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Current Source Inverter Drive System with Equivalent DC-Machine Control Characteristics

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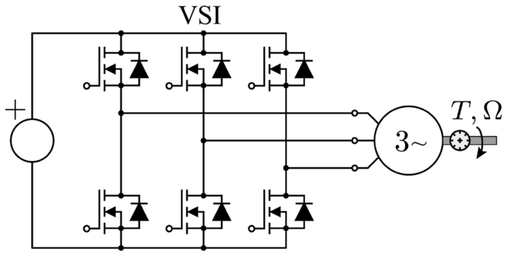
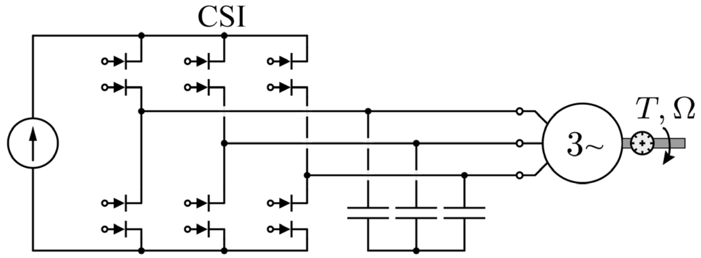
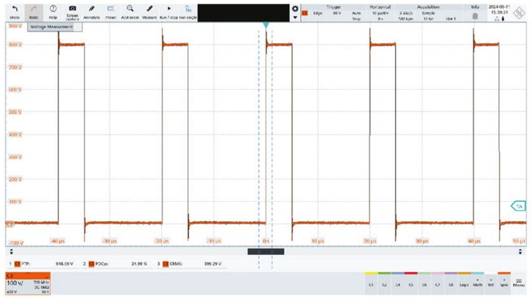
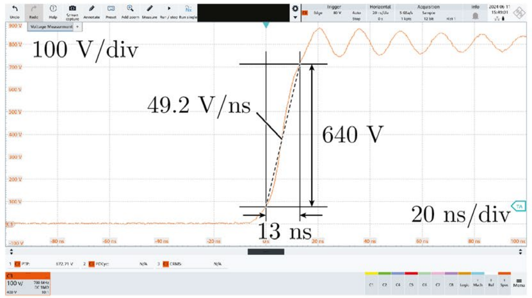
Introduction: VSI and CSI for Drive Systems

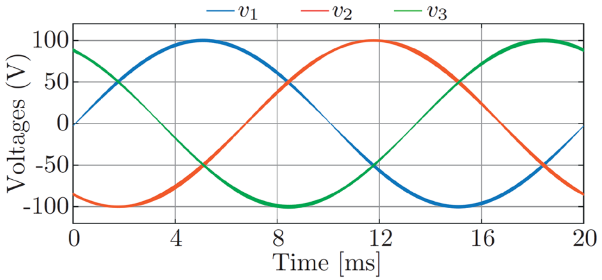
- Voltage Source Inverter (VSI) drive system → typically direct connection of the motor terminals to the switch node
- VSI generates pulsed voltage over motor windings → interturn overvoltage / harmonic losses / bearing currents / EMI / insulation aging







