{\omega}{N_r}$$

$$T = \frac{2}{5}\, m\sin\theta_i\, L_\Delta\, i_{dc}^2$$

$$k_T = \frac{2}{5}\, m\sin\theta_i\, L_\Delta$$

DC-Side Speed-Torque Characteristic

- Speed-torque characteristics are derived for steady state → inductor (L_{dc}) and dynamic resistance (R_{x}) disappear from the steady-state equiv. circuit



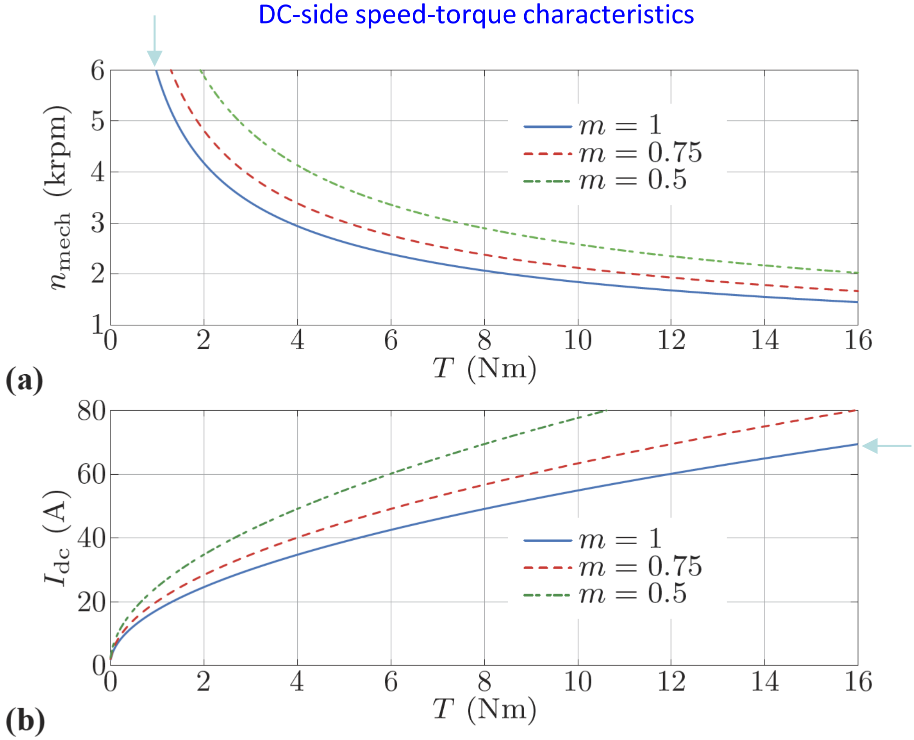
$$U_{\mathrm{a}} = R_{\mathrm{dc}} I_{\mathrm{dc}} + R_\tau(\Omega) I_{\mathrm{dc}}$$

$$R_\tau(\Omega) = k_{\mathrm{T}} \Omega$$

$$I_{\mathrm{dc}} = \sqrt{T/k_{\mathrm{T}}}$$

$$\Omega(T) = \frac{U_{\mathrm{a}}}{\sqrt{k_{\mathrm{T}} T}} - \frac{R_{\mathrm{dc}}}{k_{\mathrm{T}}}$$

DC-side speed-torque characteristics



Best: $m = 1$

Maximizing Torque per Current

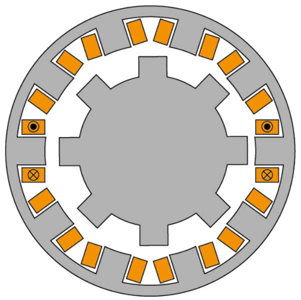
- We choose m and θ_i so that we get maximum torque per ampere → we maximise the torque constant

$$T = \frac{2}{5}\, m \sin\theta_i\, L_\Delta\, i_{\mathrm{dc}}^2 \quad \Rightarrow \quad m = M = 1 \qquad \theta_i = \theta_I = \frac{\pi}{2}$$

