Motor Control for Electrified Transportation Systems

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Outline

- Adjustable Speed Drives (ASD) in electrified transportation systems
- Electric motor torque control
- Indirect torque control: current control
- Pulse-Width Modulators
- Motor Drives
- Conclusion and challenges

Electrified Transportation Systems

Tesla Model S:

Traction Motor:

3ϕ Induction Machine

P_{max} = 310 kW

Citroen C0

Traction Motor:

PM Synchronous Machine

P_{max} = 49 kW

Lexus RX 450h:

Traction Motor:

PM Synchronous Machine

P_{max} = 130 kW

RENAULT Zoe

Traction Motor:

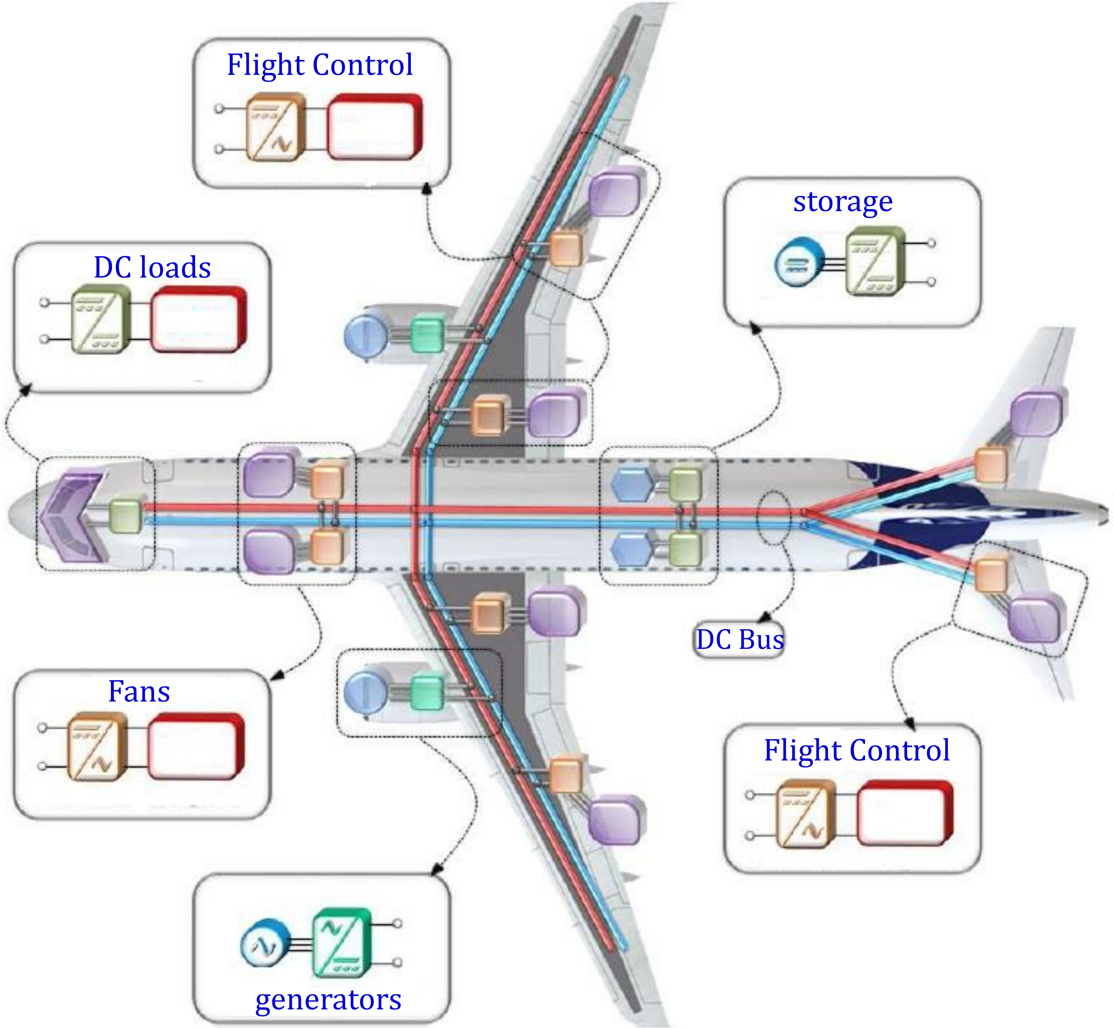
Wound Rotor Synchronous Machine

P_{max} = 65 kW

Electrified Transportation Systems

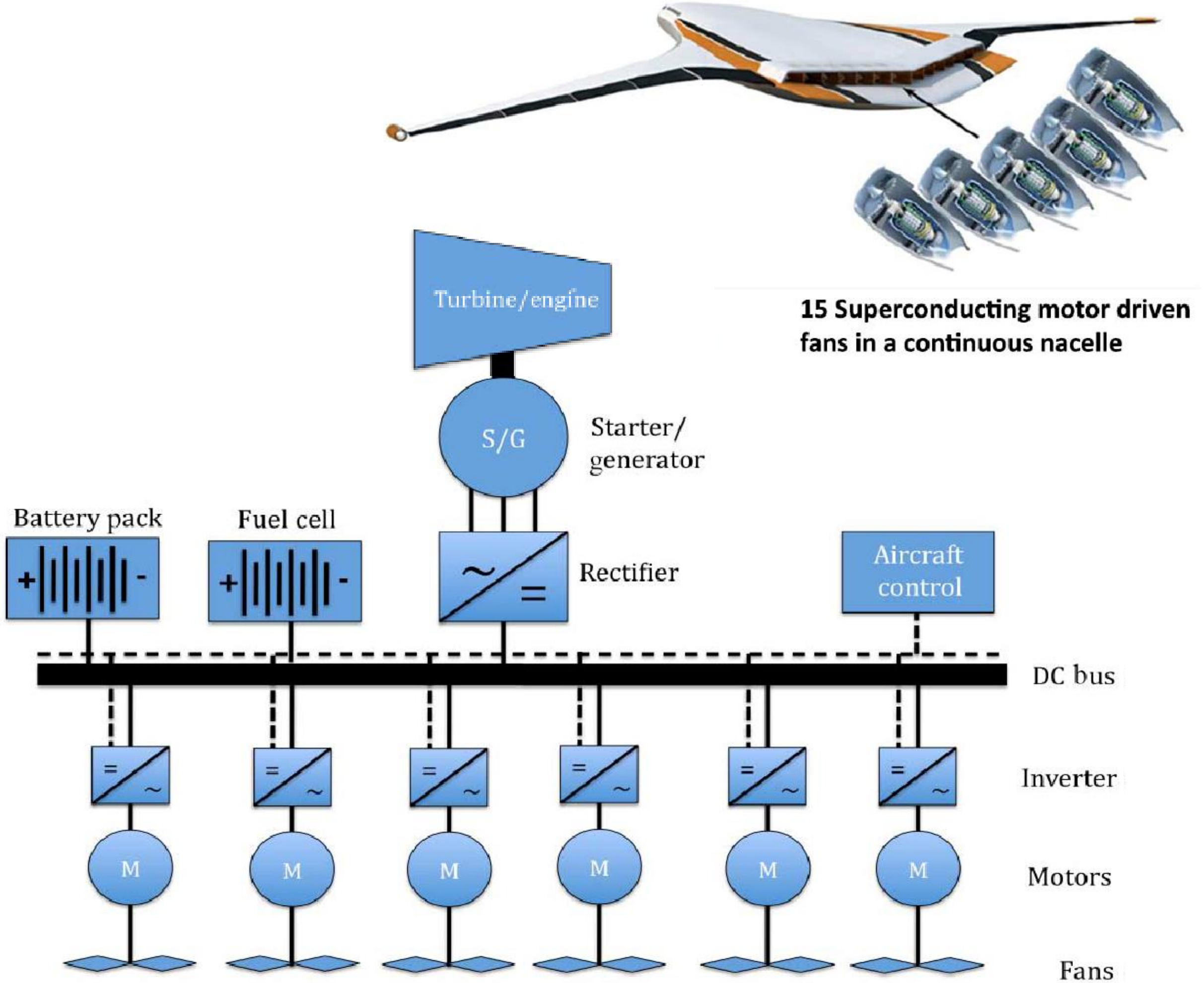
Power-by-wire: More Electric Aircraft (MEA)

replacing hydraulic actuators by electric actuators



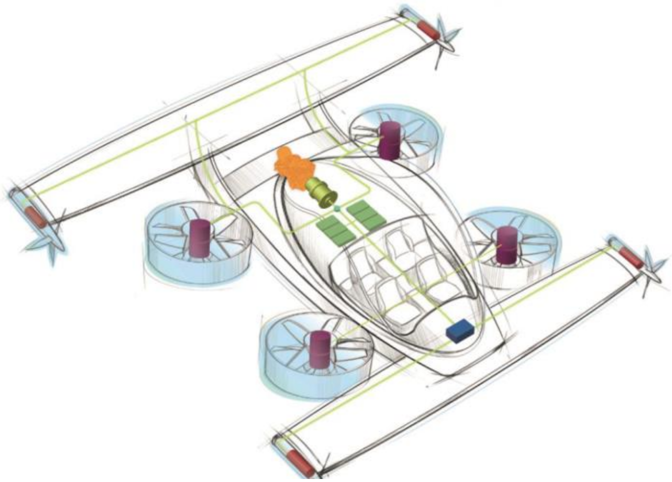
NASA N3-X HWB:

Series hybrid Electric Propulsion Aircraft (EPA)

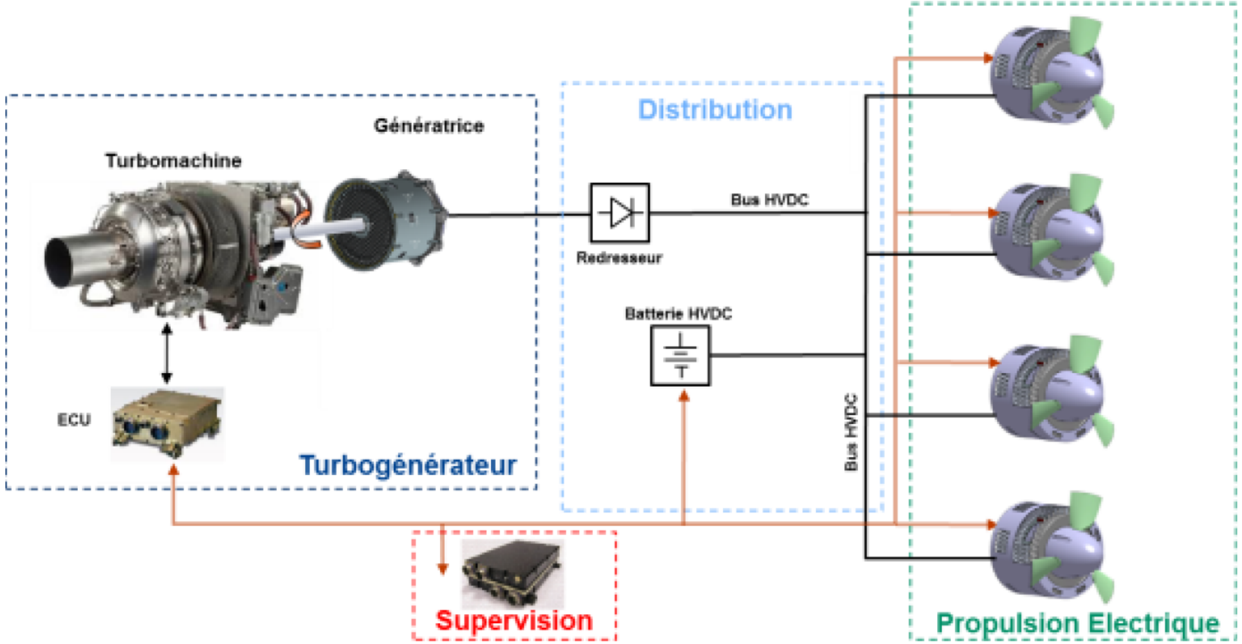


Electrified Transportation Systems: Flying Cars

Vertical Take-Off and Landing (VTOL)

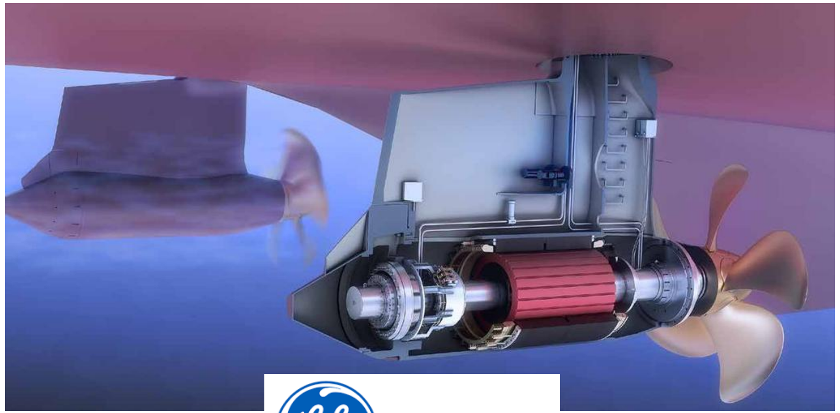


SAFRAN



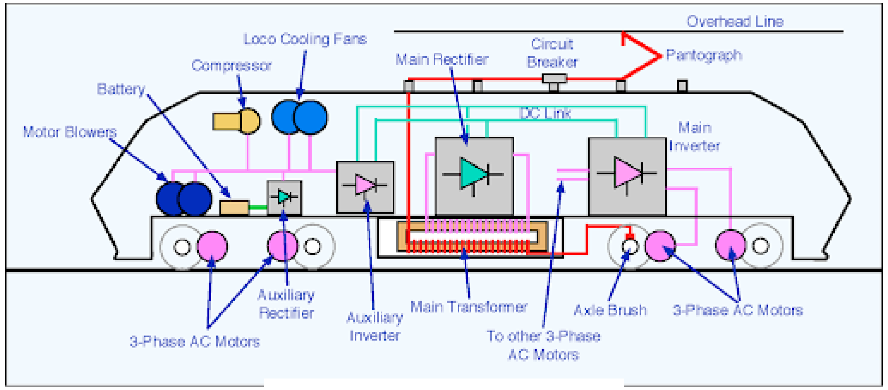
Other Examples of Electrified Transportation Systems

Sea: oil & gas offshore platforms

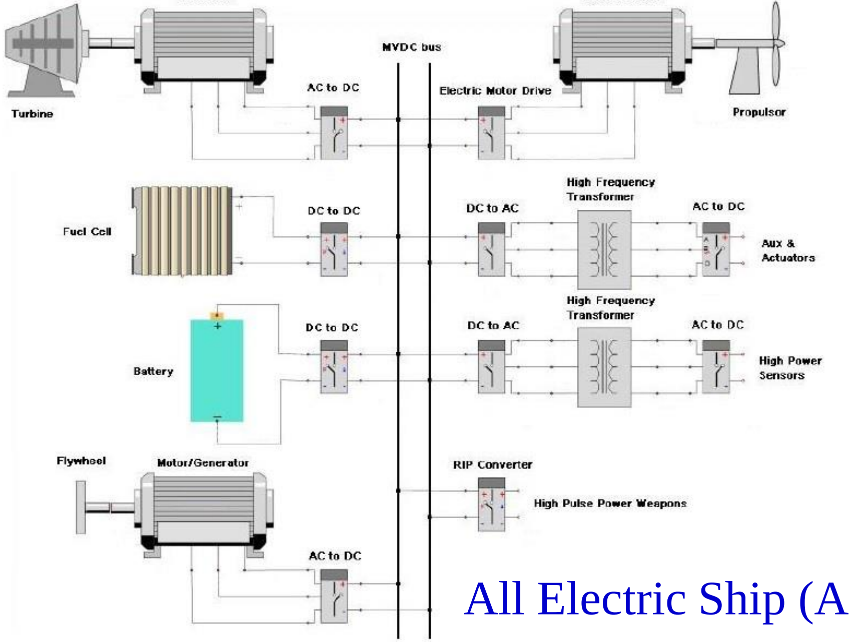


GE Power

Rail: electric locomotive



ALSTOM
• mobility by nature •



All Electric Ship (AES)