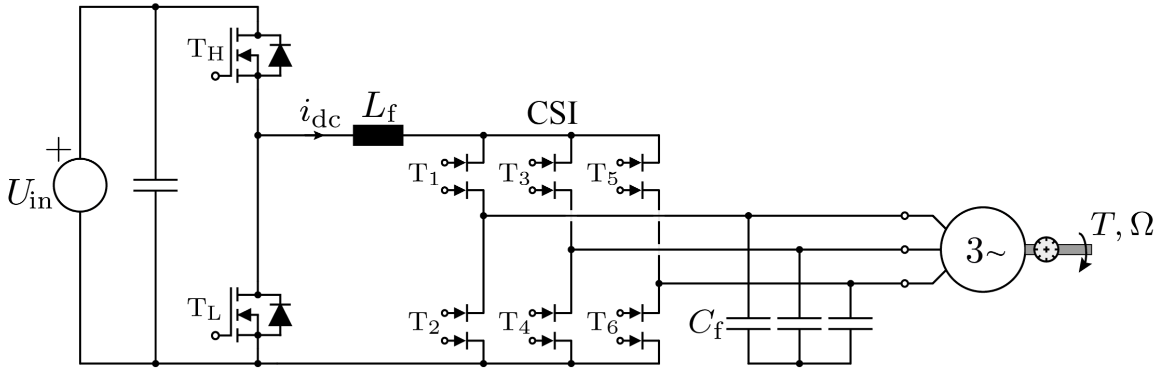


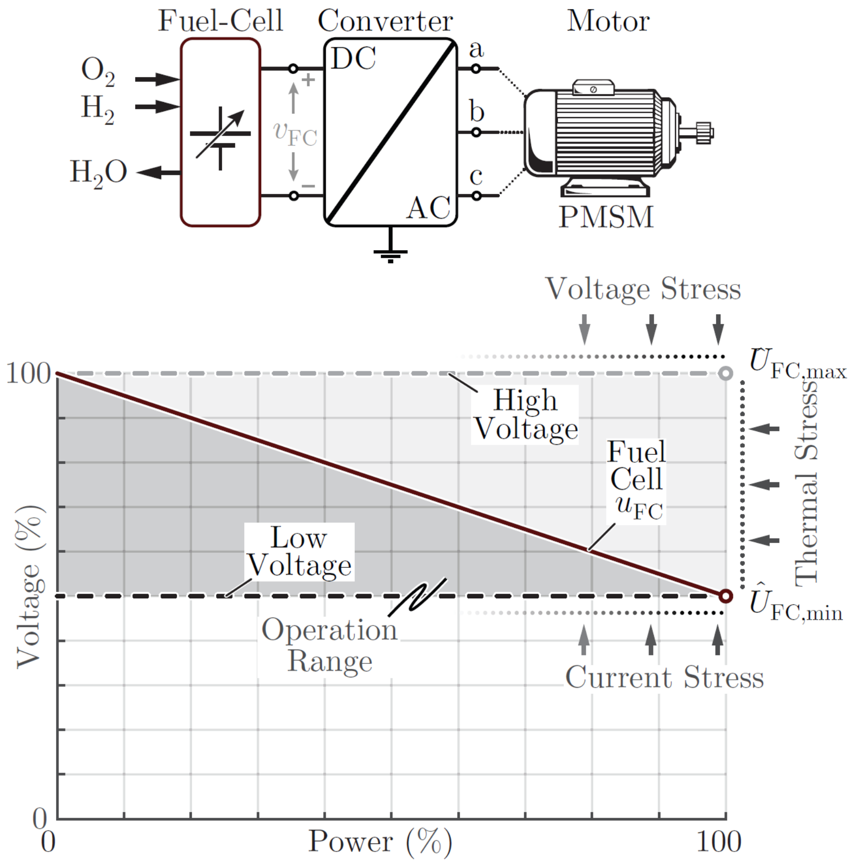


- Current Source Inverter (CSI) drive system → provides 'smooth' line voltages over the motor windings due to output filter capacitors
- Therefore, CSI 'could' potentially solve high-frequency issues typical for the VSI drive systems
- Blocking of voltage and current in both directions for CSI → Monolithic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

Introduction: Input Buck of the CSI

- CSI needs a 'current DC-link' → therefore, there is an input (buck) converter that controls the DC link current i_{dc}
- Compared to VSIs, this input converter represents an additional realization effort of the CSI



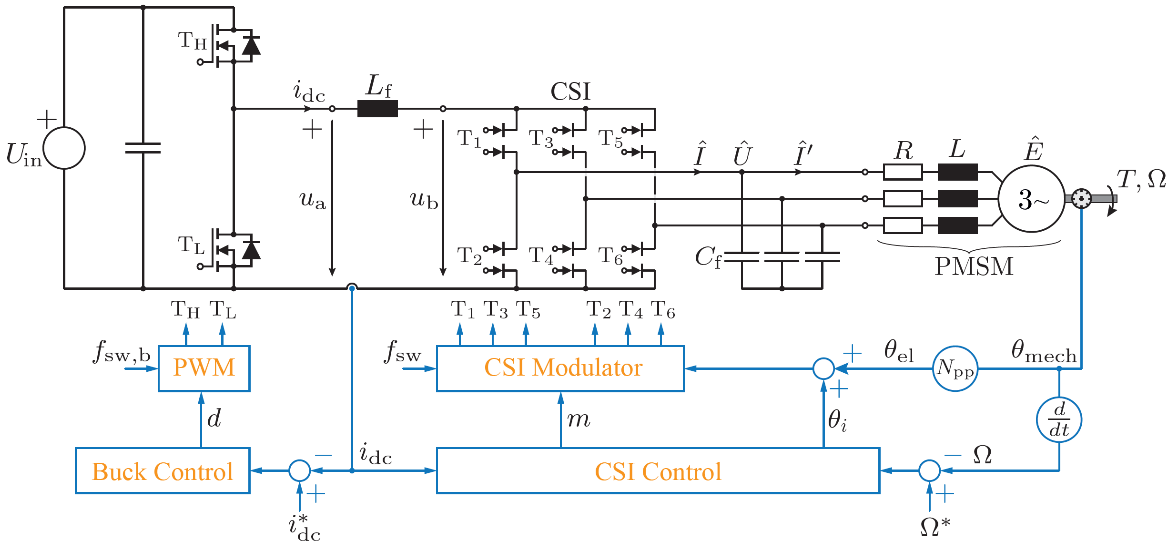


Picture source: Antivachis, M., Bortis, D., Menzi, D., & Kolar, J. W. (2018, May). Comparative evaluation of Y-inverter against three-phase two-stage buck-boost DC-AC converter systems. In 2018 International Power Electronics Conference (IPEC-Niigata 2018-ECCE Asia) (pp. 181-189). IEEE.

- In certain applications, like fuel-cell-supplied drive systems, VSIs also need an input converter due to large DC link voltage variation!
- Therefore, in such applications, VSIs and CSIs have similar realization effort!