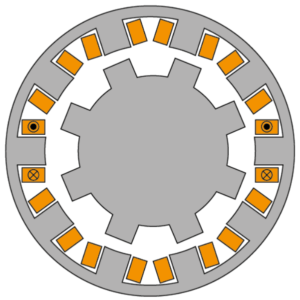
$$\frac{2}{5} L_\Delta$$

Difference between the aligned and unaligned inductances

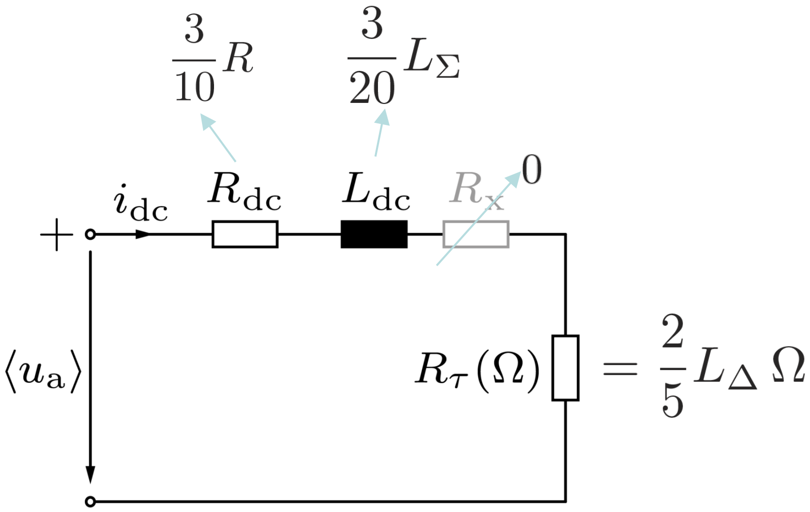
$$L_\Delta = L_\mathrm{a} - L_\mathrm{u}$$