Automated manufacturing

SEW USOCOME

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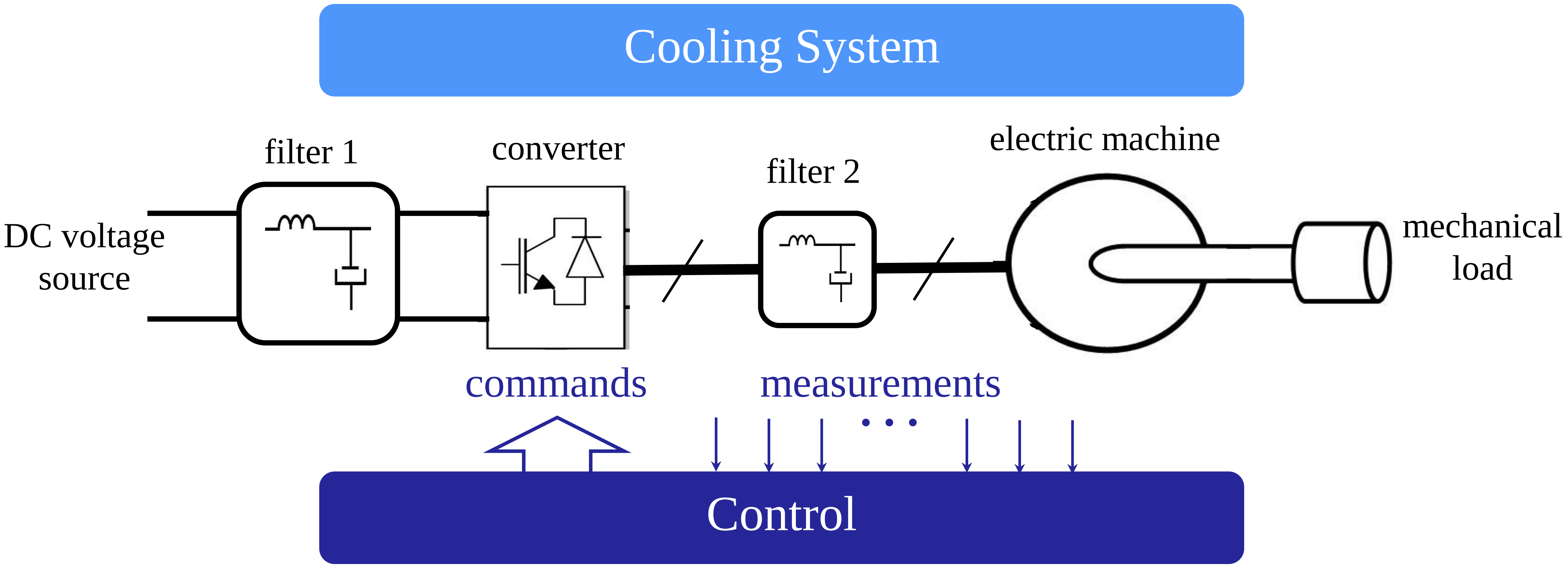
Structure of Adjustable Speed Drives



Cooling System

filter 1

converter

filter 2

electric machine

DC voltage source

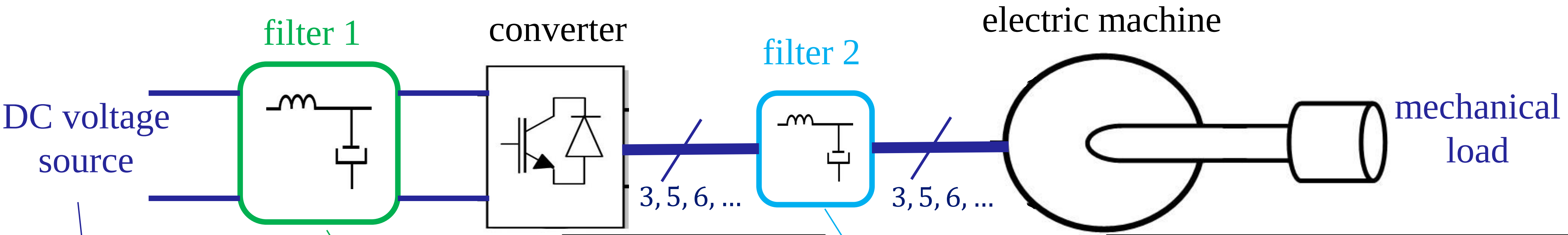
mechanical load

commands

measurements

Control

Topologies for Adjustable Speed Drives



- Battery
- Rectifier
- DC Microgrid
- PV

- C or LC filter (VSI)
- L filter (CSI)
- Z-source
- Quasi Z-source

- H-bridge
- VSI*
- CSI**
- DC/DC+VSI
- Multi-Level Inverter
- Matrix Converter
- Series Inverter

- L or LCL filter (VSI)
- C filter (CSI)

- DC Motor
- PM Synchronous Motor (PMSM)
- Induction Motor (IM)
- Wound-Rotor Synchronous Motor
- Switched-Reluctance Motor (SRM)
- Doubly-Fed IM
- Multi-Phase Motor (2 × 3ϕ, 5ϕ, 6ϕ, …)

* Voltage-Source Inverter
** Current-Source Inverter

Control of Adjustable Speed Drives

- **No unique approach** for drives with power range going from **Watt to 100+ kW**
- Main control techniques for AC drives:

1) **Open-loop control:**
    - **Control law:** very simple, pulse trains generated using a look-up table or a simple equation
    - **Sensors:** generally no sensor required
    - **Applications:** mostly low power - low cost applications
    - **Drawbacks:** accuracy, efficiency

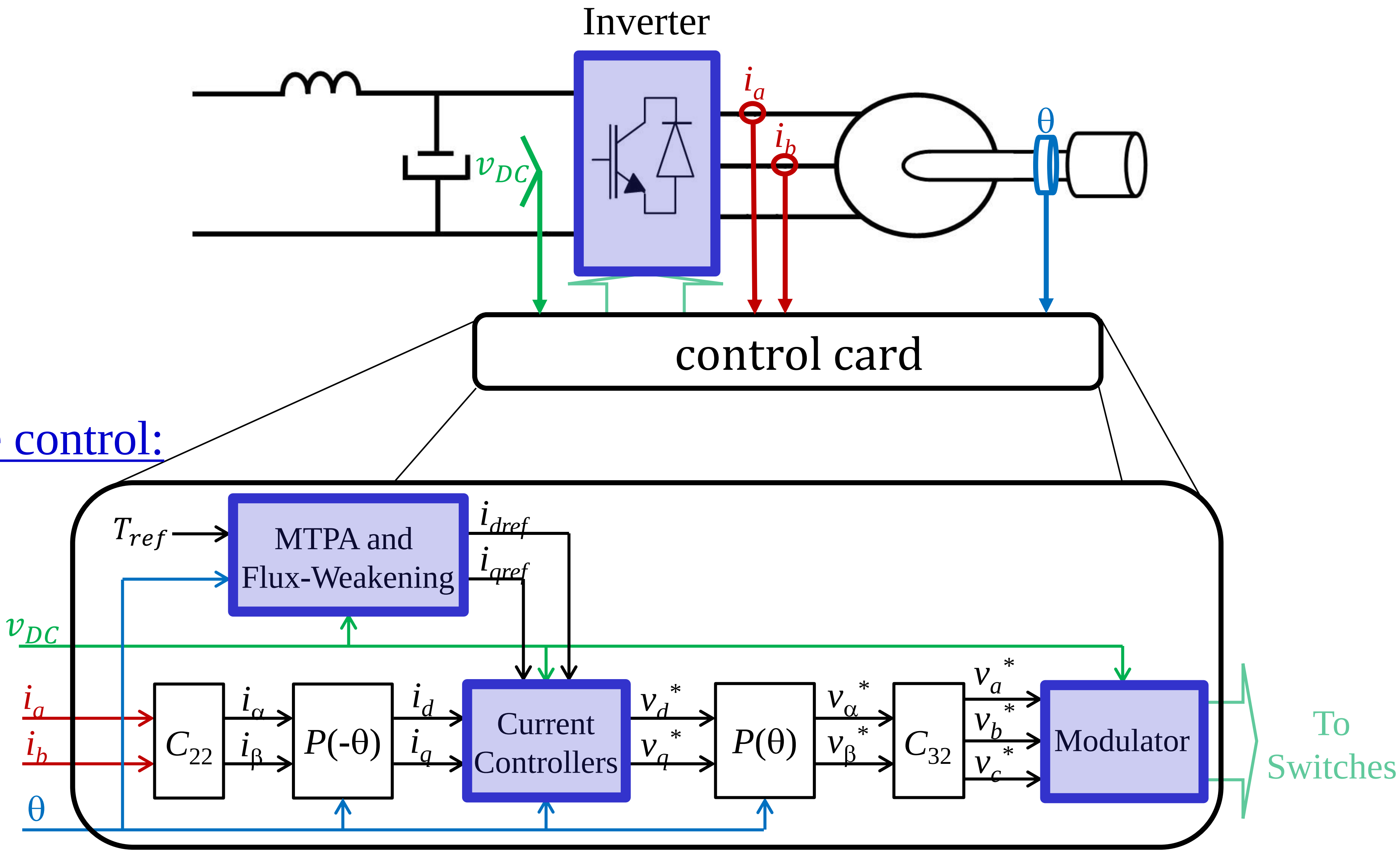
2) **Scalar control (V/f or V/Hz):**
    - **Control law:** simple relation between stator voltage magnitude and rotor speed (often under look-up table form)
    - **Sensors:** mechanical sensor (or speed estimator) required
    - **Applications:** mostly low power - low cost applications
    - **Drawbacks:** accuracy, efficiency

Control of Adjustable Speed Drives

3) **Vector control:**
   - **Direct Torque Control (DTC):**
     - **Control law:** torque and flux estimators AND switch pattern selection OR current regulators + modulator
     - **Sensors:** phase current sensors and mechanical sensor, DC-link voltage sensor optional
     - **Applications:** widely applied to motor control
     - **Drawbacks:** noise, torque ripples, cost
   - **Indirect Torque Control or Field-Oriented Control (FOC):**
     - **Control law:** Park transformation + current regulators + modulator OR switch pattern selection, flux estimator in some variants
     - **Sensors:** phase current sensors and mechanical sensor, DC-link voltage sensor optional
     - **Applications:** very widely applied to motor and generator control
     - **Drawbacks:** cost

Vector Control of Adjustable Speed Drives

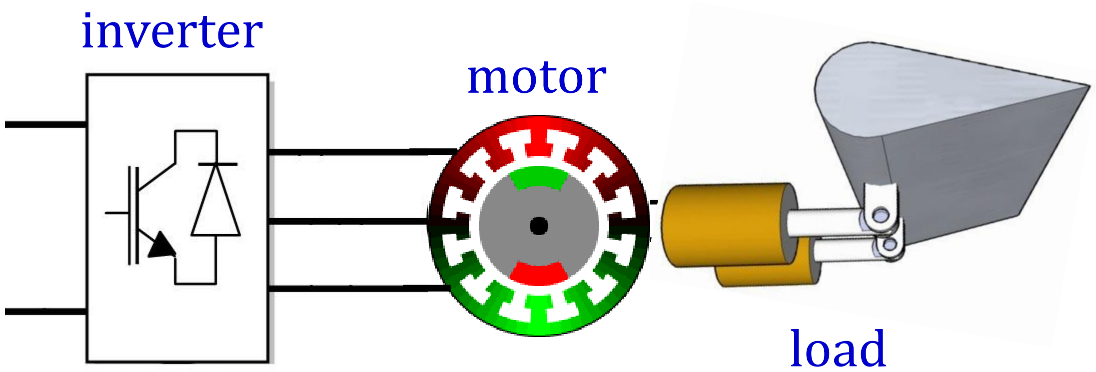
Indirect torque control:

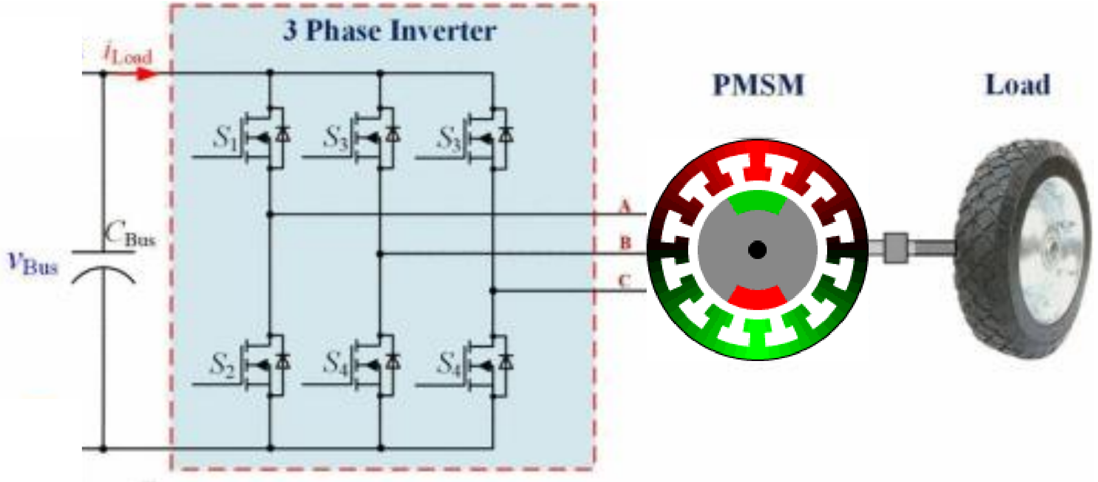


Motor Drives in Electrified Transportation Systems

Missions:

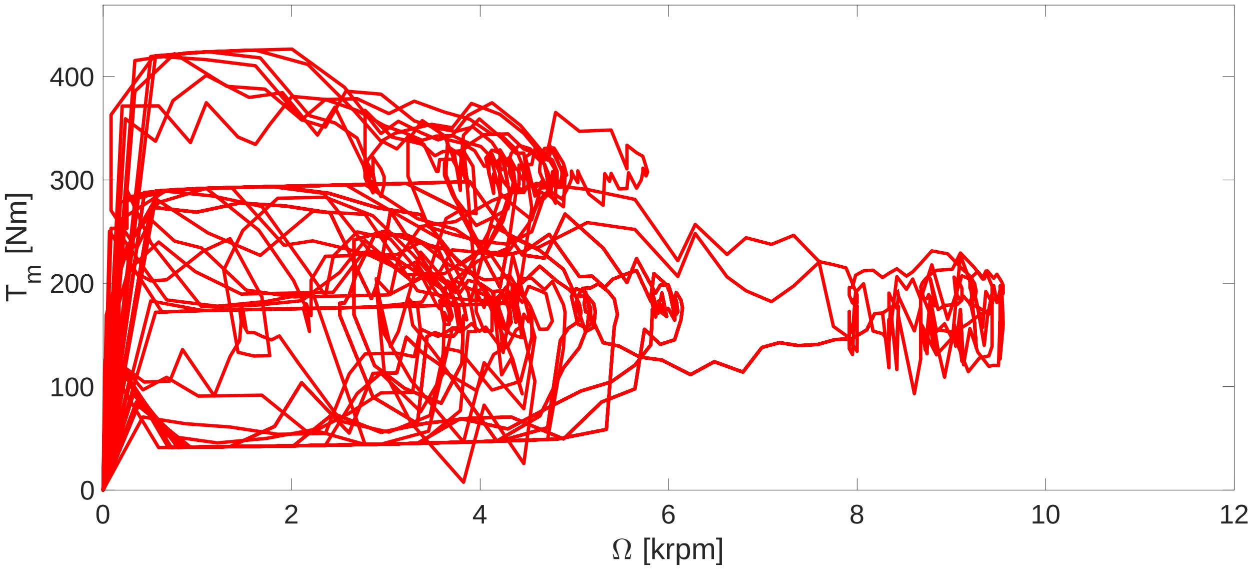
- Electromechanical actuators (EMA):
    - few Watts to kW motor drives
    - fixed or adjustable speed drives
- Pumps and fans:
    - hundreds of Watts to tens of kW
    - mainly adjustable speed drives
- Electric motors for propulsion/traction:
    - few kW to hundreds of kW
    - adjustable speed drives