Introduction: CSI Drive System Control

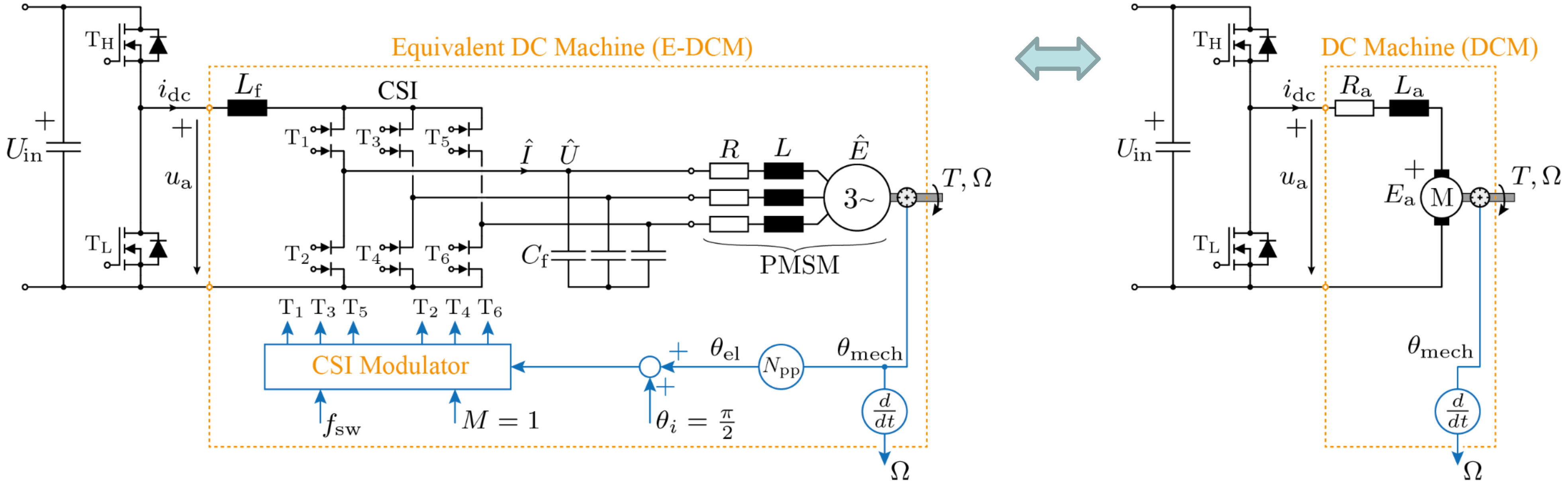
- Speed-control CSI-based drive system → input buck controls the DC link current to typically constant value
- CSI 'modulates' the DC link current to provide the desired phase PMSM currents required to achieve the desired torque to manage speed



- The user of the CSI drive system has to 'deal with' the CSI modulation and control
- Challenge of the CSI acceptance in the industry → majority of engineers are familiar with VSI modulation but not with CSI

Motivation: 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

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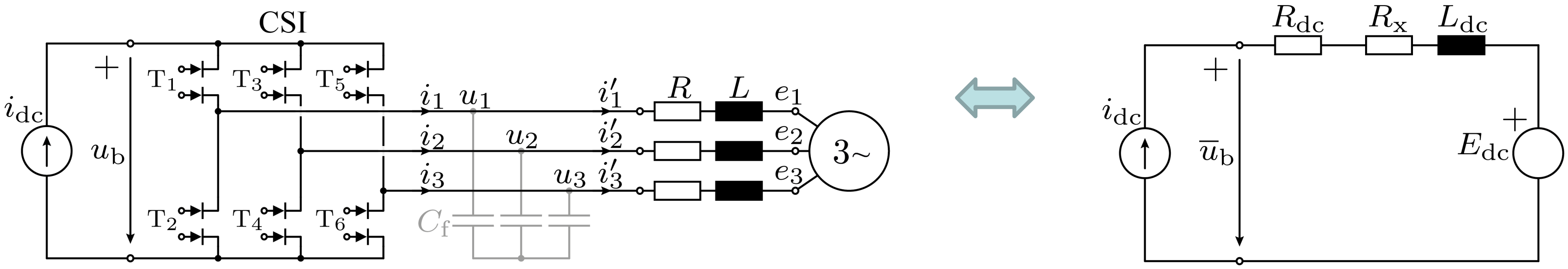
DC-Side Equivalent Circuit of CSI

- Since we want to control the PMSM torque directly with the DC link current → equivalent circuit of the CSI DC-side
- Equivalent circuit cover fundamental frequency range → neglect impact of the filter capacitors: $i_1 = i_1'$, $i_2 = i_2'$, $i_3 = i_3'$



Power Balance: $\bar{u}_b \cdot i_{dc} = u_1 \cdot i_1 + u_2 \cdot i_2 + u_3 \cdot i_3$

$$i_1 = m\, i_{dc} \cos(\theta_{el} + \theta_i)$$
$$i_2 = m\, i_{dc} \cos(\theta_{el} + \theta_i - \frac{2\pi}{3})$$
$$i_3 = m\, i_{dc} \cos(\theta_{el} + \theta_i + \frac{2\pi}{3})$$

- We derive the equivalent circuit based on the power balance between the DC and the AC side
- The voltage $\bar{u}_b$ is the switching-frequency average of u_b
- The derivation is done for a general value of modulation index 'm'
- We assume sinusoidal waveforms for the voltages and currents on the AC side
- We derive the DC-side equivalent for: Resistance, Inductance, AC Voltage (back-EMF)

$$u_1 = R\, i_1 + L \frac{di_1}{dt} + e_1$$
$$u_2 = R\, i_2 + L \frac{di_2}{dt} + e_2$$
$$u_3 = R\, i_3 + L \frac{di_3}{dt} + e_3$$