$L_1 = L_\mathrm{a}$

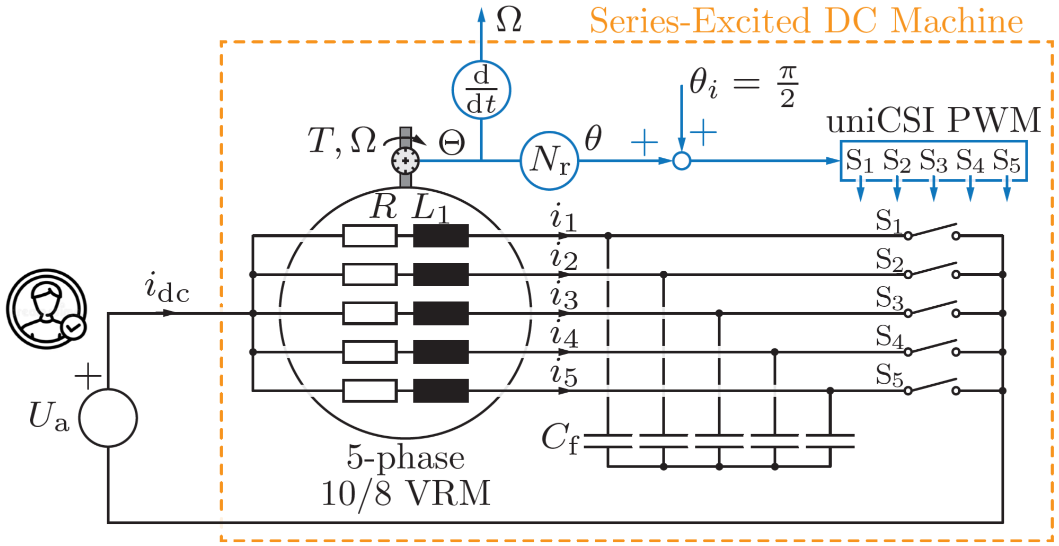


$L_1 = L_\mathrm{u}$

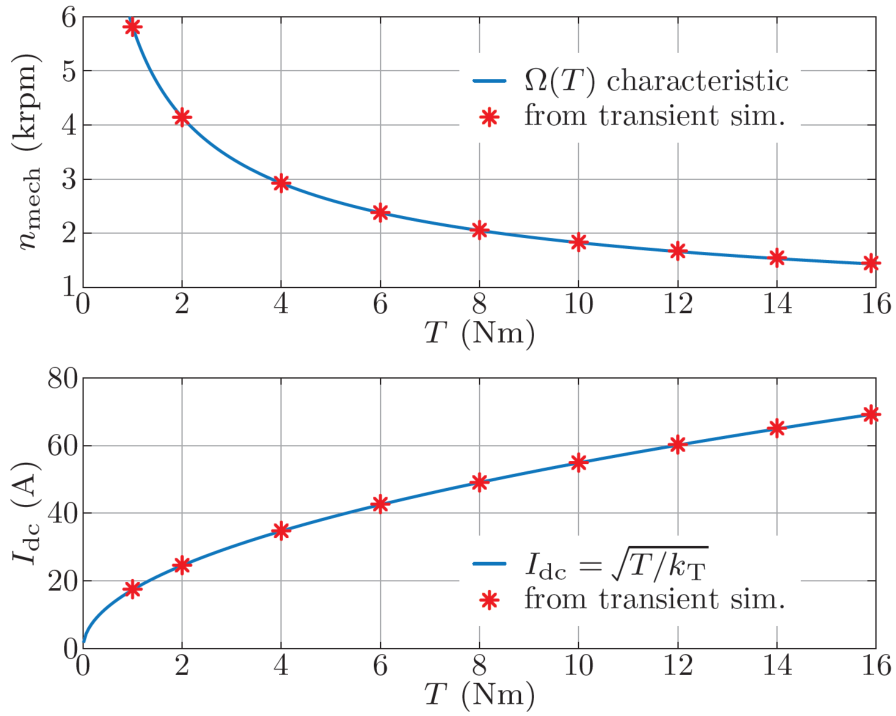


Open-Loop Operation of the uniCSI Supplied VRM

- We fixed modulation index $m = 1$ and the phase shift $\theta_i = \pi/2$ → phase currents are open-loop locked to the motor's shaft position
- This results that the uniCSI supplied VRM behaves like a series-excited DC machine from the DC side connections
- This enables a user to operate such drive system from the DC connections → no user interaction with the VRM and uniCSI



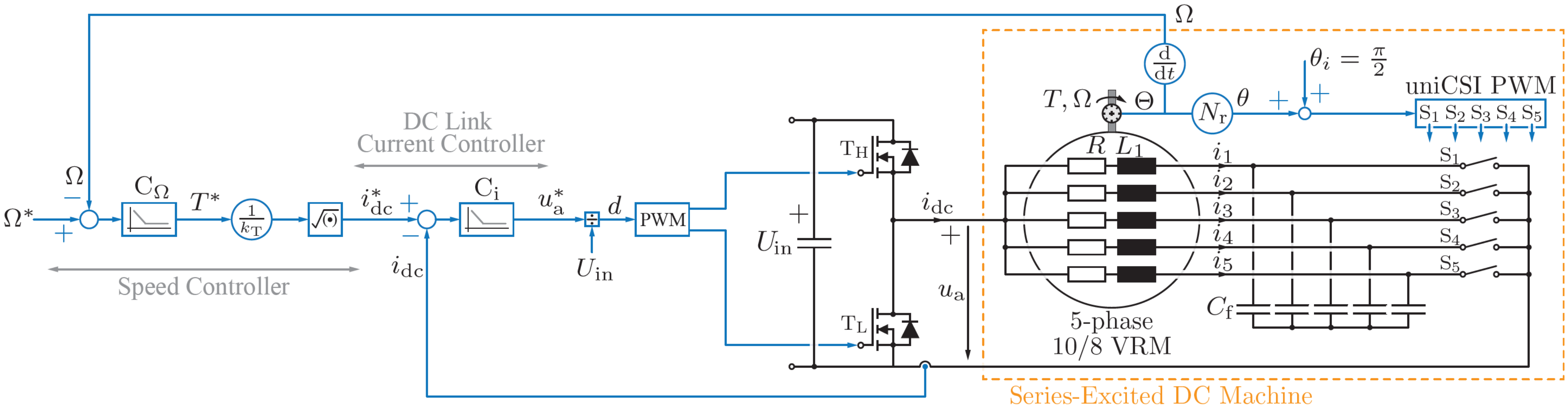
$$d_k = \frac{i_k}{i_{dc}} = \frac{m}{n} \cos\left(\theta + \theta_i - (k-1)\frac{2\pi}{n}\right) + \frac{1}{n}$$



Each star represents a steady state value of the transient time domain simulation!