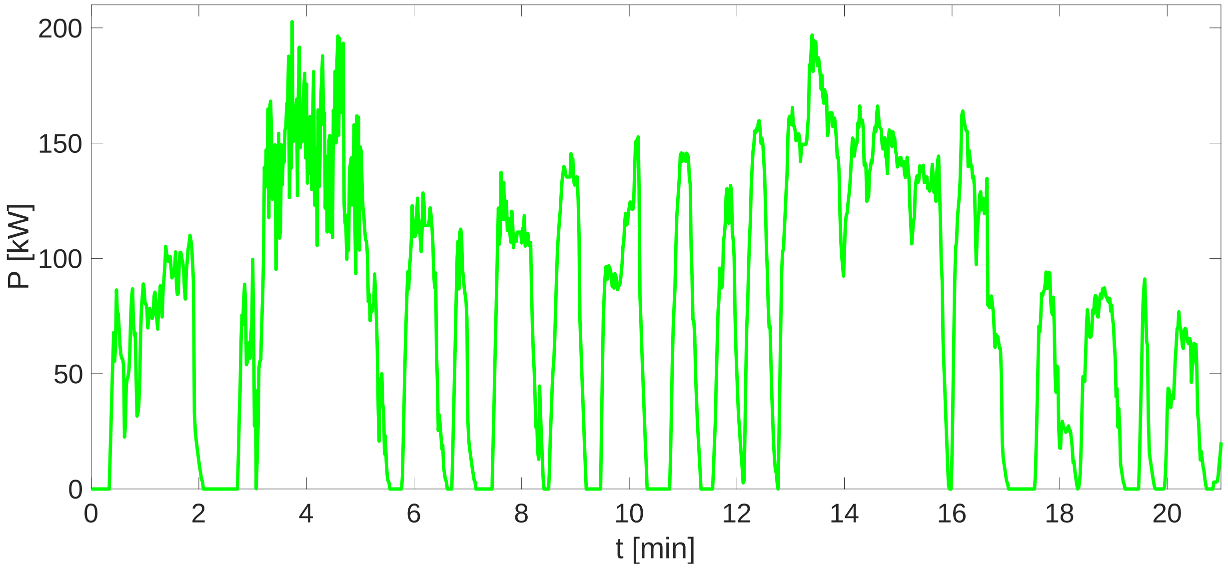


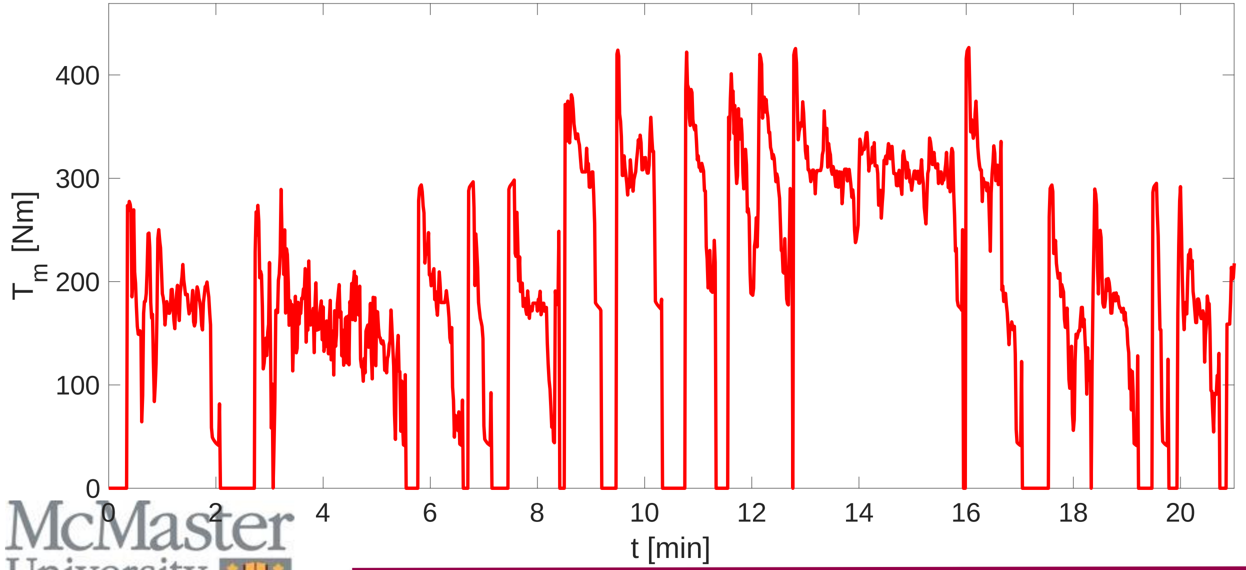


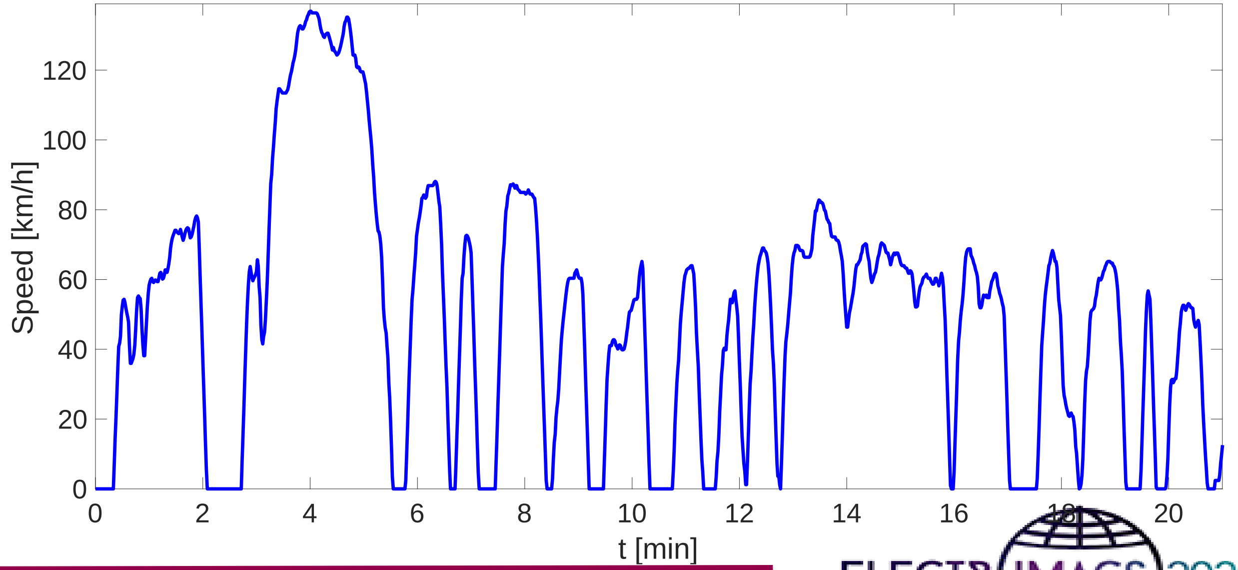
Mission Profile: Electric Vehicle

Urban/extra-urban vehicle



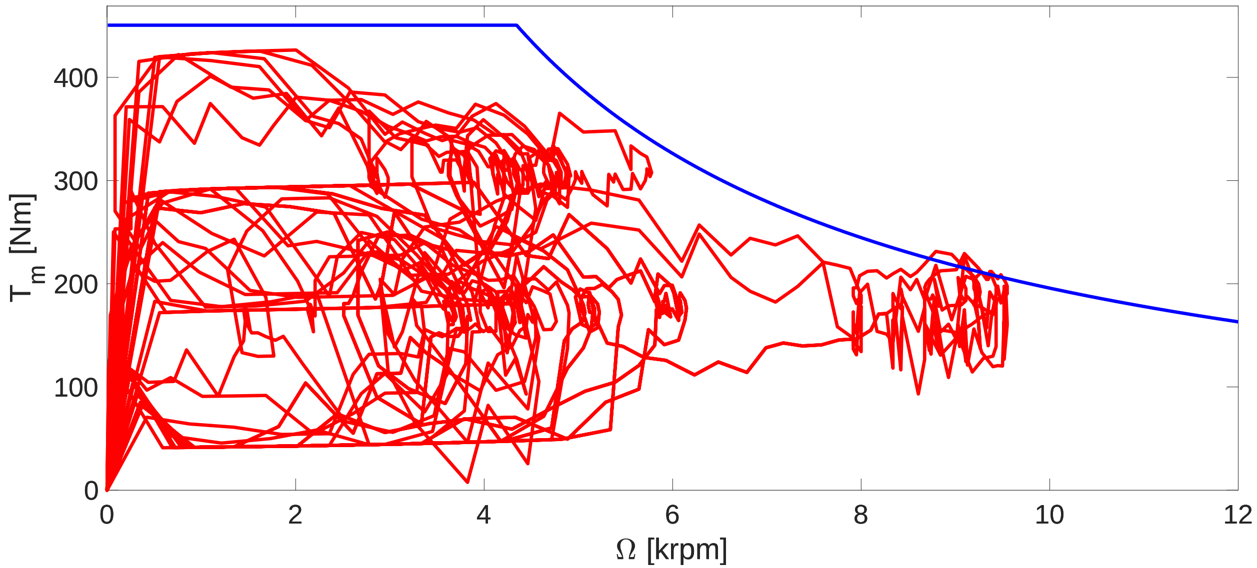


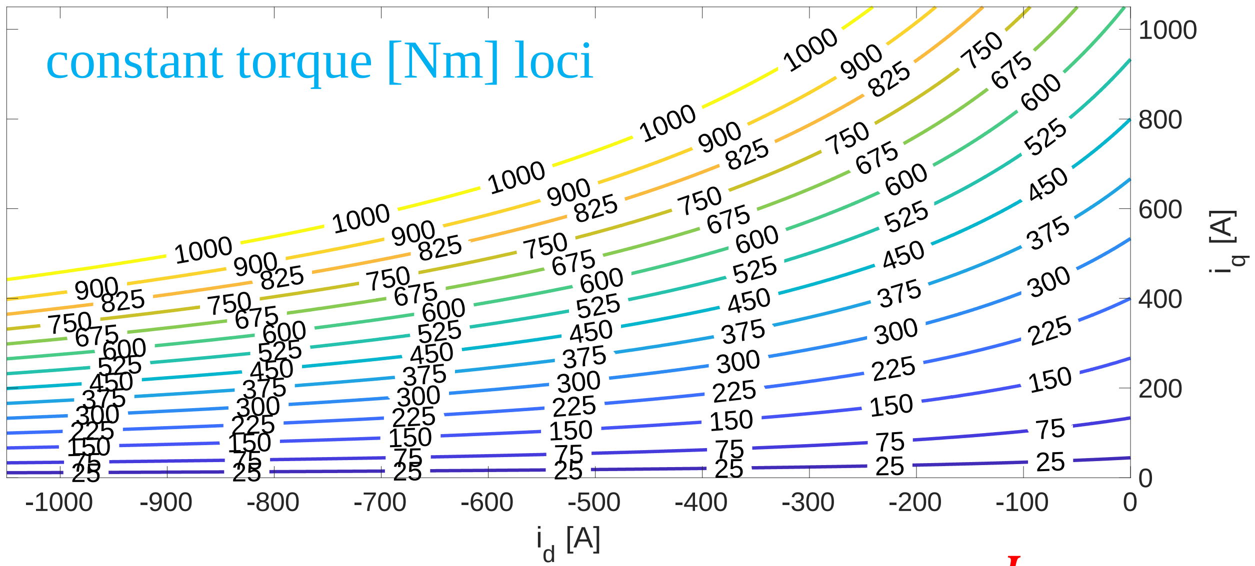


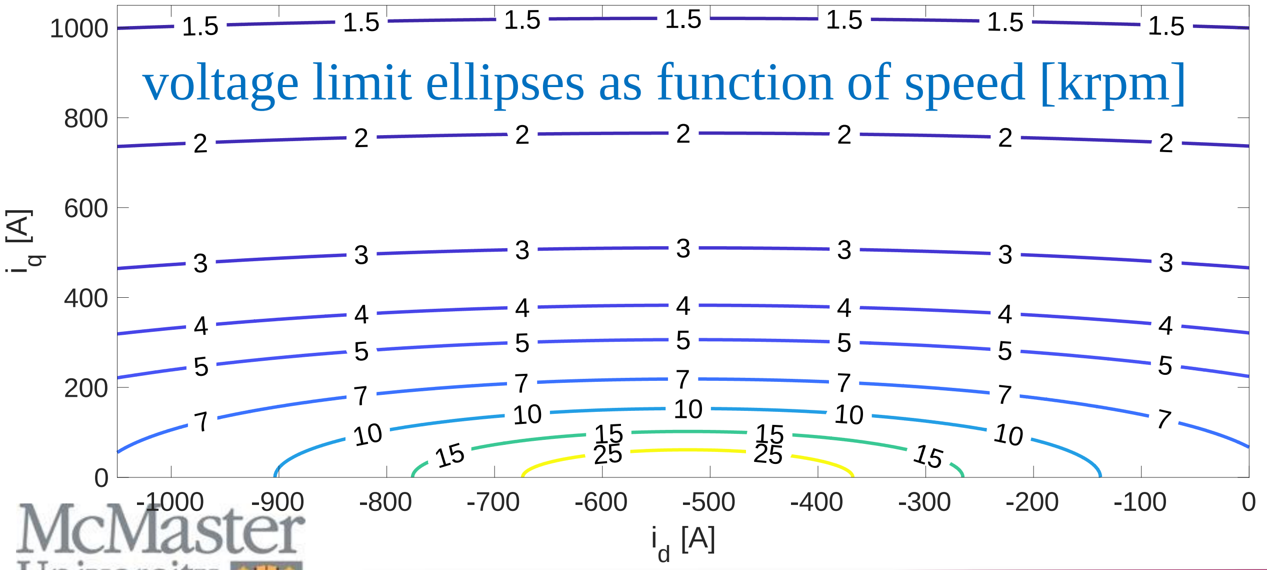


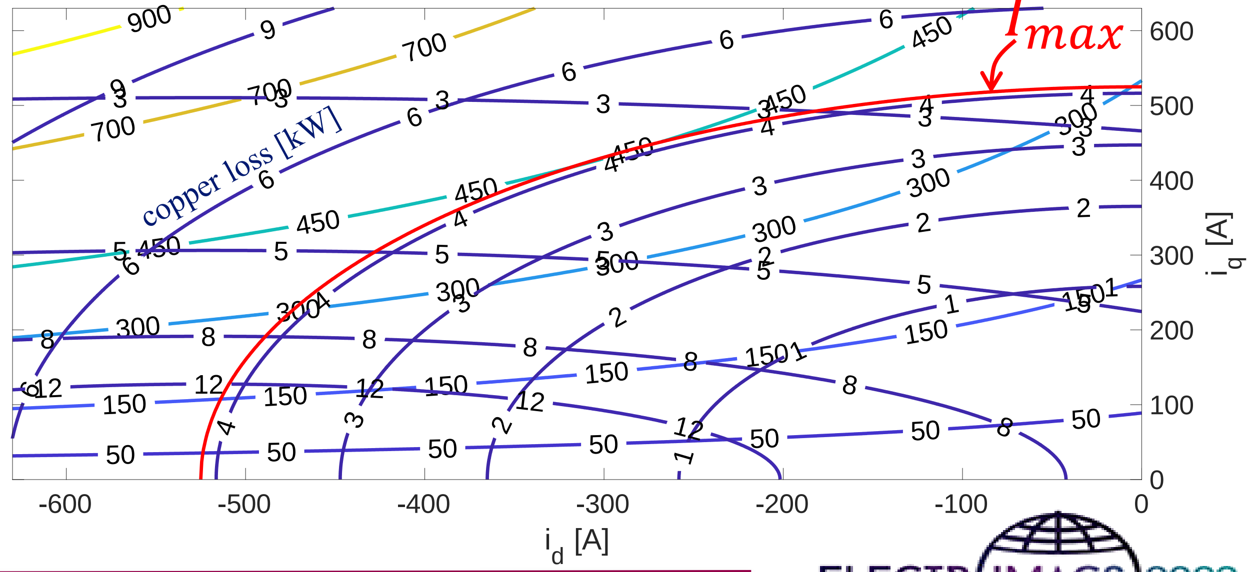
Electric Motor Torque Control

Adjustable Speed Drives: Torque Control Problem