DC-Side Equivalent Resistance

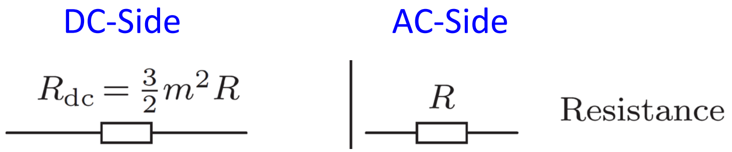
- We start from the power balance $\bar{u}_b \cdot i_{dc} = u_1 \cdot i_1 + u_2 \cdot i_2 + u_3 \cdot i_3$ and apply it for the resistance R

$$u_1 = R\,i_1 \qquad u_2 = R\,i_2 \qquad u_3 = R\,i_3$$

$$\Rightarrow \quad \bar{u}_b\, i_{dc} = R\,(i_1^2 + i_2^2 + i_3^2) \quad \Rightarrow \quad \bar{u}_b\, i_{dc} = \frac{3}{2} R\, m^2\, i_{dc}^2 \quad \Rightarrow \quad \bar{u}_b = \underbrace{\frac{3}{2} m^2\, R}_{=R_{dc}}\, i_{dc}$$

$$i_1 = m\, i_{dc} \cos(\theta_{el} + \theta_i)$$
$$i_2 = m\, i_{dc} \cos(\theta_{el} + \theta_i - \frac{2\pi}{3})$$
$$i_3 = m\, i_{dc} \cos(\theta_{el} + \theta_i + \frac{2\pi}{3})$$

DC-Side Resistance: $R_{dc} = \frac{3}{2} m^2 R$



DC-Side Equivalent Inductance

- We start from the power balance $\overline{u}_\mathrm{b} \cdot i_\mathrm{dc} = u_1 \cdot i_1 + u_2 \cdot i_2 + u_3 \cdot i_3$ and apply it for the inductance L

$$u_1 = L\frac{\mathrm{d}i_1}{\mathrm{d}t}, \quad u_2 = L\frac{\mathrm{d}i_2}{\mathrm{d}t}, \quad u_3 = L\frac{\mathrm{d}i_3}{\mathrm{d}t}$$

$$\Rightarrow \overline{u}_\mathrm{b}\, i_\mathrm{dc} = L\left(\frac{\mathrm{d}i_1}{\mathrm{d}t}\, i_1 + \frac{\mathrm{d}i_2}{\mathrm{d}t}\, i_2 + \frac{\mathrm{d}i_3}{\mathrm{d}t}\, i_3\right)$$

$$\frac{\mathrm{d}f(t)^2}{\mathrm{d}t} = 2\, f(t)\frac{\mathrm{d}f(t)}{\mathrm{d}t}$$

$$\Rightarrow \overline{u}_\mathrm{b}\, i_\mathrm{dc} = L\,\frac{1}{2}\left(\frac{\mathrm{d}i_1^2}{\mathrm{d}t} + \frac{\mathrm{d}i_2^2}{\mathrm{d}t} + \frac{\mathrm{d}i_3^2}{\mathrm{d}t}\right)$$

$$\Rightarrow \overline{u}_\mathrm{b}\, i_\mathrm{dc} = L\,\frac{1}{2}\,\frac{\mathrm{d}}{\mathrm{d}t}\left(i_1^2 + i_2^2 + i_3^2\right)$$

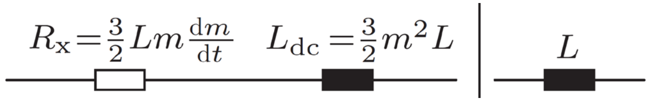
$$\Downarrow$$

$$\overline{u}_\mathrm{b}\, i_\mathrm{dc} = \frac{3}{2}\,L\,\frac{1}{2}\,\frac{\mathrm{d}(m^2\, i_\mathrm{dc}^2)}{\mathrm{d}t}$$

$$\Downarrow$$

$$\overline{u}_\mathrm{b} = \underbrace{\frac{3}{2}\,L\,m\frac{\mathrm{d}m}{\mathrm{d}t}}_{=R_\mathrm{x}}\, i_\mathrm{dc} + \underbrace{\frac{3}{2}\,m^2\,L}_{=L_\mathrm{dc}}\,\frac{\mathrm{d}i_\mathrm{dc}}{\mathrm{d}t}$$

DC-Side | AC-Side



Inductance

DC-Side Equivalent Back EMF

- We start from the power balance $\bar{u}_\mathrm{b} \cdot i_\mathrm{dc} = u_1 \cdot i_1 + u_2 \cdot i_2 + u_3 \cdot i_3$ and apply it for the back EMF

$$u_1 = e_1 \qquad u_2 = e_2 \qquad u_3 = e_3$$

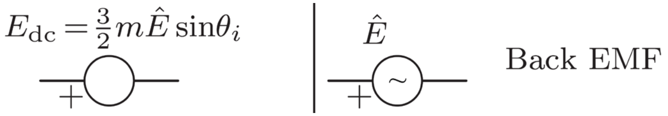
$$\Rightarrow \quad \bar{u}_\mathrm{b}\, i_\mathrm{dc} = e_1 i_1 + e_2 i_2 + e_3 i_3 \quad \Rightarrow \quad \bar{u}_\mathrm{b}\, i_\mathrm{dc} = \underbrace{\frac{3}{2} m \, \sin\theta_i \, \hat{E}}_{=E_\mathrm{dc}} \, i_\mathrm{dc}$$

$$e_1 = \omega \hat{\Psi} \cos(\theta_\mathrm{el} + \frac{\pi}{2})$$
$$e_2 = \omega \hat{\Psi} \cos(\theta_\mathrm{el} + \frac{\pi}{2} - \frac{2\pi}{3})$$
$$e_3 = \omega \hat{\Psi} \cos(\theta_\mathrm{el} + \frac{\pi}{2} + \frac{2\pi}{3})$$

$$i_1 = m \, i_\mathrm{dc} \cos(\theta_\mathrm{el} + \theta_i)$$
$$i_2 = m \, i_\mathrm{dc} \cos(\theta_\mathrm{el} + \theta_i - \frac{2\pi}{3})$$
$$i_3 = m \, i_\mathrm{dc} \cos(\theta_\mathrm{el} + \theta_i + \frac{2\pi}{3})$$