Speed Control with uniCSI-VRM Drive

- Torque and therefore speed control is managed with the input converter, like with a conventional DC machine
- Open-loop operation of the uniCSI → no controllers | constant $m = 1$ | constant $\theta_i = \pi/2$ | no user interaction with uniCSI
- This drive systems decouples any expertise of reluctance machines from the user → 'plug-and-play' DC drive system

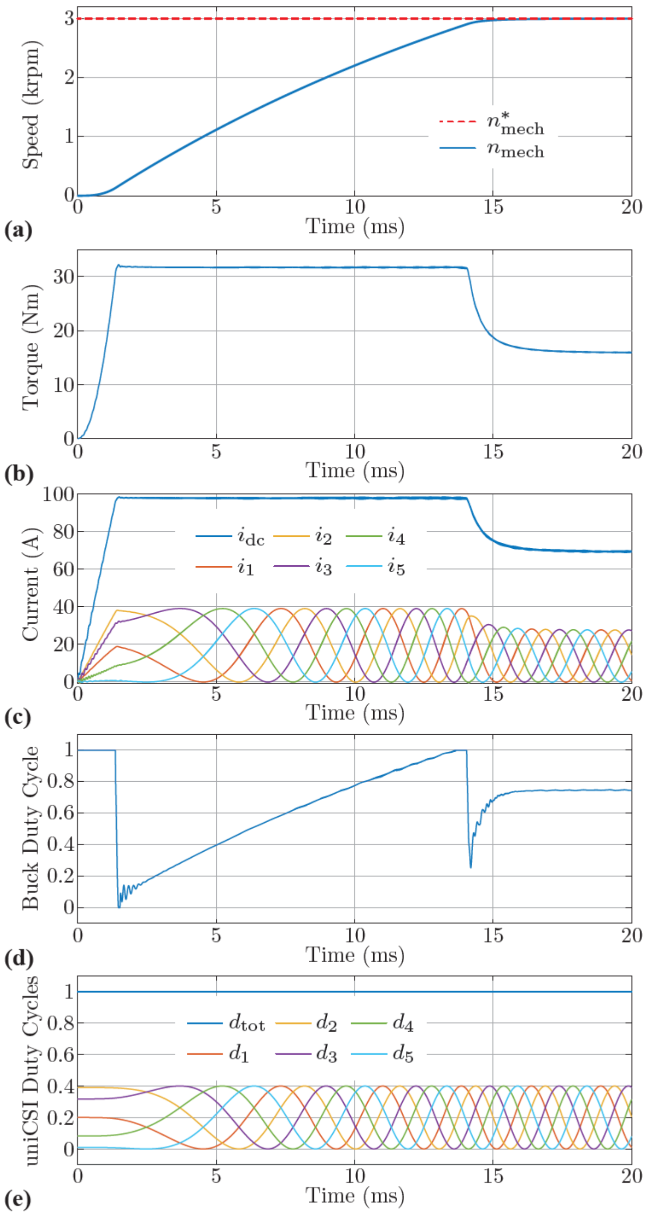


Simulation Results – Speed Transient

- Speed transient from standstill to nominal speed
- Quadratic relationship between the DC link current and the torque