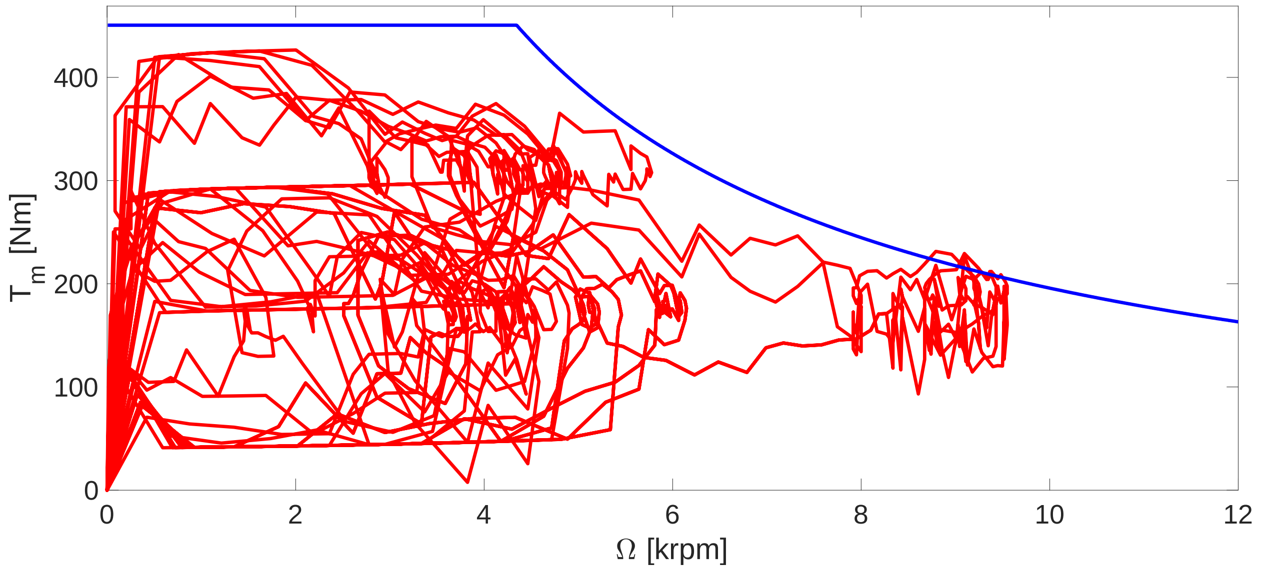


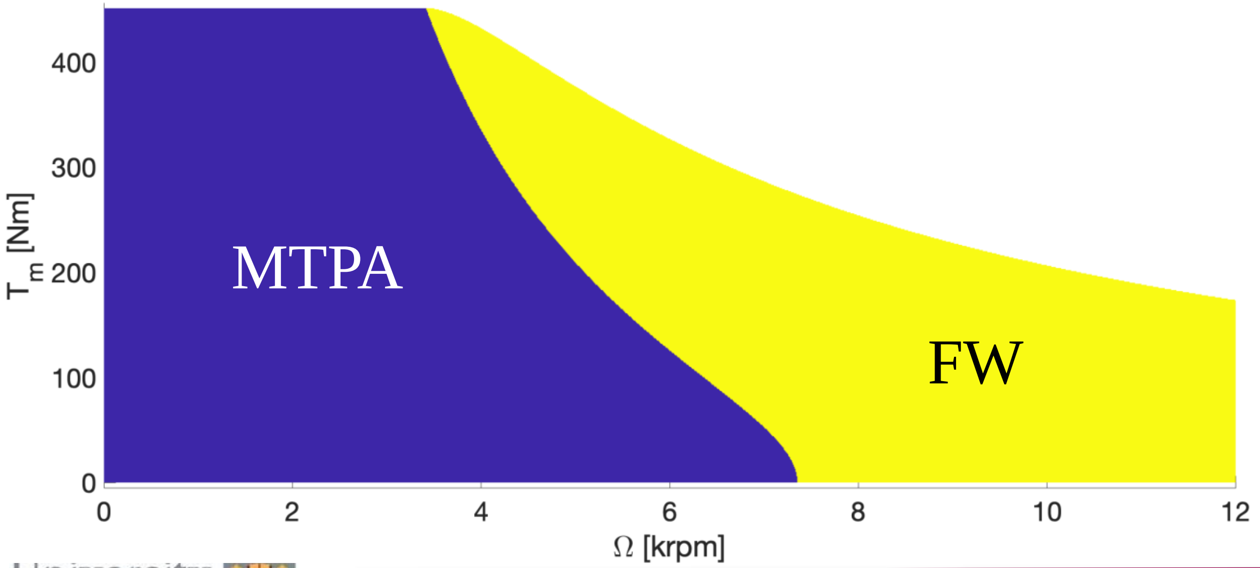

constant torque [Nm] loci

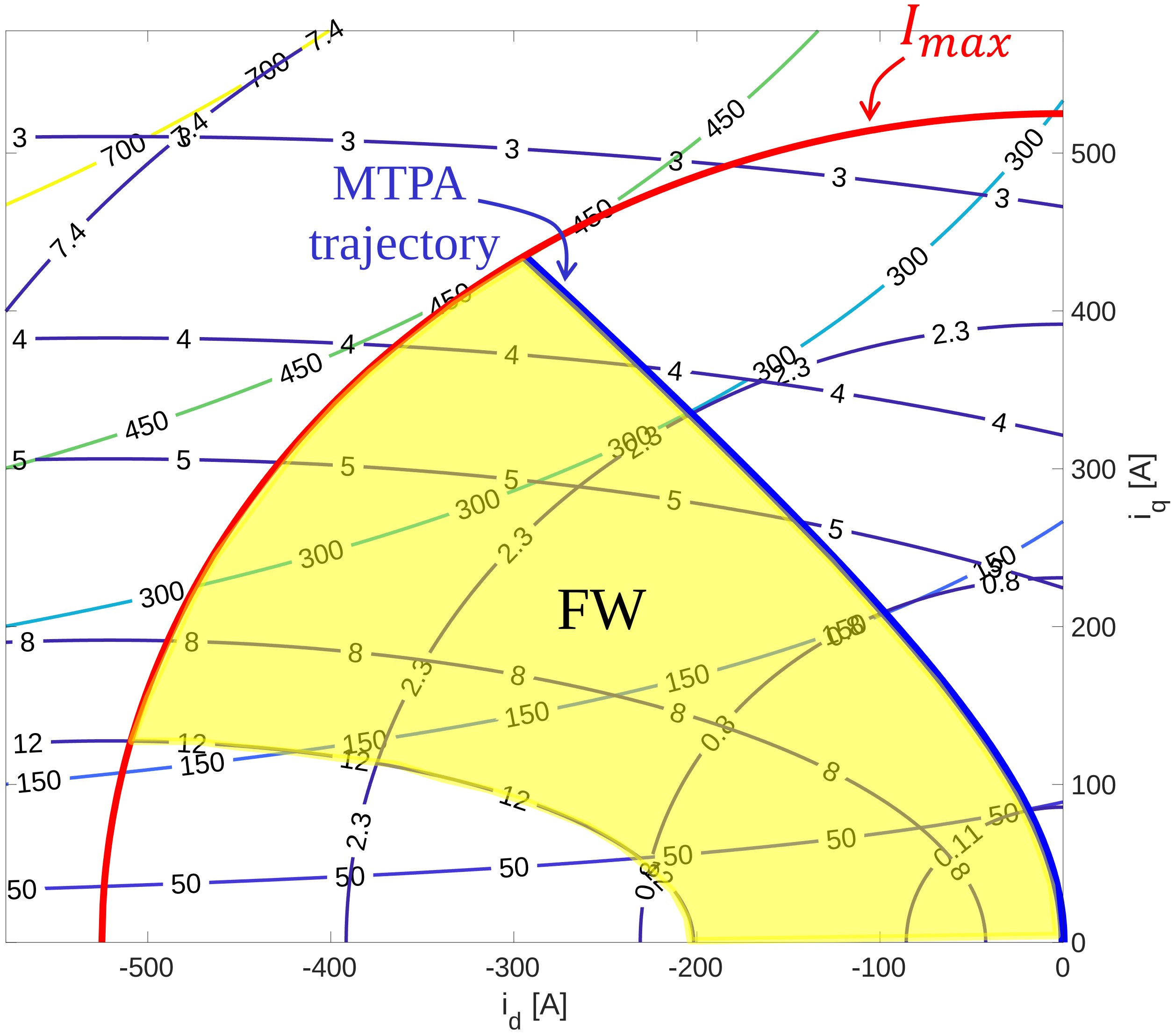

voltage limit ellipses as function of speed [krpm]



Maximum Torque Per Ampere (MTPA) and Flux-Weakening (FW)

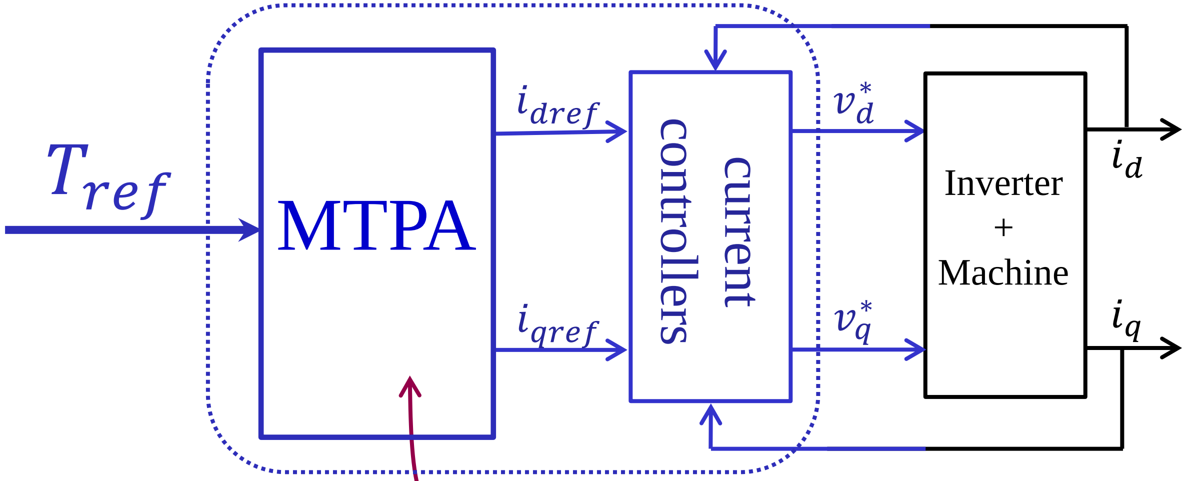




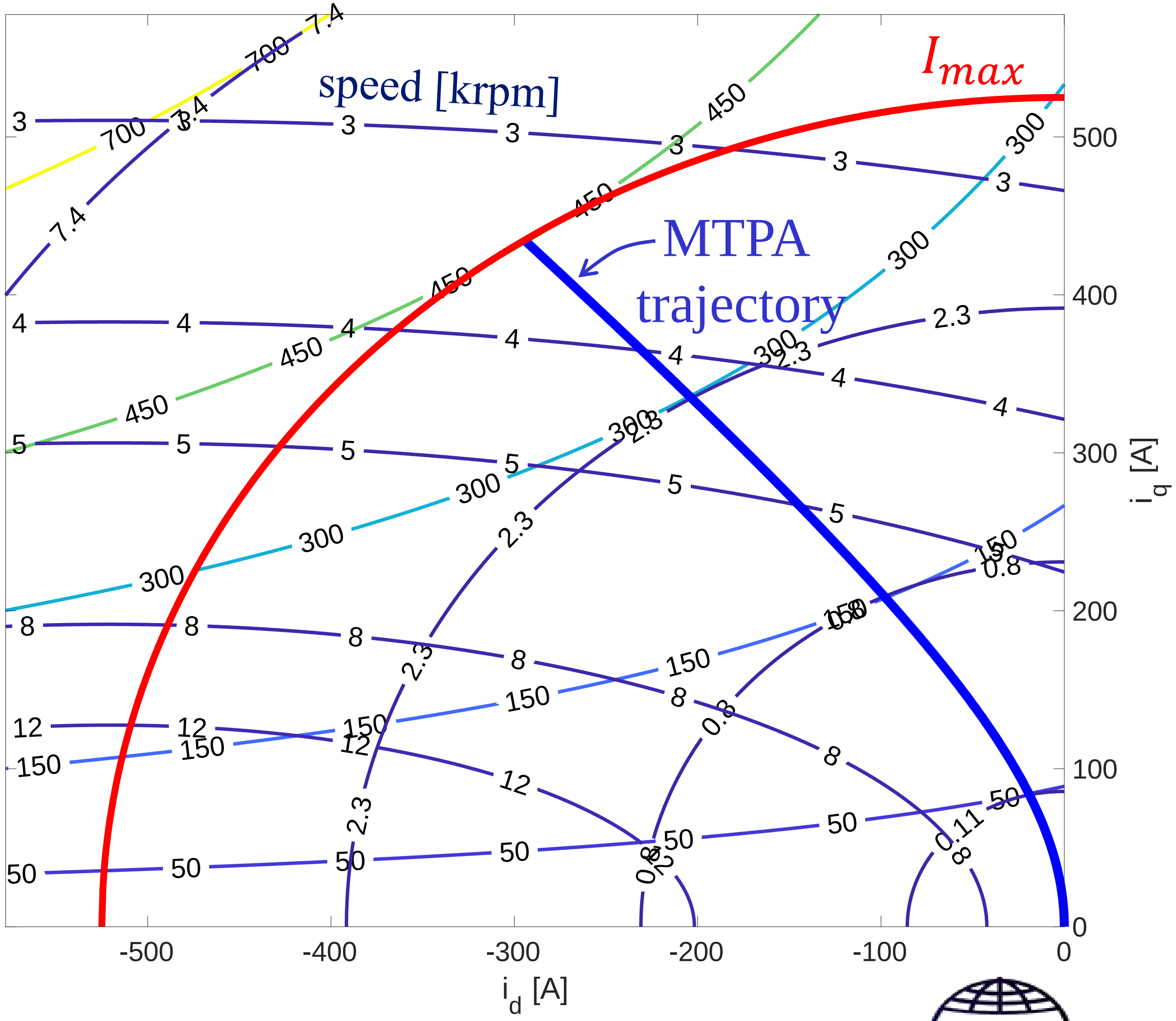


Adjustable Speed Drives: Torque Control Strategy

Indirect Torque Control:

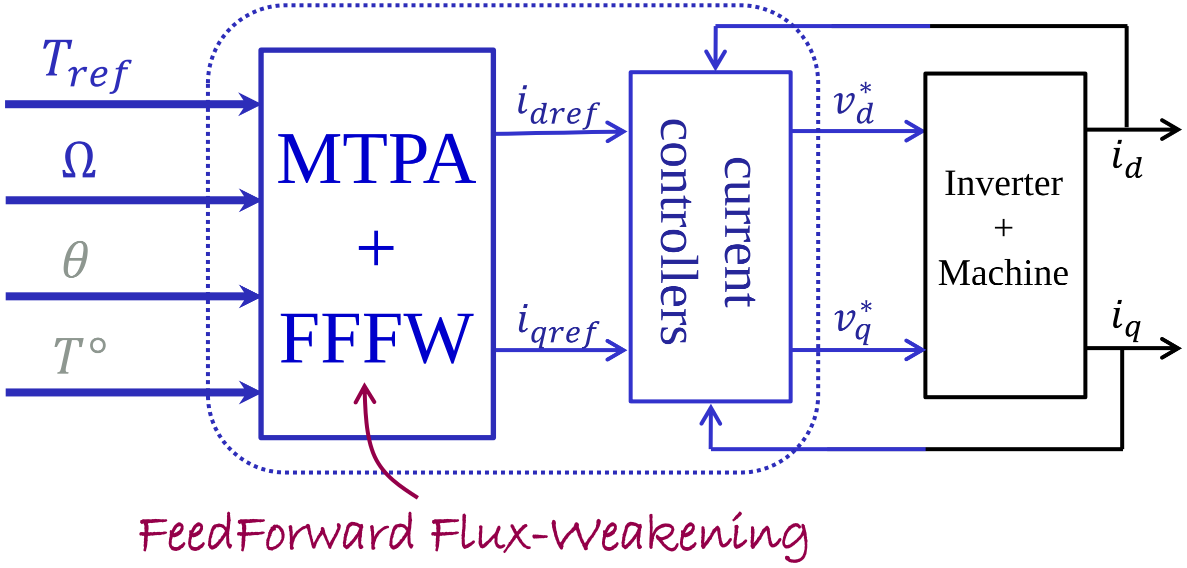


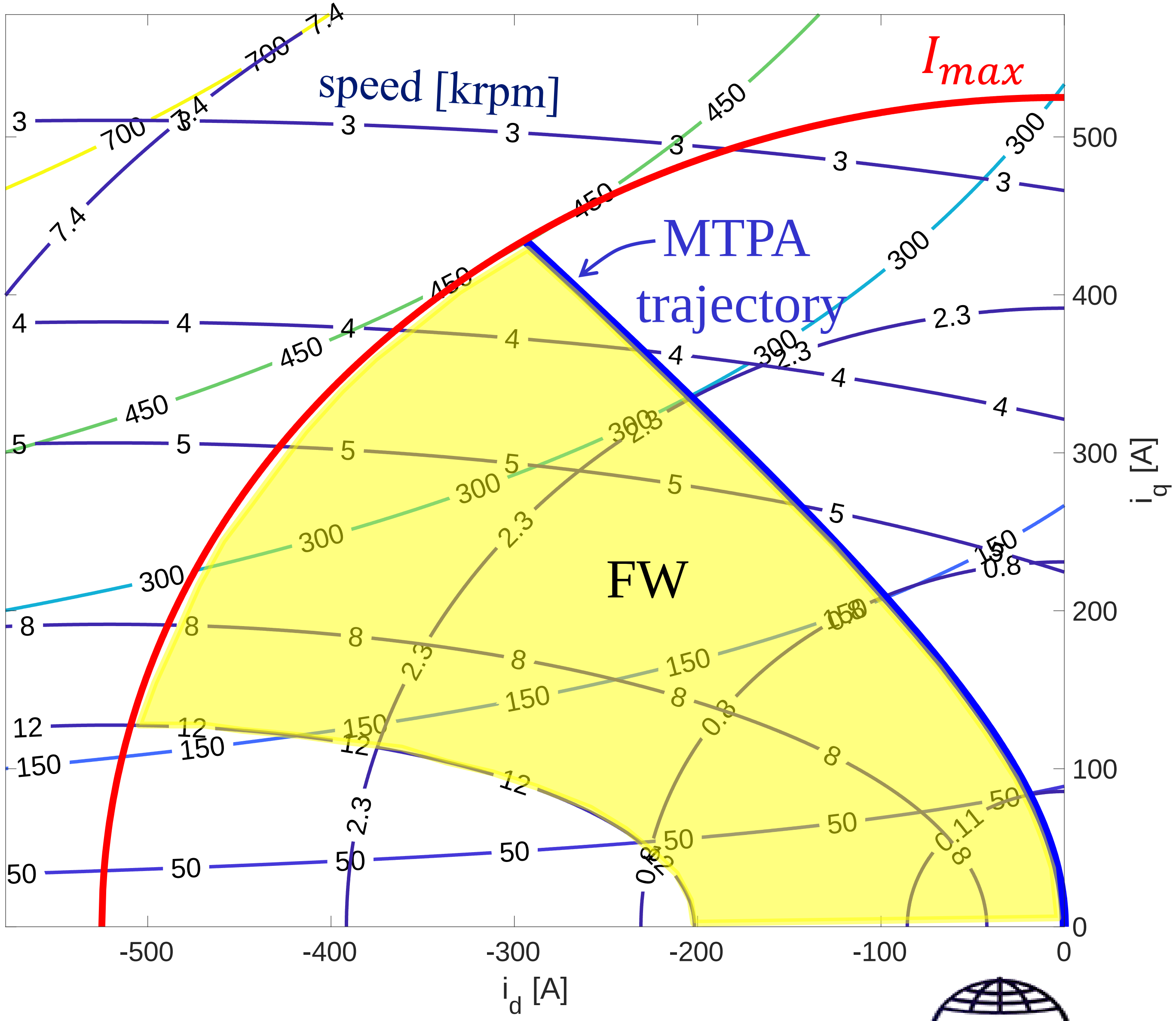
Look-Up Table (LUT) for Maximum Torque Per Ampere (MTPA)



Adjustable Speed Drives: Torque Control Strategy + FW

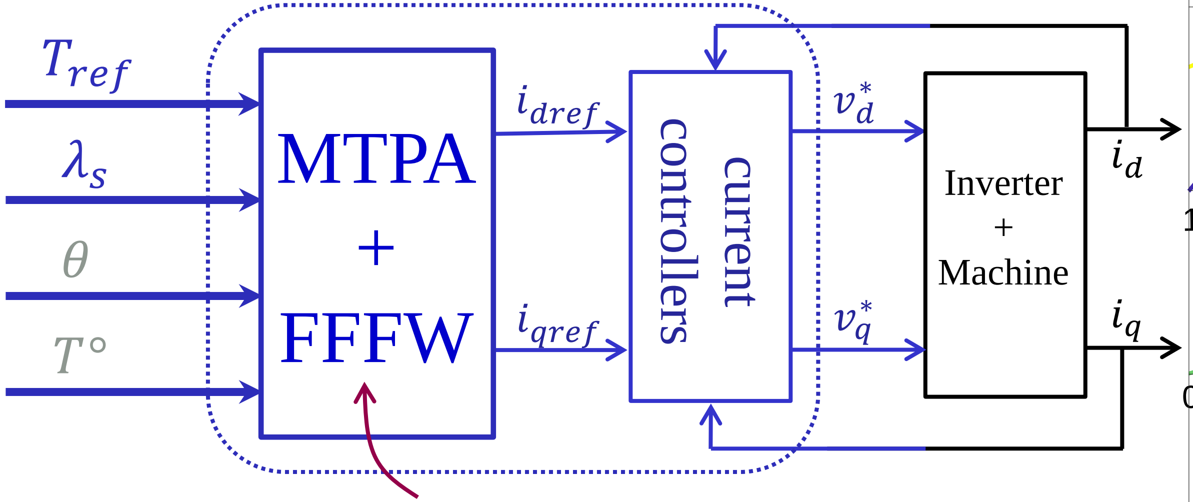
Indirect Torque Control:





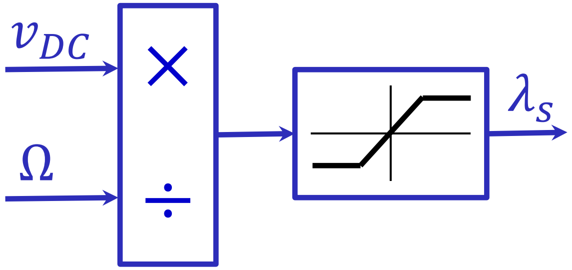
Adjustable Speed Drives: Torque Control Strategy + FW

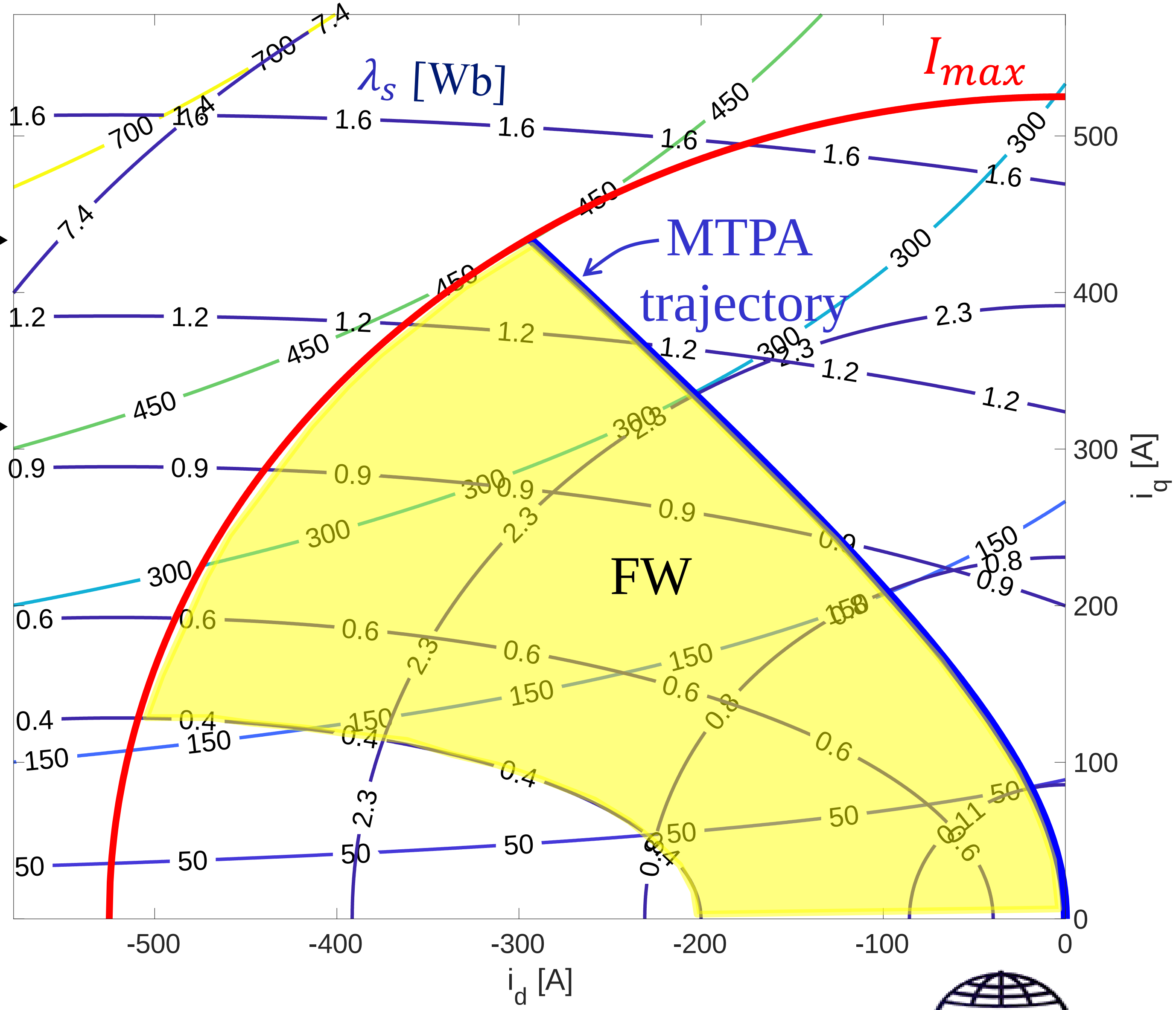
Indirect Torque Control:



FeedForward Flux-Weakening

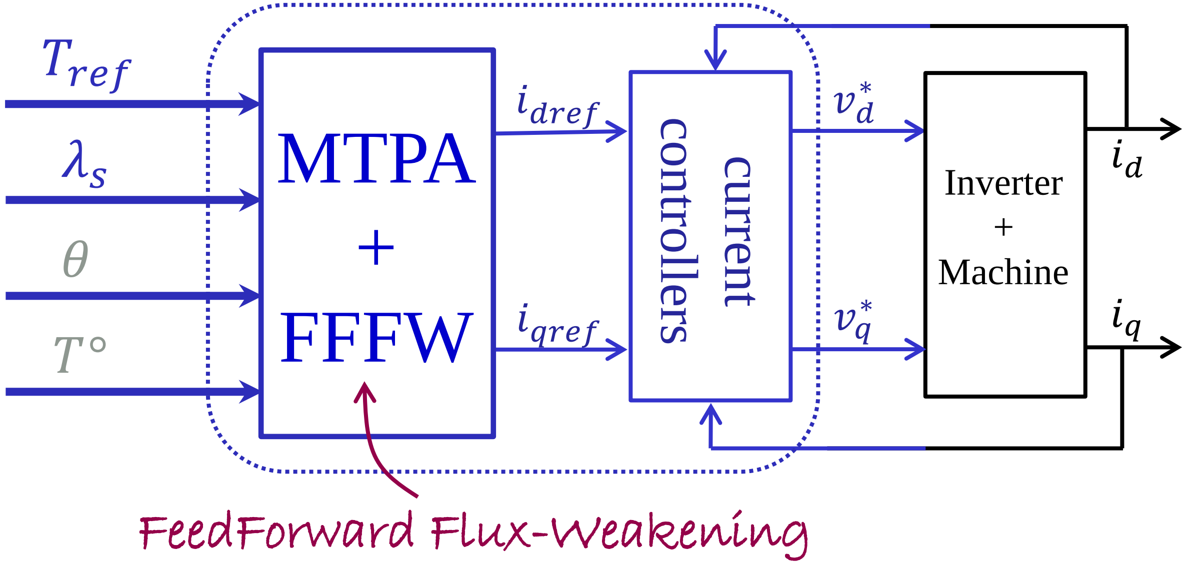
Advantage: Taking v_{DC} into account





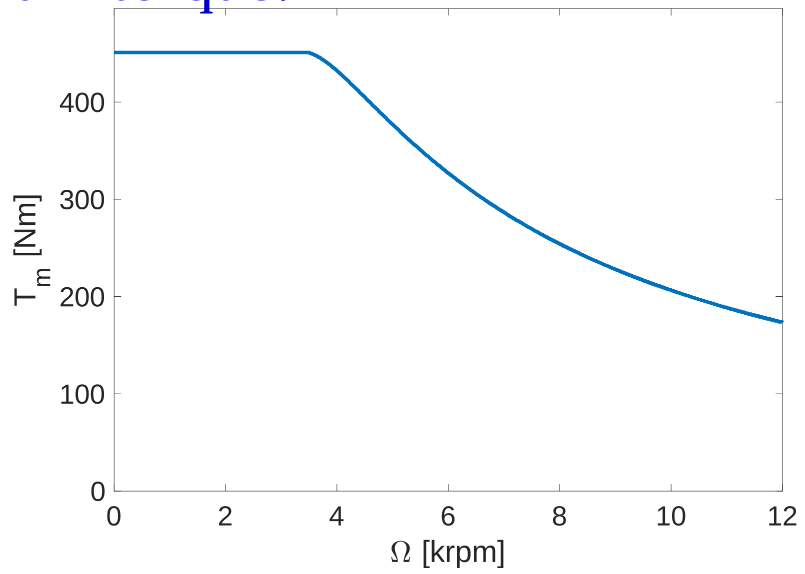
Adjustable Speed Drives: Torque Control Strategy + FW

Indirect Torque Control:

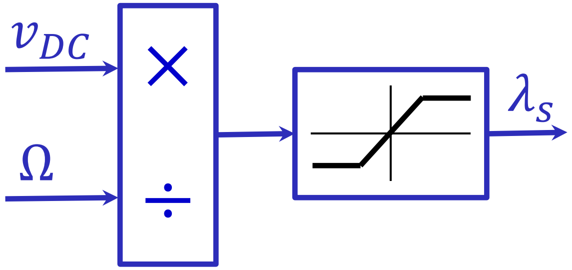


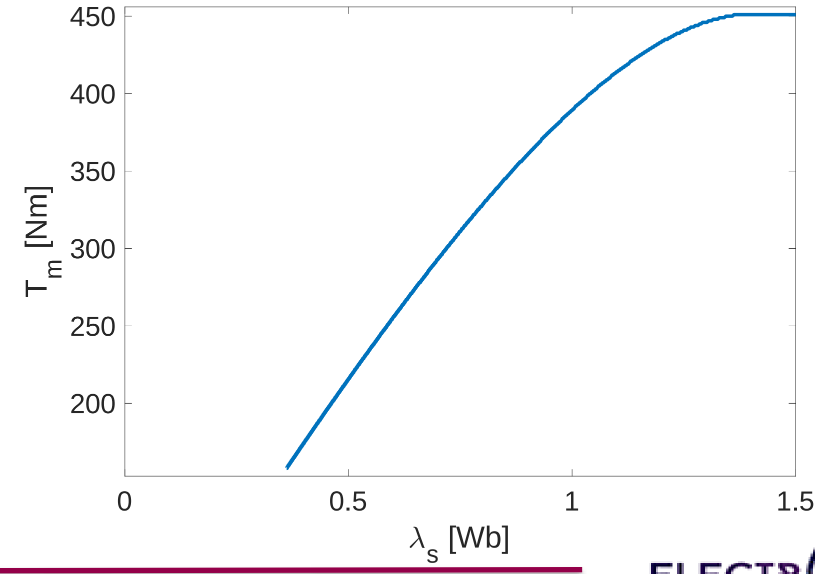
FeedForward Flux-Weakening

Maximum torque:



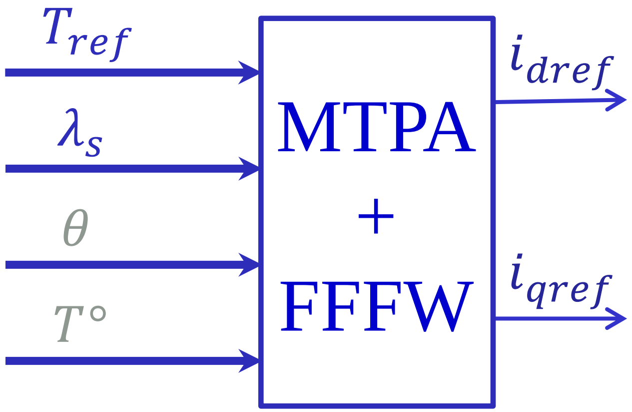
Advantage: Taking v_{DC} into account





Torque Control Strategy + FW: Current References

Look-UP Table (LUT) for torque control:



T_{ref}

λ_s

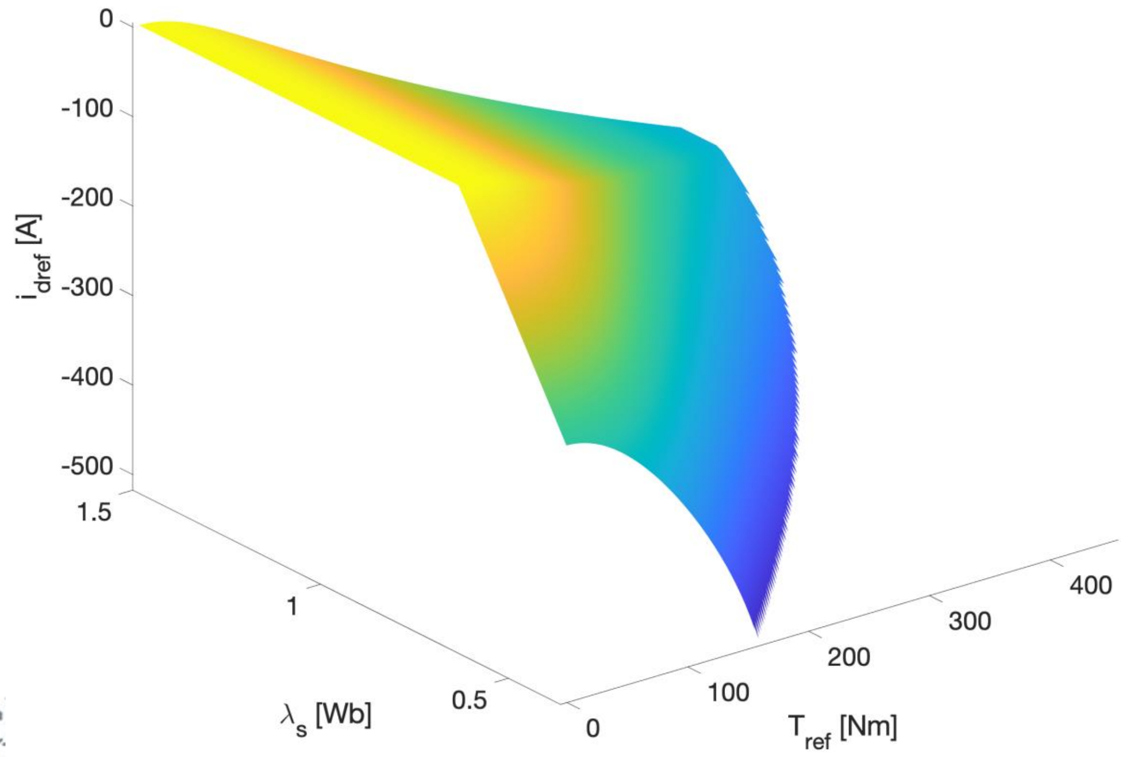
θ

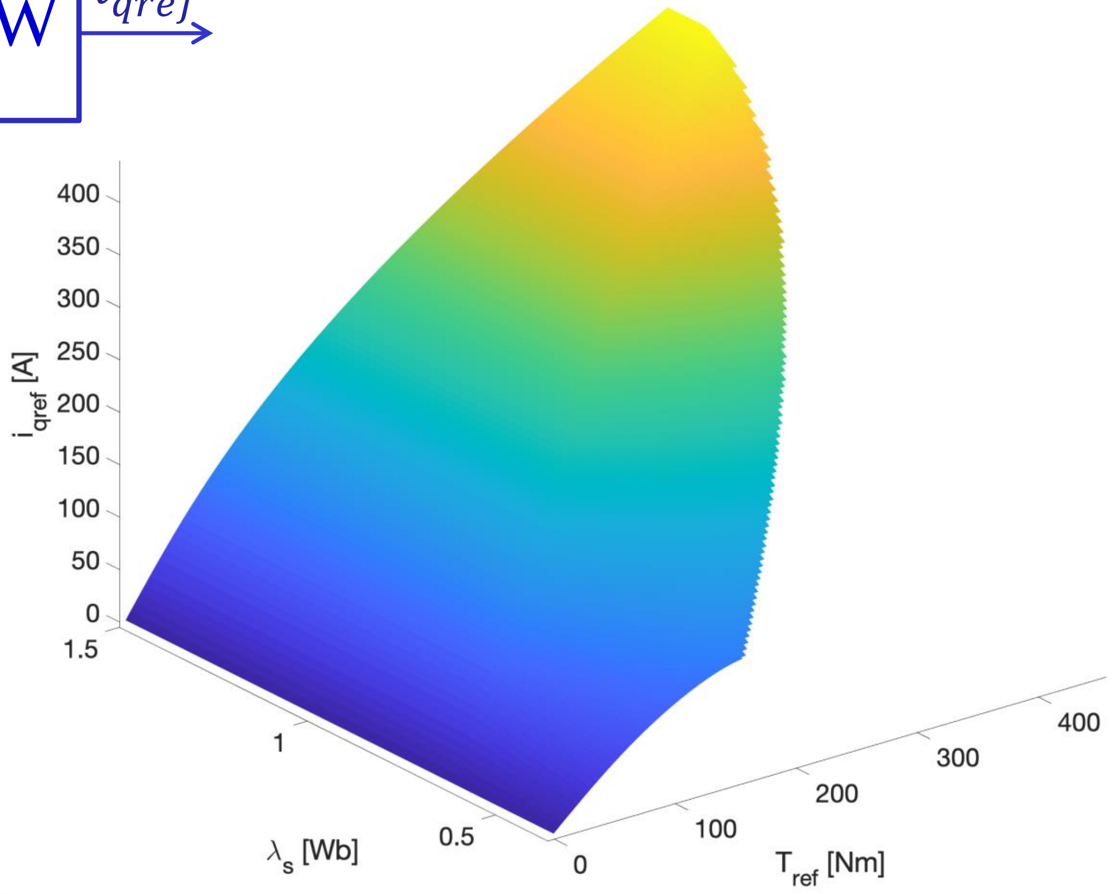
T°

MTPA + FFFW

i_{dref}

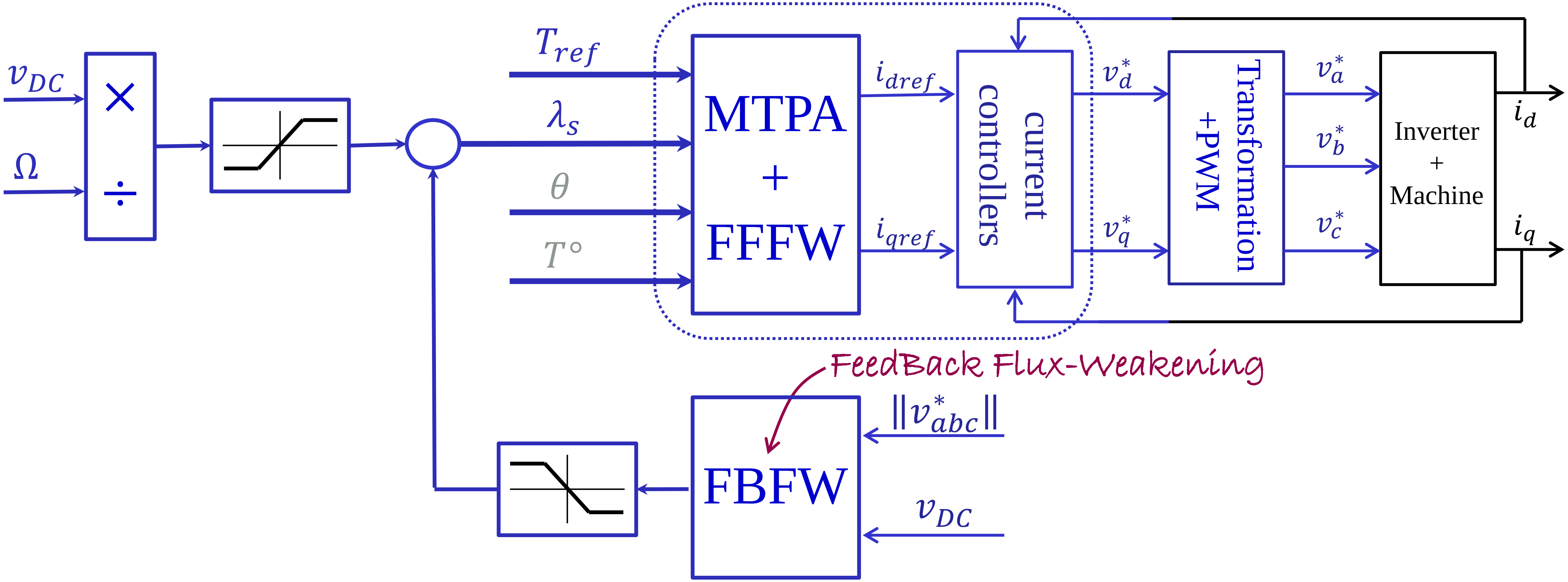
i_{qref}





Adjustable Speed Drives: Feedback Flux-Weakening

Torque Control Strategy:



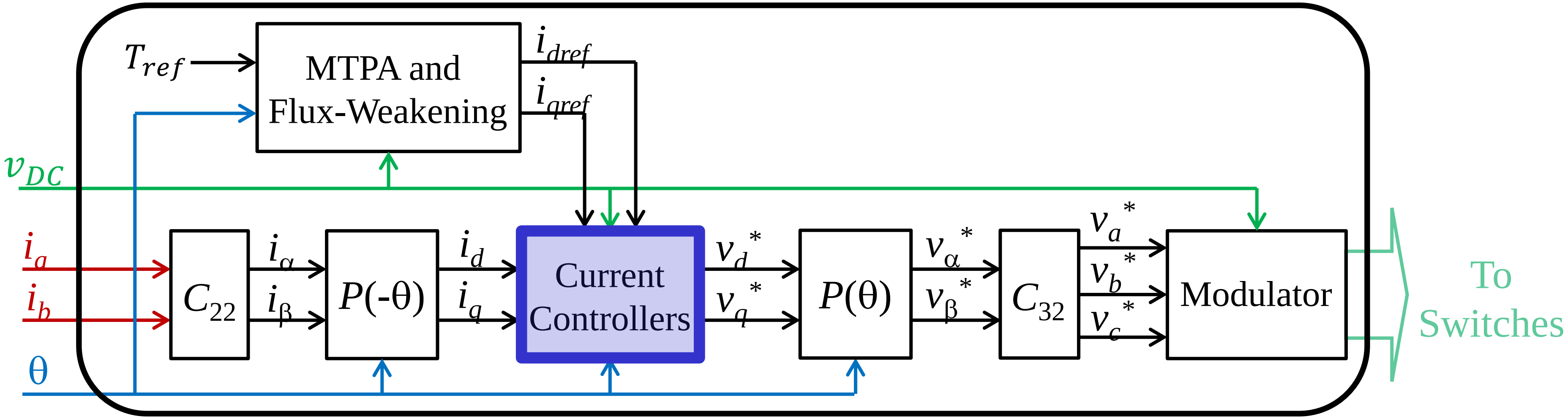
Advantage: Improvement of robustness with respect to model uncertainties

Challenges: Tuning of FBFW, anti wind-up if integral action, fast dynamic

Electric Motor Torque Control for Electrified Transportation Systems

Indirect Torque Control: Torque control through current control

- **Advantage:** smooth current (so torque) control
- **Challenges:** accurate model, DC-link voltage utilization, efficiency, sensorless control (cost/reliability)
- **Requirements:** look-up tables (or functions) relating torque to currents in MTPA and FW regions, <u>current controllers</u>

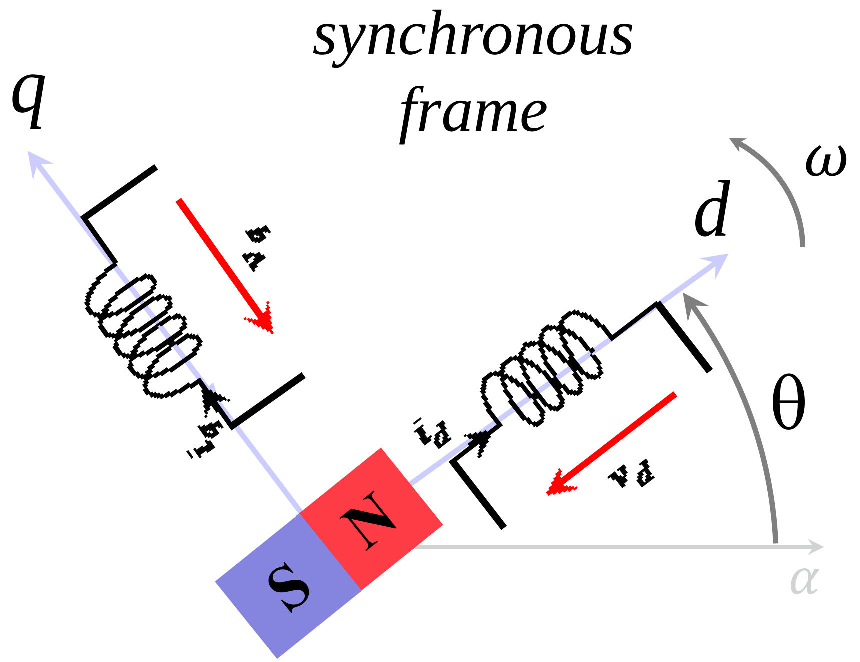


Current Control

Current Control: PMSM Model

Park model of PMSM:

$$\begin{bmatrix} v_d^* \\ v_q^* \end{bmatrix} = R_s \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \omega \cdot \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} \Delta v_d \\ \Delta v_q \end{bmatrix}$$



with: $\begin{cases} \psi_d = L_d(i_d, i_q, \theta, T°) \cdot i_d + \Psi_f(i_d, i_q, \theta, T°) \\ \psi_q = L_q(i_d, i_q, \theta, T°) \cdot i_q \end{cases}$

and inverter nonlinearities: $\begin{cases} \Delta v_d = \Delta V \cdot f_d\ (\theta) \\ \Delta v_q = \Delta V \cdot f_q\ (\theta) \end{cases}$

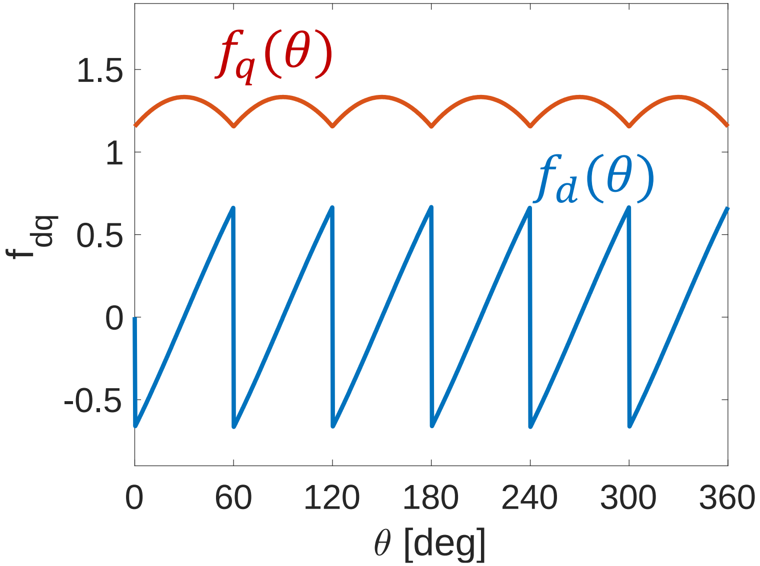
Motor torque (Clarke transformation):

$$T_m = \frac{3}{2} \cdot P \cdot \left(\psi_d \cdot i_q - \psi_q \cdot i_d\right) = \frac{3}{2} \cdot P \cdot \left[\Psi_f + (L_d - L_q) \cdot i_d\right] \cdot i_q$$