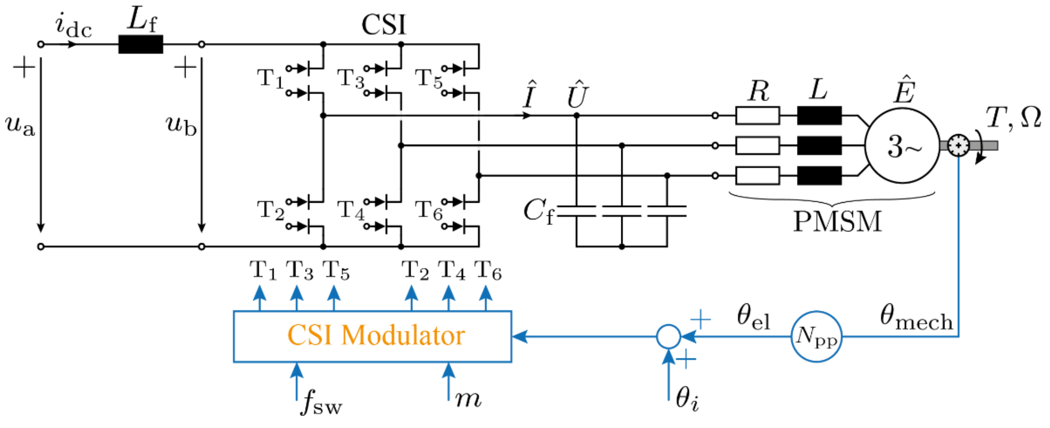
$$\psi_1 = \hat{\Psi} \cos(\theta_\mathrm{el})$$
$$\psi_2 = \hat{\Psi} \cos(\theta_\mathrm{el} - \frac{2\pi}{3})$$
$$\psi_3 = \hat{\Psi} \cos(\theta_\mathrm{el} + \frac{2\pi}{3})$$

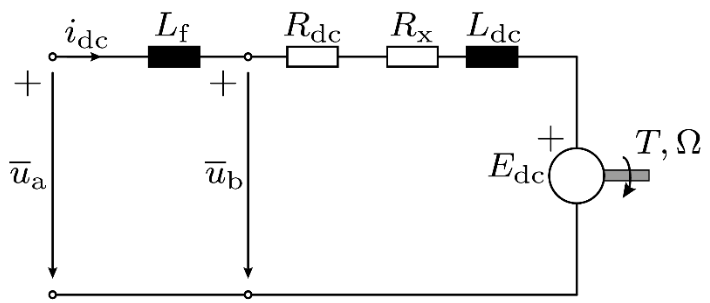
DC-Side | AC-Side



Summary of the DC-Side Equivalent Circuit of CSI

- Equivalent circuit of the CSI-supplied PMSM with general modulation index m and the current angle θ_i values





Averaged DC Side Circuit	AC Side Circuit	
$R_{dc} = \frac{3}{2} m^2 R$	R	Resistance
$R_x = \frac{3}{2} L m \frac{dm}{dt}$ $L_{dc} = \frac{3}{2} m^2 L$	L	Inductance
$E_{dc} = \frac{3}{2} m \hat{E} \sin\theta_i$	$\hat{E}$	Back EMF

- The AC inductance has equivalent resistance R_x on the AC side that exists only when the modulation index changes.
- The resistance R_x models the power necessary to increase/decrease the energy in the inductances.

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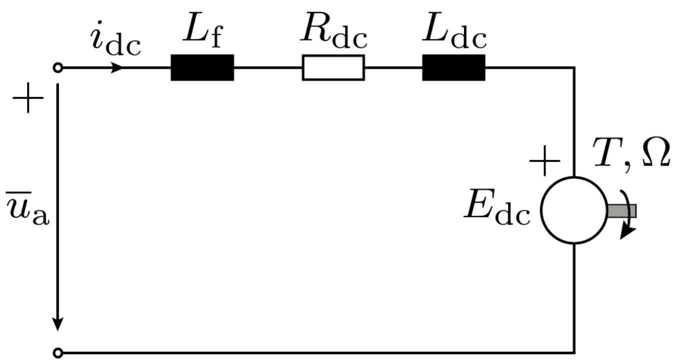
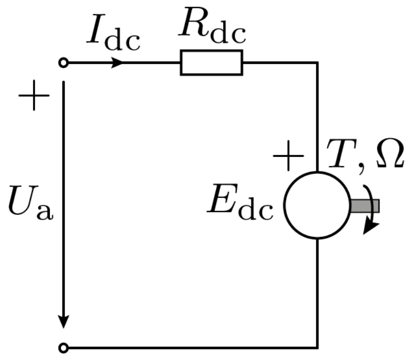
DC-Side Speed-Torque Characteristic

- **For the proposed Equivalent DC Machine (E-DCM) concept → constant modulation index $m = M$**
- **For constant modulation index → the dynamic resistance disappears: $\boldsymbol{R_x = \frac{3}{2} L \cdot m \cdot \frac{dm}{dt} = 0}$, since $\boldsymbol{\frac{dm}{dt} = \frac{dM}{dt} = 0}$**



Equivalent circuit with $m = M$, no R_x.



Steady-state circuit.