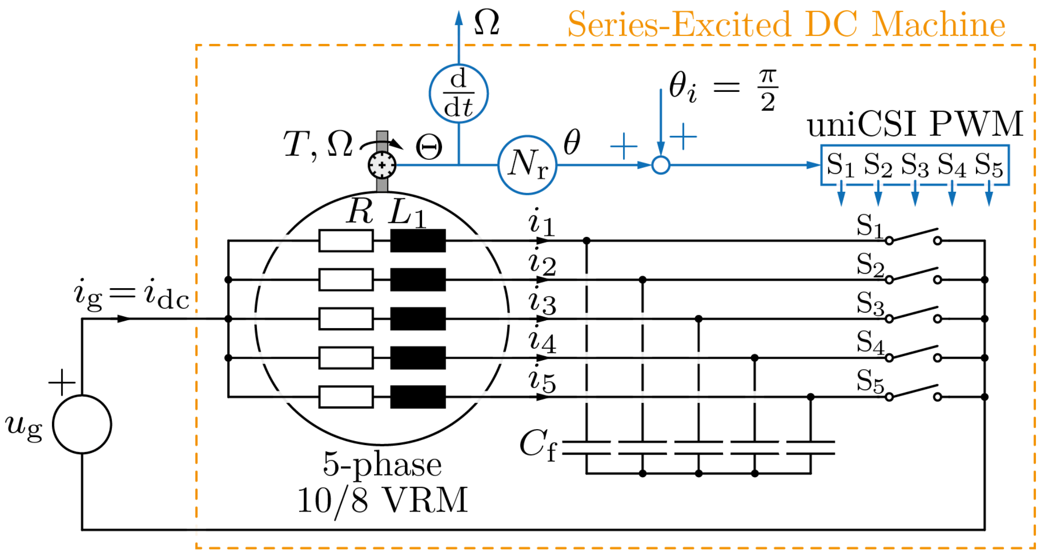
Parameter	Symbol	Value
Buck		
Input voltage	U_{in}	100 V
Switching frequency	$f_{\mathrm{sw,b}}$	300 kHz
CSI		
Output capacitance	C_{f}	0.2 µF
Switching frequency	f_{sw}	300 kHz
Modulaiton index	M	1
Current angle	θ_I	$\pi/2$
VRM		
Phase resistance	R	0.05 Ω
Unaligned inductance	L_{u}	0.5 mH
Aligned inductance	L_{a}	8.8 mH
Number of stator teeth	N_{s}	10
Number of rotor teeth	N_{r}	8
Moment of inertia	J	0.001 kgm^2
Nominal mech. power	P_{mech}	5 kW
Nominal mech. speed	n_{mech}	3000 rpm
DC-side		
DC-side resistance	R_{dc}	0.015 Ω
DC-side inductance	L_{dc}	1.395 mH
Torque constant	k_{T}	3.32 $\mathrm{mN\,m\,A^{-2}}$
Controller gains		
$\mathrm{C_i}$ closed-loop bandwidth	f_{cc}	5 kHz
$\mathrm{C_i}$ proportional gain	K_{pc}	43.82 V/A
$\mathrm{C_i}$ integral gain	K_{ic}	33 143 V/(As)
$\mathrm{C_\Omega}$ cross-over frequency	f_{cs}	0.5 kHz
$\mathrm{C_\Omega}$ proportional gain	K_{ps}	3.14 s N m
$\mathrm{C_\Omega}$ integral gain	K_{is}	1974 N m

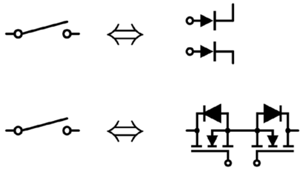
TABLE II: Simulation Parameters.