Current Control: PMSM Model

Modeling: voltage drops in the inverter

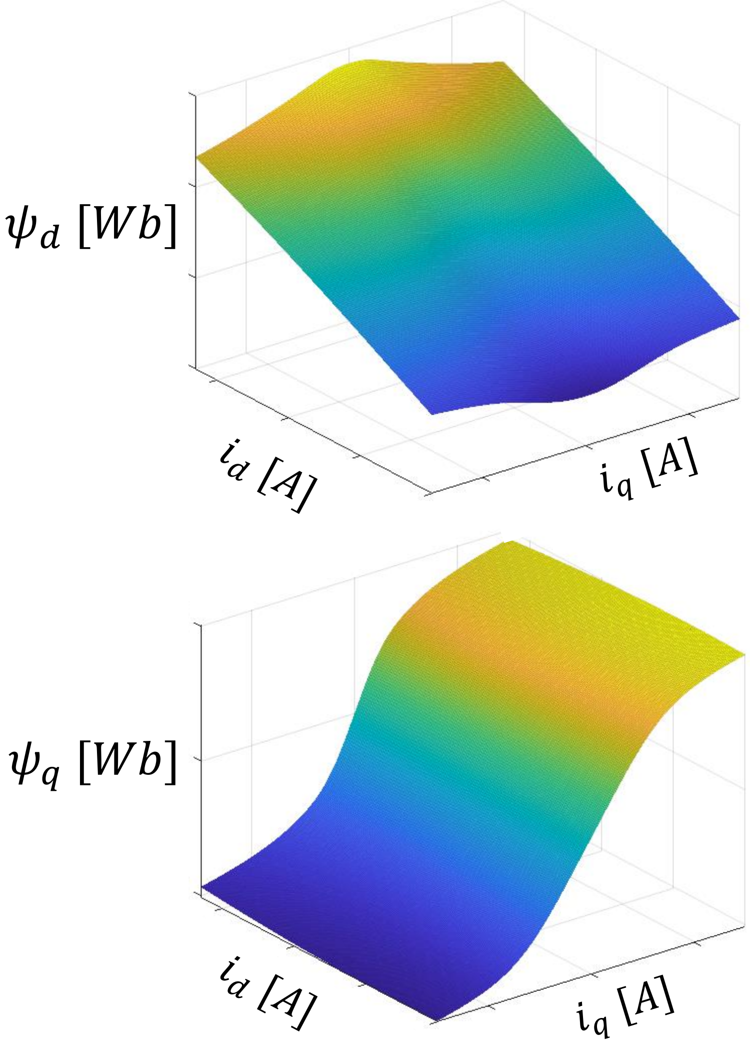
$$\begin{cases}\Delta v_d = \Delta V \cdot f_d\,(\theta)\\ \Delta v_q = \Delta V \cdot f_q\,(\theta)\end{cases}$$



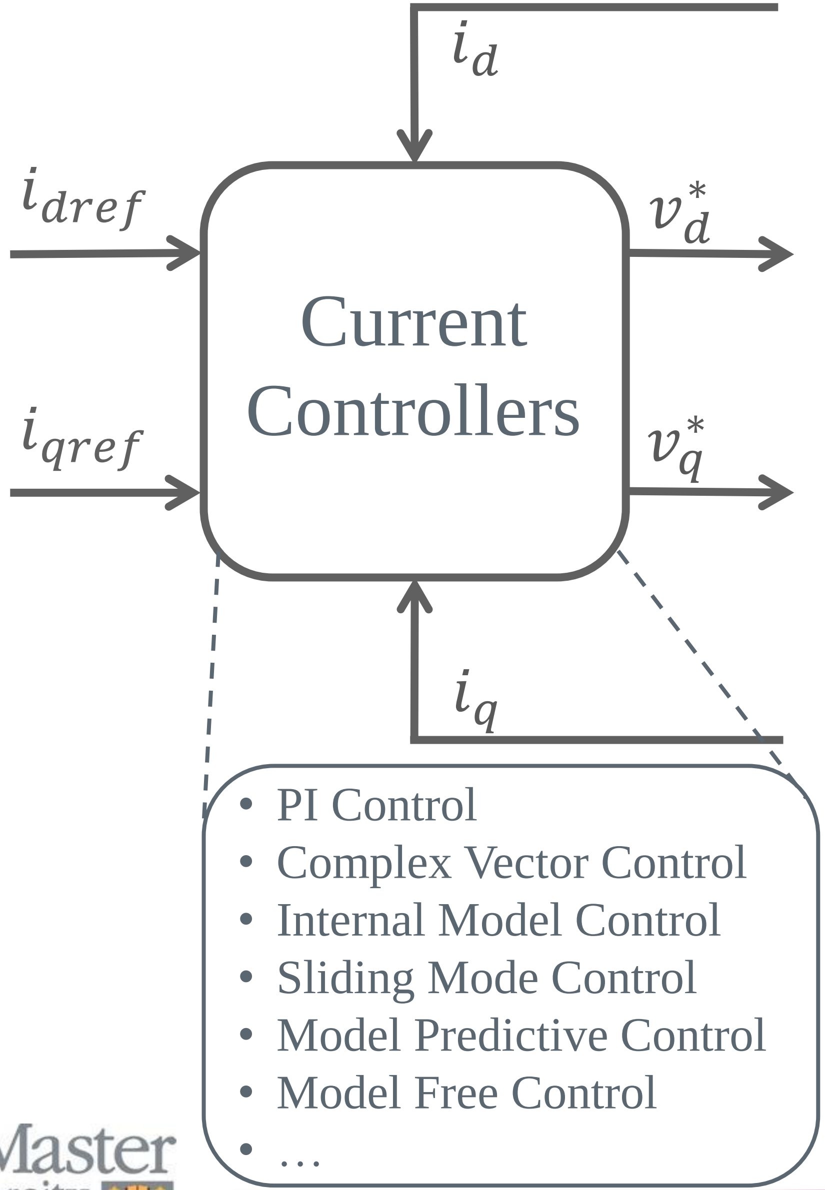
Self-commissioning:

- Estimation of R_s
- Estimation of ΔV
- Estimation of Ψ_f

Modeling: mapping flux linkages

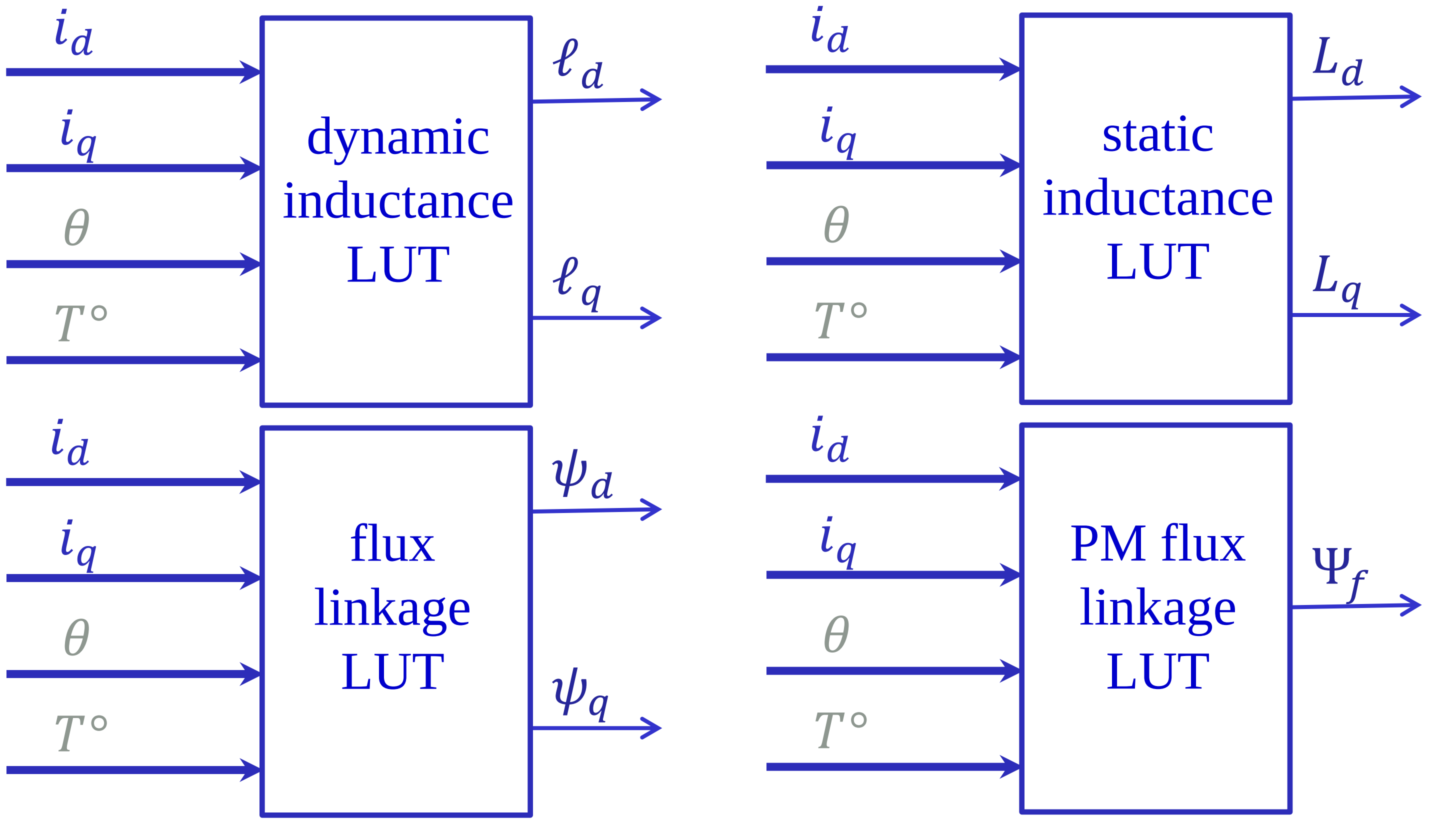


PMSM Current Control



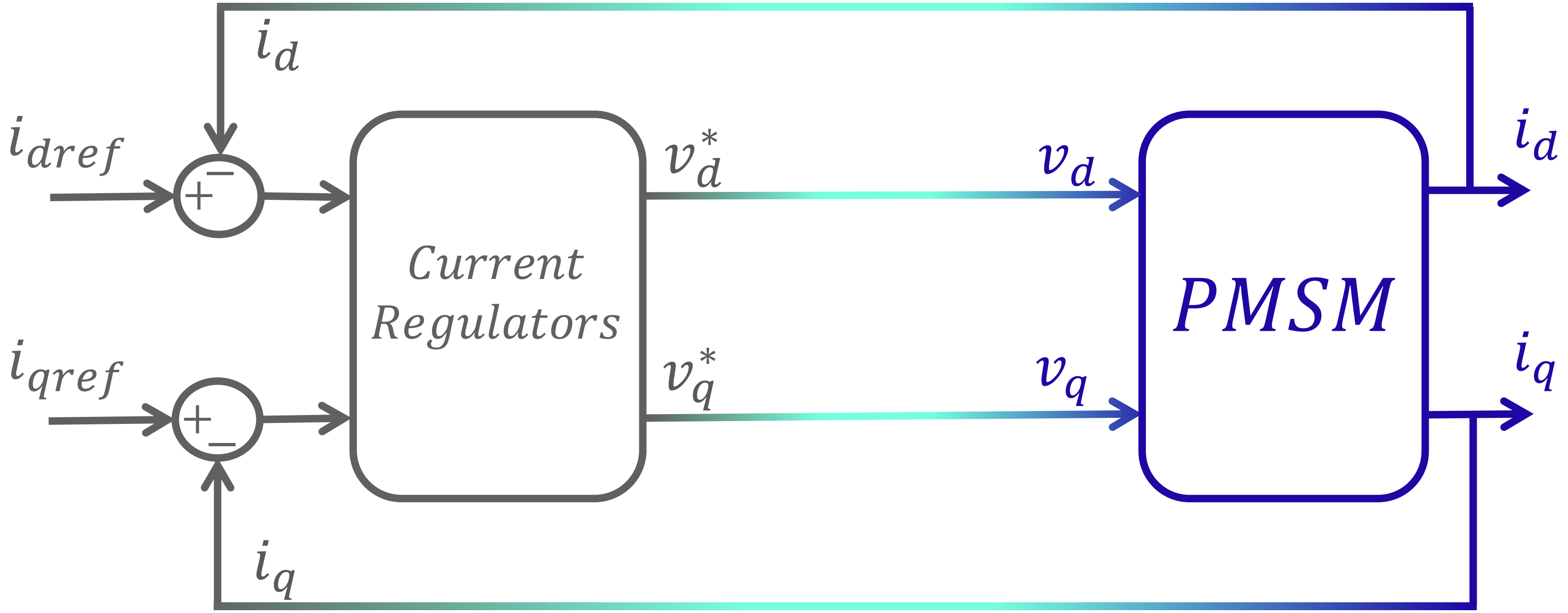
- PI Control
- Complex Vector Control
- Internal Model Control
- Sliding Mode Control
- Model Predictive Control
- Model Free Control
- …

Model-based control: available knowledge on the model under look-up table (LUT) form



Definition: $\ell_d = \frac{\partial \psi_d}{\partial i_d}$, $\ell_q = \frac{\partial \psi_q}{\partial i_q}$, $L_d = \frac{\psi_d - \Psi_f}{i_d}$, $L_q = \frac{\psi_q}{i_q}$

PMSM Current Control: Design and Analysis



Current control objectives:

- Zero steady-state error: $\lim_{t\to\infty} i_{dq}(t) = i_{dq\,ref}$
- No overshoot (or overshoot < 5% ~ 10%)
- Requested response time t_r (in *ms*) or current (torque) control bandwidth (in Hz or rad/s)
- Fast set-point tracking with small tracking error

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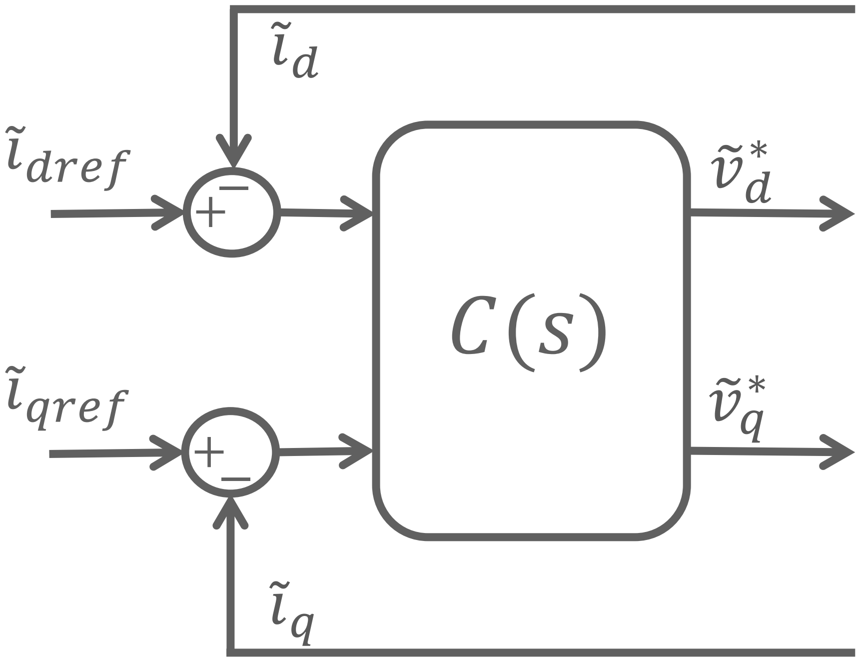
PI Current Control: Design

Current controller transfer function:

$$\begin{bmatrix}\tilde{v}_d^* \\ \tilde{v}_q^*\end{bmatrix} = C(s)\cdot\left\{\begin{bmatrix}\tilde{i}_{dref} \\ \tilde{i}_{qref}\end{bmatrix} - \begin{bmatrix}\tilde{i}_d \\ \tilde{i}_q\end{bmatrix}\right\}$$



Controller transfer function **without decoupling**:

$$C(s) = \begin{bmatrix} K_{pd}\dfrac{1+\tau_{id}\cdot s}{\tau_{id}\cdot s} & 0 \\ 0 & K_{pq}\dfrac{1+\tau_{iq}\cdot s}{\tau_{iq}\cdot s}\end{bmatrix}$$

$K_{id} = R_s \cdot \omega_{BWd}$

$K_{pd} = \ell_d \cdot \omega_{BWd}$

$\tau_{id} = K_{pd}/K_{id}$

desired bandwidth of d −current control loop

$K_{iq} = R_s \cdot \omega_{BWq}$

$K_{pq} = \ell_q \cdot \omega_{BWq}$

$\tau_{iq} = K_{pq}/K_{iq}$

desired bandwidth of q − current control loop

PI Current Control: Analysis

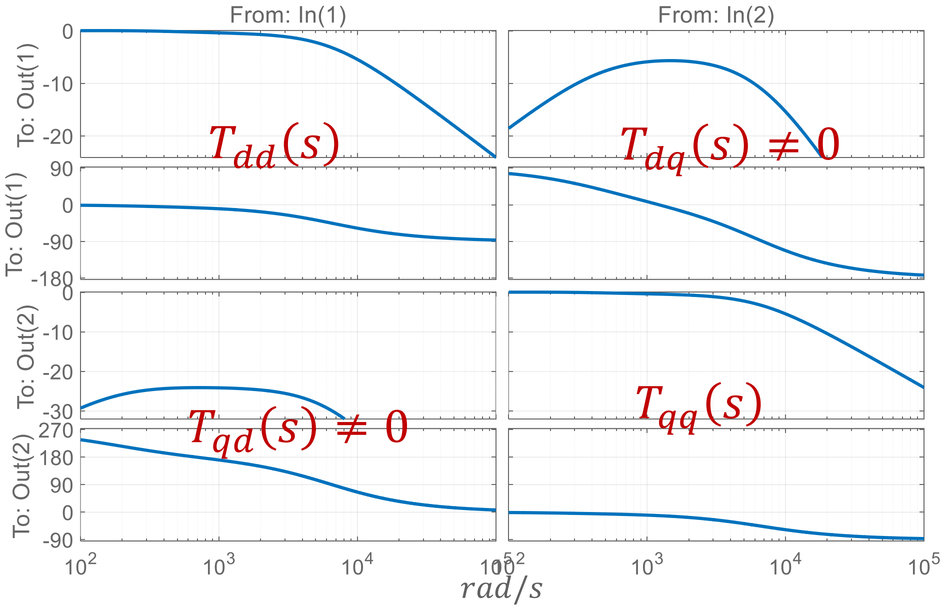
Closed-loop transfer function: **without decoupling**

$$\begin{bmatrix}\tilde{\imath}_d\\ \tilde{\imath}_q\end{bmatrix} = [I + Y(s)\cdot C(s)]^{-1}\cdot Y(s)\cdot C(s)\cdot\begin{bmatrix}\tilde{\imath}_{dref}\\ \tilde{\imath}_{qref}\end{bmatrix} = \begin{bmatrix}T_{dd}(s) & T_{dq}(s)\\ T_{qd}(s) & T_{qq}(s)\end{bmatrix}\cdot\begin{bmatrix}\tilde{\imath}_{dref}\\ \tilde{\imath}_{qref}\end{bmatrix}$$