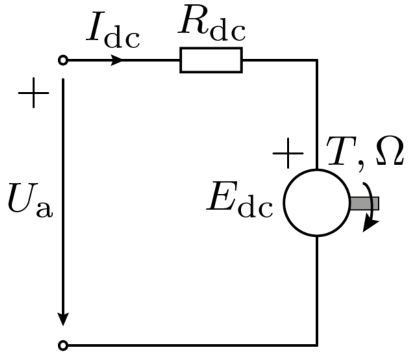
$\overline{u}_a \to U_a$ and $i_{dc} \to I_{dc}$

$m \to M$ and $\theta_i \to \theta_I$

- **For the derivation of the mechanical DC-side speed-torque characteristic, we assume steady state operation.**

DC-Side Speed-Torque Characteristic

- **We start the derivation assuming steady-state conditions → in voltage equation we relate the current to torque and back EMF to mech. speed**



$$E_{dc} = \frac{3}{2} M \sin\theta_I \, p\hat{\Psi} \cdot \Omega$$

Relate back EMF to mechanical speed

$$U_a = R_{dc} I_{dc} + E_{dc}$$

Relate current to Torque

$$i_q = \hat{I} \sin\theta_I$$

$$T = k_T \, I_{dc} \, M \sin\theta_I$$

$$k_T = \frac{3}{2} p\hat{\Psi}$$

$$U_a = M^2 \frac{3}{2} R \frac{T}{M \sin\theta_I \, k_T} + M \sin\theta_I \, k_T \, \Omega$$

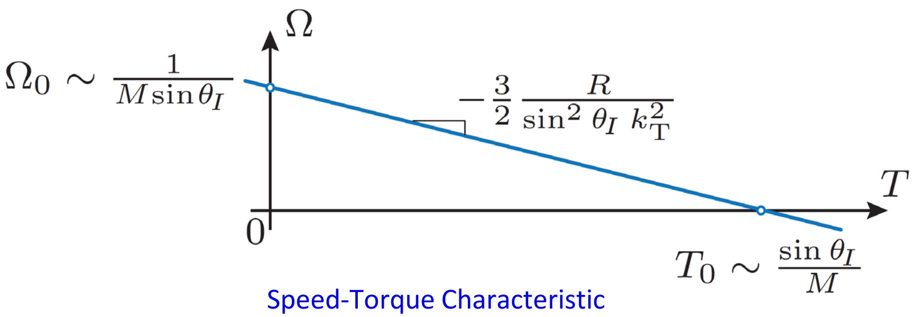
$$\Omega = \frac{1}{M \sin\theta_I \, k_T} U_a - \frac{3}{2} \frac{R}{\sin^2\theta_I \, k_T^2} T$$

No-Load Speed

$$\Omega_0 = \frac{U_a}{M \sin\theta_I k_T}$$

Standstill Torque

$$T_0 = \frac{2}{3} \frac{\sin\theta_I k_T}{M R} U_a$$



Speed-Torque Characteristic

- **DC-Side Speed-Torque characteristic is function of M and θ_I**
- **M has the same effect is the number of rotor turns in a DC machine**
- **θ_I has similar effect as the excitation flux in a DC machine**

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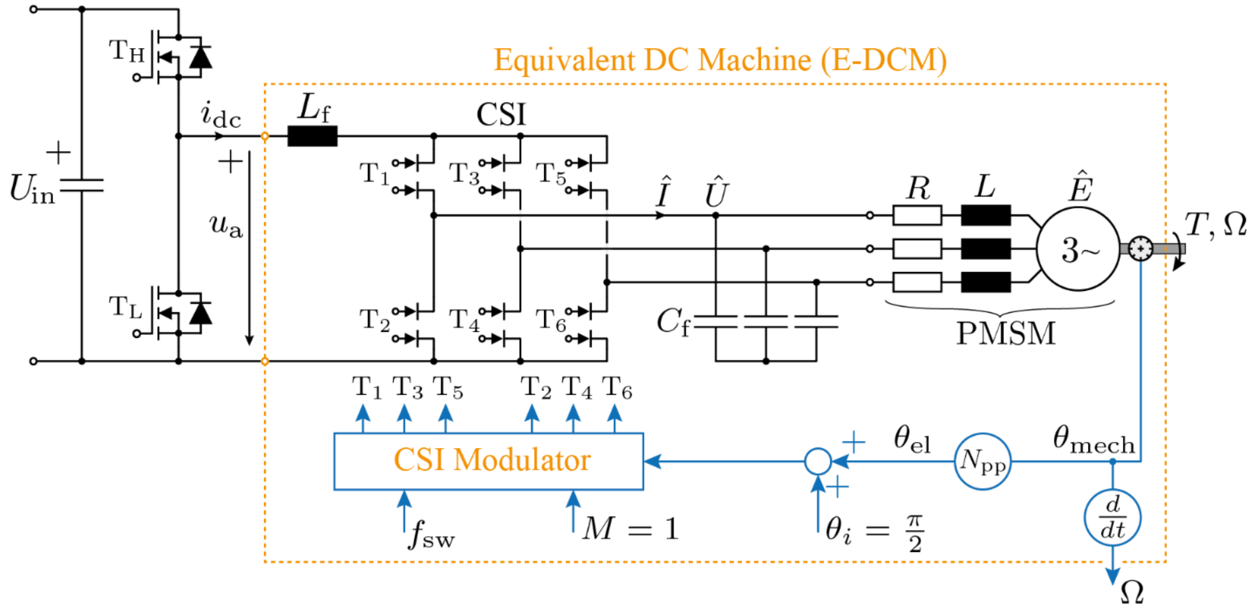
Equivalent DC-Machine Concept (E-DCM)