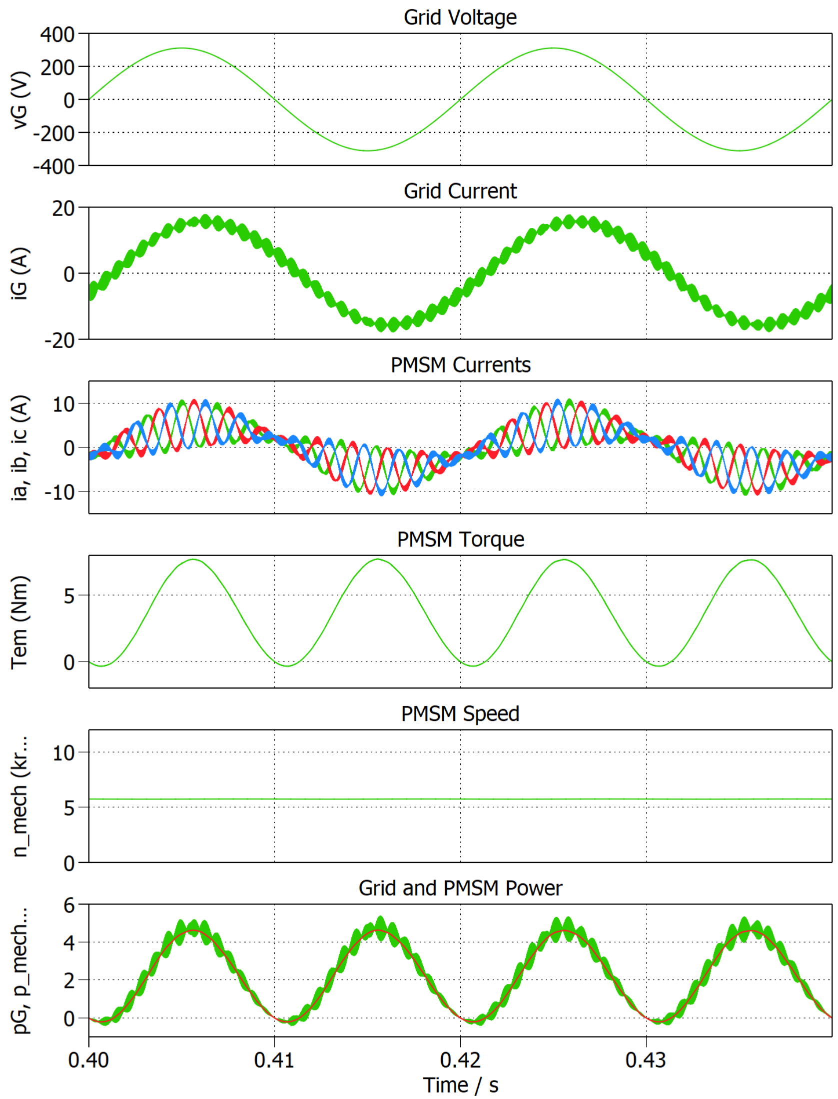


Grid Supplied uniCSI-VRM: Universal Machine

- Open loop controlled uniCSI behaves like a series excited DC machine
- Series excited DC machine → universal machine
- Grid power pulsation → buffered in drive train's inertia
- Future work → speed regulation capabilities