- The equivalent DC-machine concept → DC link current directly proportional to the torque on the PMSM shaft
- For E-DCM, CSI modulation index M and the current angle θ_I are kept constant

$$T = k_{\mathrm{Tdc}}\, i_{\mathrm{dc}}$$

$$k_{\mathrm{Tdc}} = k_{\mathrm{T}}\, M\, \sin\theta_I$$



- Reasonable choice of M and θ_I to maximize k_{Tdc}:

$$0 \leq M \leq 1$$

$$-1 \leq \sin\theta_I \leq 1$$

$$M = 1 \quad \text{and} \quad \theta_I = \frac{\pi}{2} \qquad\qquad k_{\mathrm{Tdc}} = k_{\mathrm{T}}$$

- Finally, for the analyzed E-DCM, the DC torque constant is equal to the PMSM torque constant → $T = k_{\mathrm{T}} \cdot i_{\mathrm{dc}}$
- The voltage u_a is the 'Equivalent Armature Voltage'

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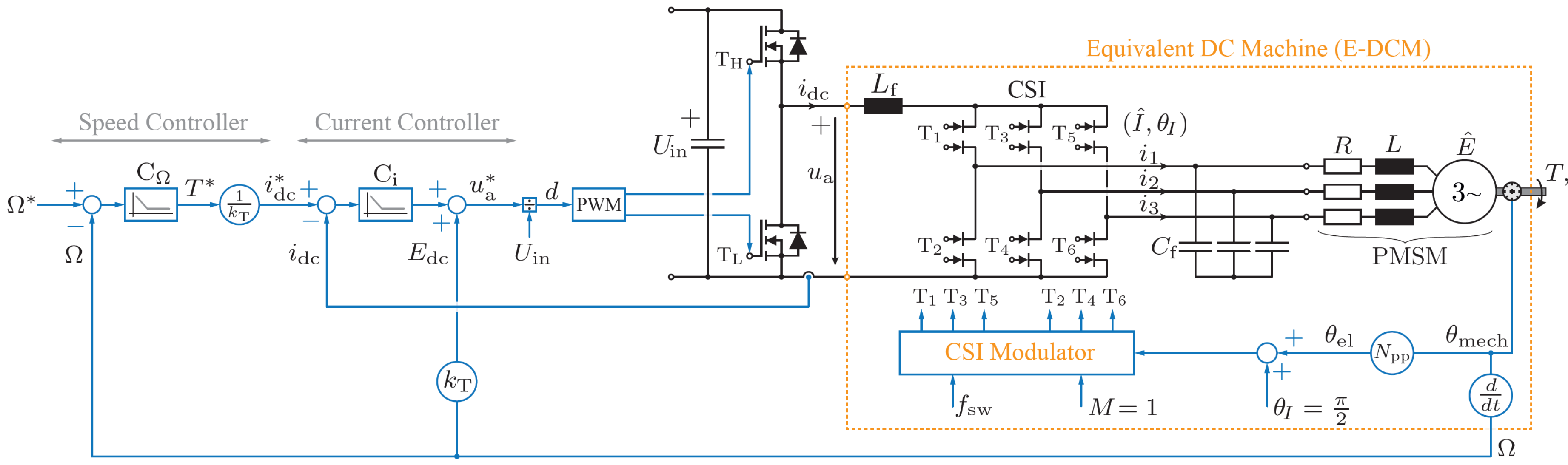
E-DCM Speed Control Drive System

- 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)



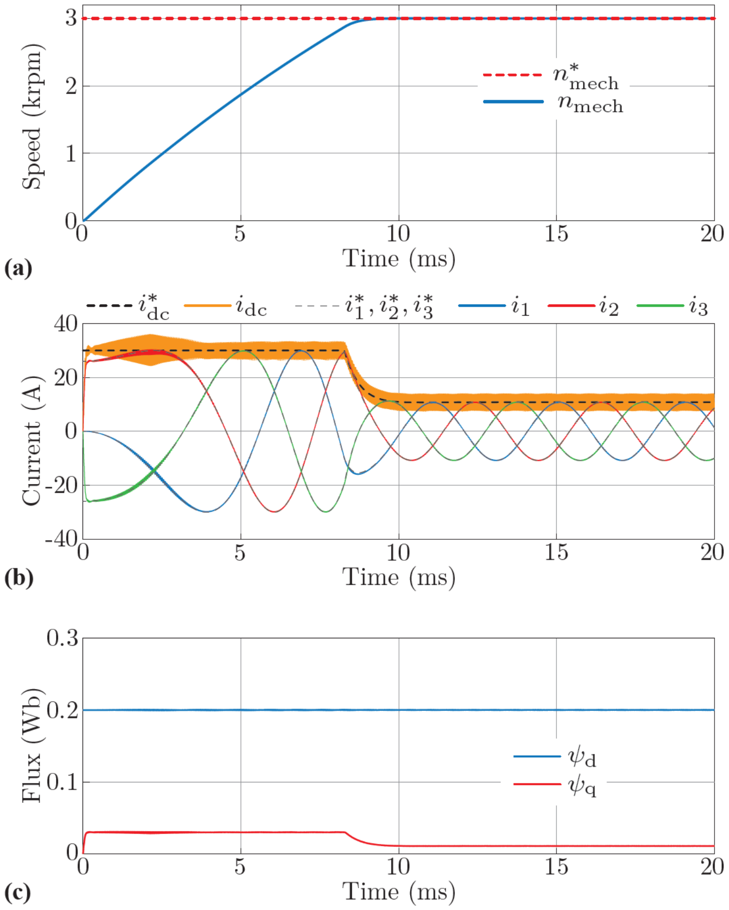
- The DC link current reference directly calculated from the speed controller torque reference: $i_{dc}^* = \frac{T^*}{k_T}$
- For tuning the current controller, the sum of the DC link inductance L_f and the DC-side equivalent inductance L_{dc} are considered: $L_f + L_{dc}$
- The user has manage only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