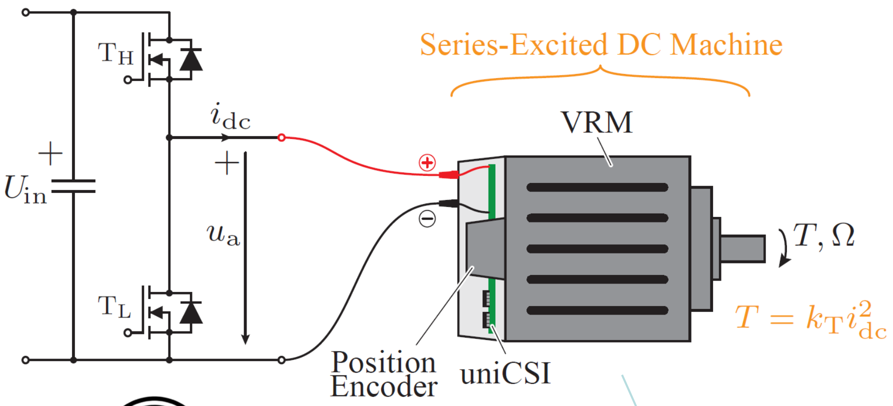


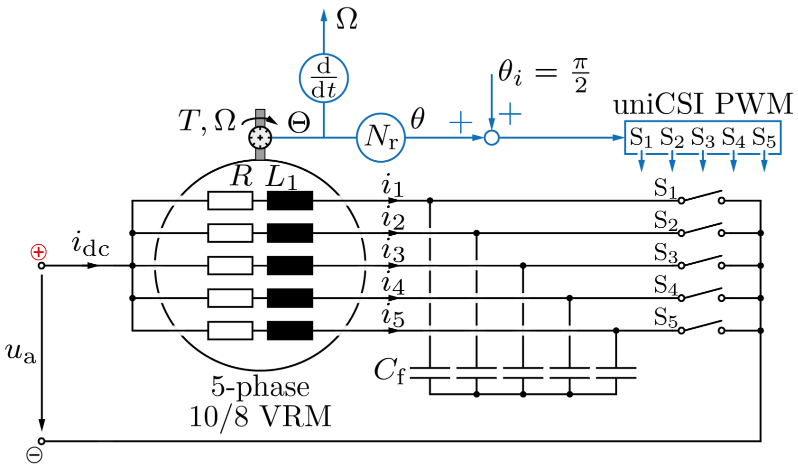


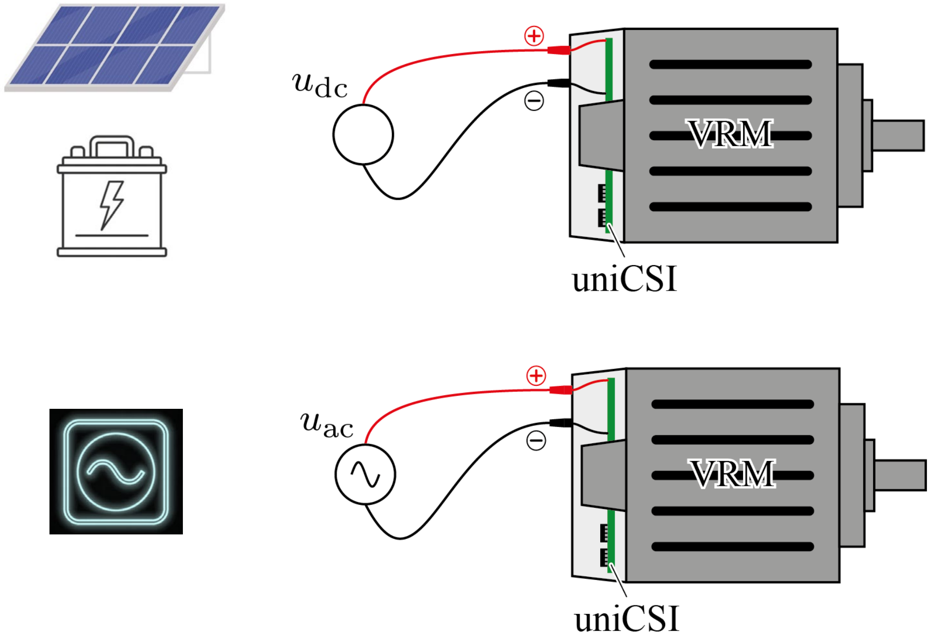


DC Machine Behavior of the uniCSI VRM

- With shown open loop control of the uniCSI, the whole drive behaves like a series excited DC machine (universal motor)
- High end speed control applications → DC link current control
- Simple applications → it can run without the DC link current control from DC and AC grid (ongoing work)



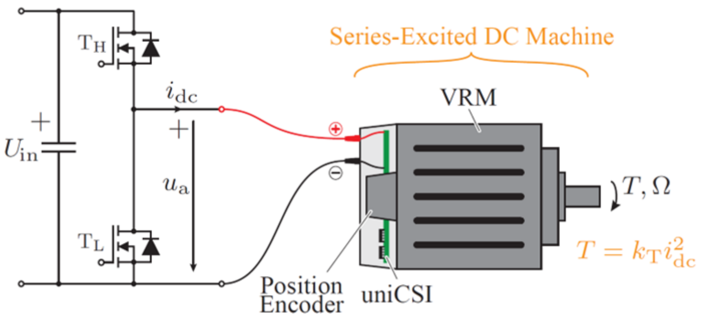




Conclusions

- Novel uniCSI topology
- Open-loop control
- DC-side speed torque characteristic
- No user interaction with the inverter nor VRM control
- User ‘sees’ a DC machine
- Speed-controlled drive system through input converter
- Universal machine

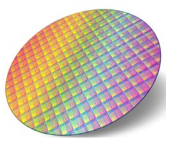
- Future work: Hardware verification and DC/AC voltage supply operation



Future motor building materials:


iron


copper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Thank you!