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

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** $\theta_I = \frac{\pi}{2}$

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

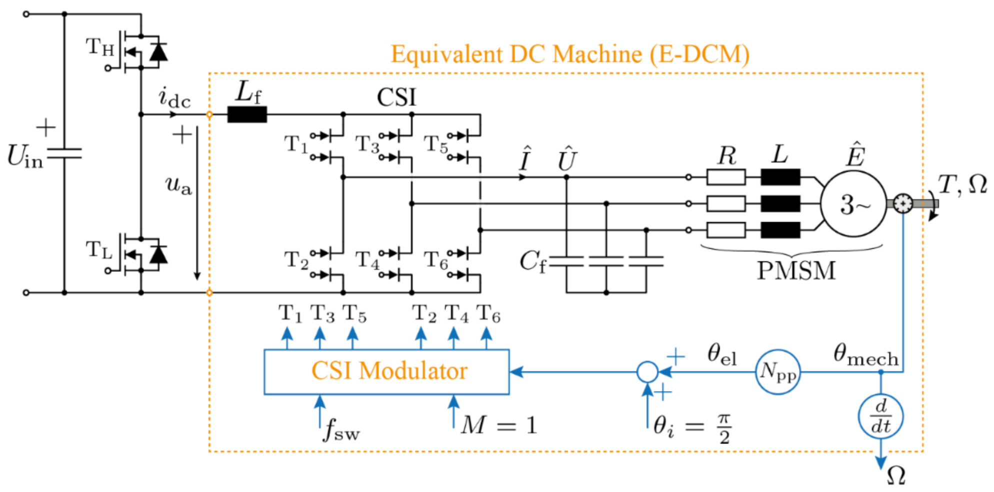


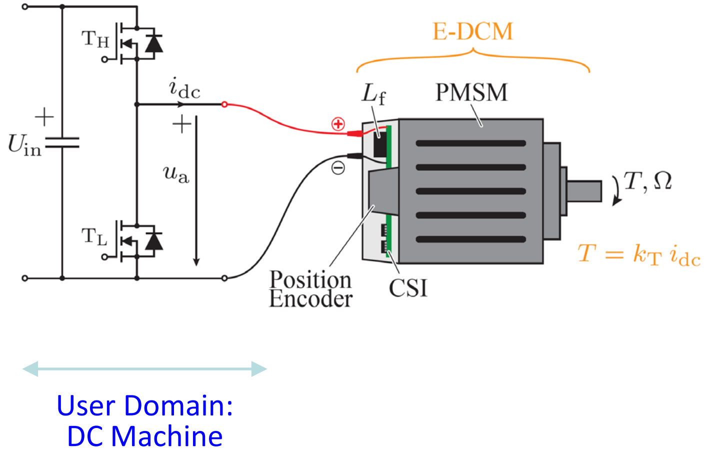
Parameter	Symbol	Value
Buck		
Input voltage	U_{in}	800 V
Switching frequency	$f_{\mathrm{sw,b}}$	80 kHz
CSI		
DC link inductance	L_{f}	450 µH
Output capacitance	C_{f}	0.1 µF
Switching frequency	f_{sw}	140 kHz
Max. DC link current	$I_{\mathrm{dc,max}}$	30 A
PMSM		
Phase resistance	R	0.2 Ω
Phase inductance	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		
$\mathrm{C_i}$ closed-loop bandwidth	f_{cc}	4 kHz
$\mathrm{C_i}$ proportional gain	K_{pc}	49 V/A
$\mathrm{C_i}$ integral gain	K_{ic}	10 000 V/(As)
$\mathrm{C_\Omega}$ cross-over frequency	f_{cs}	0.8 kHz
$\mathrm{C_\Omega}$ proportional gain	K_{ps}	3.3 sNm
$\mathrm{C_\Omega}$ 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.

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!

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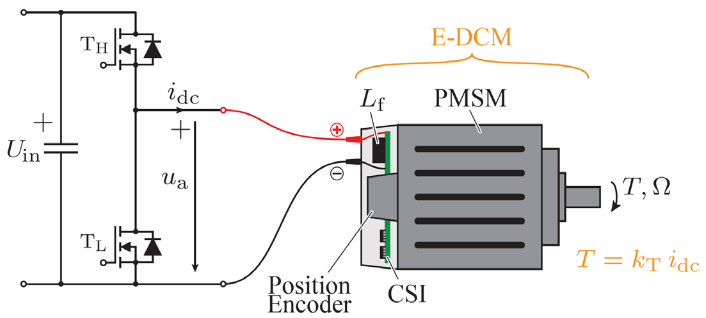
Conclusions

- CSIs can provide 'smooth' voltages over motor windings – an advantage over VSIs
- Input buck converter for DC link current regulation
- Proposed E-DCM Concept: CSI with $M = 1$ and $\theta_I = \frac{\pi}{2}$
- E-DCM allows PMSM torque management through DC link current
- DC-Side equivalent circuit of the PMSM
- DC-Side equivalent speed-torque characteristic of the PMSM
- E-DCM speed-controlled drive – torque and speed control of the PMSM like for DC machine
- E-DCM concept is an enabler for wide adoption of CSIs in drive systems

- Future work: E-DCM concept hardware verification



CSI with
$M = 1$ and $\theta_I = \frac{\pi}{2}$

Thank you!