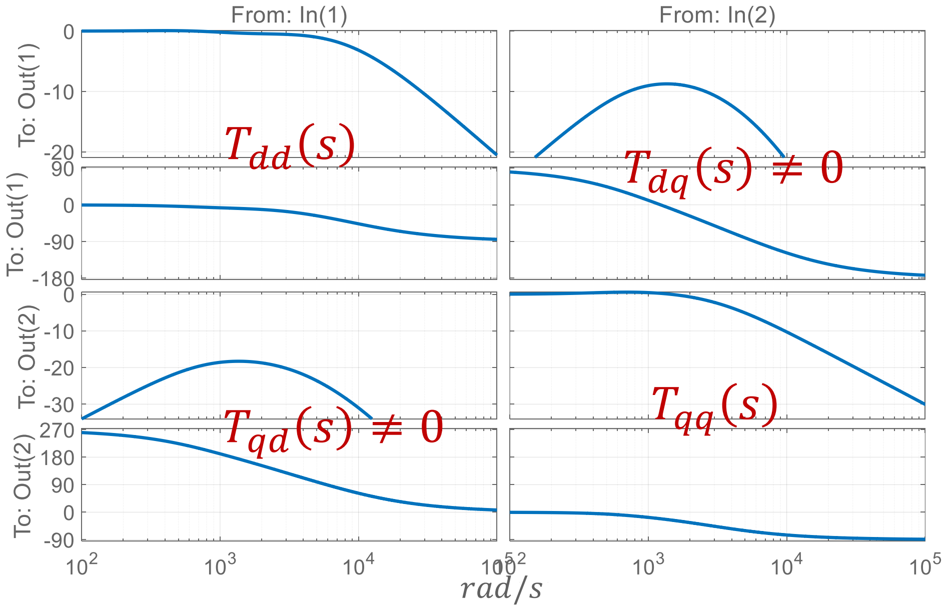
identity matrix

$$\Rightarrow\begin{cases}\tilde{\imath}_d = T_{dd}(s)\cdot\tilde{\imath}_{dref} + T_{dq}(s)\cdot\tilde{\imath}_{qref}\\ \tilde{\imath}_q = T_{qd}(s)\cdot\tilde{\imath}_{dref} + T_{qq}(s)\cdot\tilde{\imath}_{qref}\end{cases}$$

known model

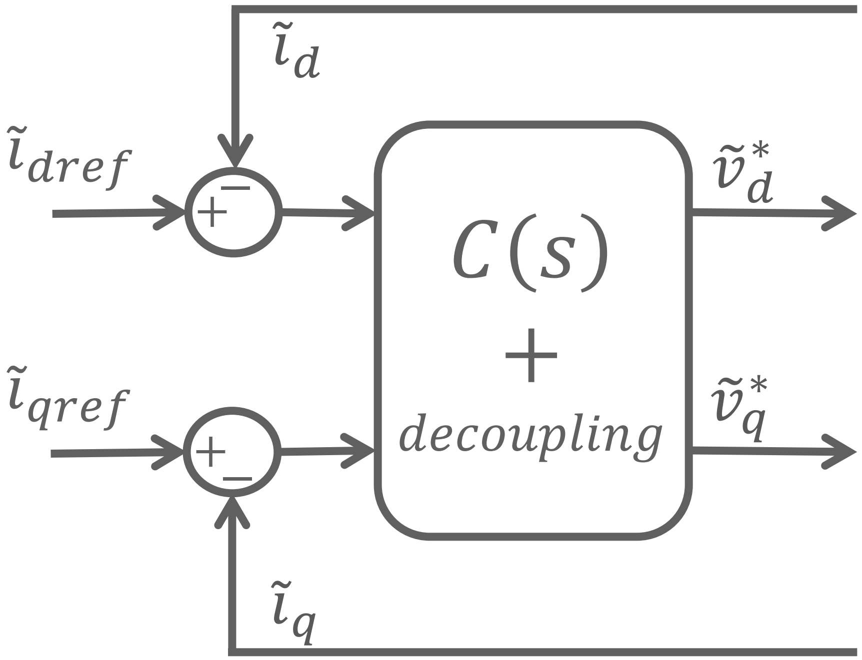


parameters uncertainty



PI Current Control + Feedforward Decoupling: Design

Current controller transfer function:



$$\begin{bmatrix}\tilde{v}_d^* \\ \tilde{v}_q^*\end{bmatrix} = C(s)\cdot\left\{\begin{bmatrix}\tilde{i}_{dref} \\ \tilde{i}_{qref}\end{bmatrix} - \begin{bmatrix}\tilde{i}_d \\ \tilde{i}_q\end{bmatrix}\right\}$$

$$K_{pd} = \ell_d \cdot \omega_{BWd} \qquad K_{pq} = \ell_q \cdot \omega_{BWq}$$

$$\tau_{id} = \ell_d / R_s \qquad \tau_{iq} = \ell_q / R_s$$

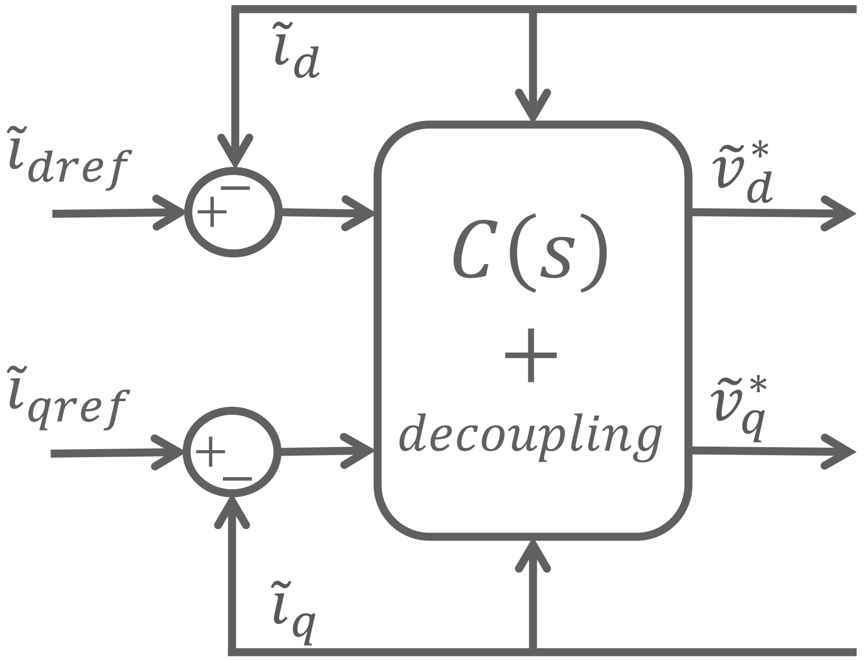
With **feedforward decoupling**, it yields:

$$C(s) = \begin{bmatrix} 1 & \dfrac{-L_q\omega}{R_s + L_q \cdot s} \\ \dfrac{L_d\omega}{R_s + L_d \cdot s} & 1 \end{bmatrix} \cdot \begin{bmatrix} K_{pd}\dfrac{1+\tau_{id}\cdot s}{\tau_{id}\cdot s} & 0 \\ 0 & K_{pq}\dfrac{1+\tau_{iq}\cdot s}{\tau_{iq}\cdot s} \end{bmatrix}$$

PI Current Control + Feedback Decoupling: Design

With **feedback decoupling**, it gives:

$$\begin{bmatrix} \tilde{v}_d^* \\ \tilde{v}_q^* \end{bmatrix} = C(s) \cdot \left\{ \begin{bmatrix} \tilde{\imath}_{dref} \\ \tilde{\imath}_{qref} \end{bmatrix} - \begin{bmatrix} \tilde{\imath}_d \\ \tilde{\imath}_q \end{bmatrix} \right\} + D \cdot \begin{bmatrix} \tilde{\imath}_d \\ \tilde{\imath}_q \end{bmatrix}$$



$$K_{pd} = \ell_d \cdot \omega_{BWd} \qquad K_{pq} = \ell_q \cdot \omega_{BWq}$$

$$\tau_{id} = \ell_d / R_s \qquad \tau_{iq} = \ell_q / R_s$$

with:

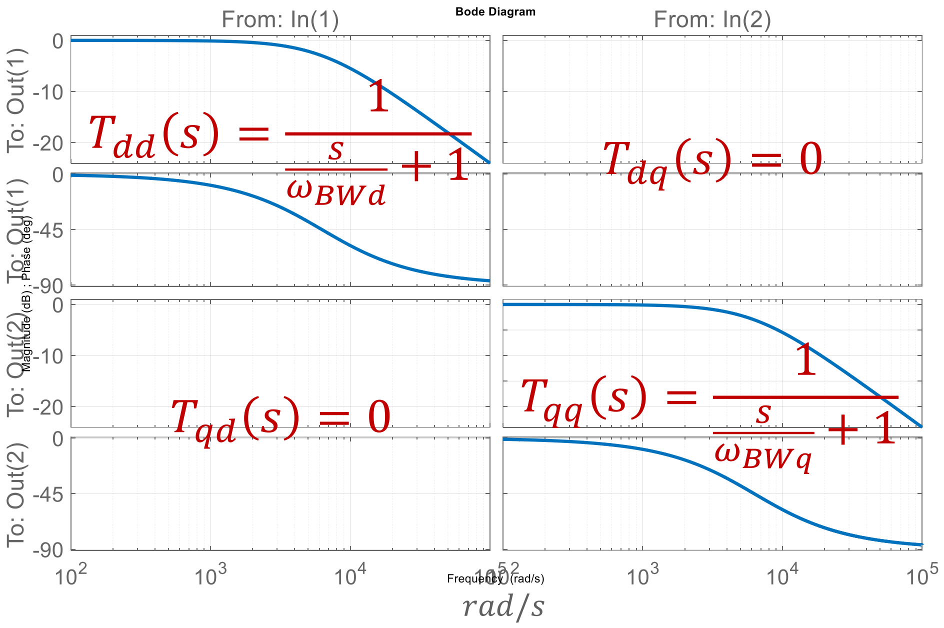
$$C(s) = \begin{bmatrix} K_{pd} \dfrac{1 + \tau_{id} \cdot s}{\tau_{id} \cdot s} & 0 \\ 0 & K_{pq} \dfrac{1 + \tau_{iq} \cdot s}{\tau_{iq} \cdot s} \end{bmatrix}, \qquad D = \begin{bmatrix} 0 & -L_q \omega \\ L_d \omega & 0 \end{bmatrix}$$

PI Current Control + Decoupling: Analysis

Closed-loop transfer function: **known parameters**

$$\begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} = \begin{bmatrix} T_{dd}(s) & 0 \\ 0 & T_{qq}(s) \end{bmatrix} \cdot \begin{bmatrix} \tilde{i}_{dref} \\ \tilde{i}_{qref} \end{bmatrix}$$

PI + **feedback decoupling**:



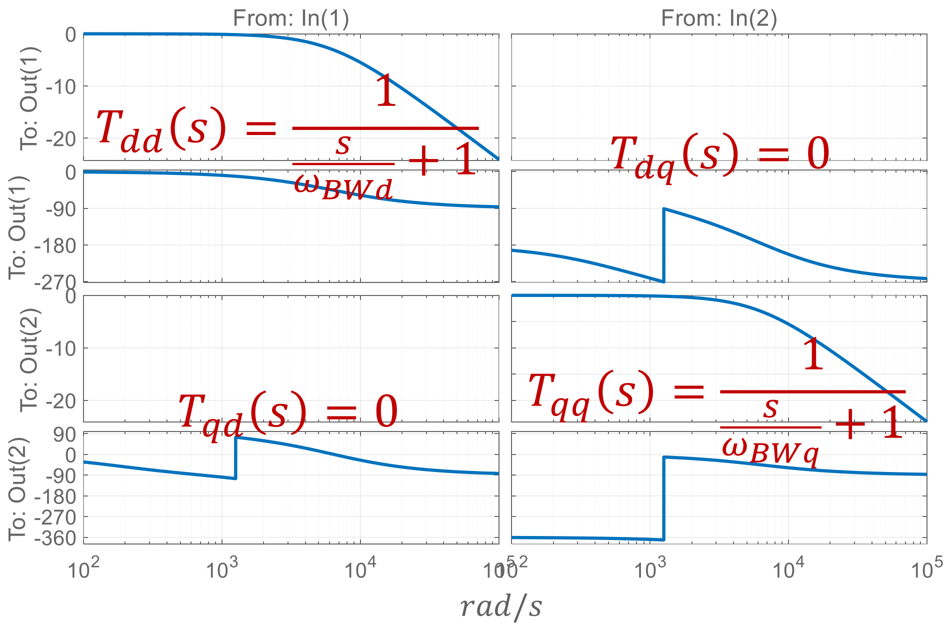
$$T_{dd}(s) = \frac{1}{\frac{s}{\omega_{BWd}} + 1}$$

$$T_{dq}(s) = 0$$

$$T_{qd}(s) = 0$$

$$T_{qq}(s) = \frac{1}{\frac{s}{\omega_{BWq}} + 1}$$

PI + **feedforward decoupling**:



$$T_{dd}(s) = \frac{1}{\frac{s}{\omega_{BWd}} + 1}$$

$$T_{dq}(s) = 0$$

$$T_{qd}(s) = 0$$

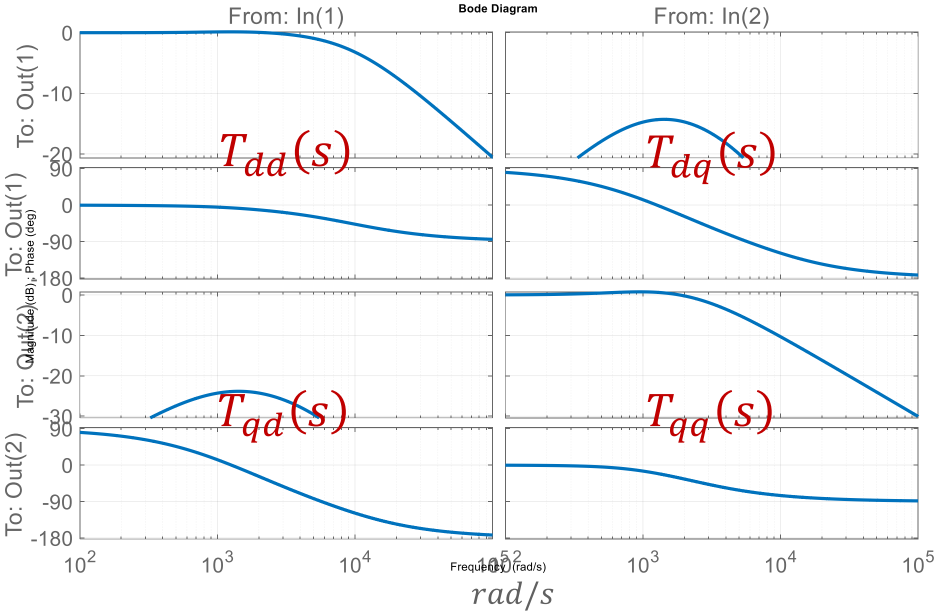
$$T_{qq}(s) = \frac{1}{\frac{s}{\omega_{BWq}} + 1}$$

PI Current Control + Decoupling: Analysis

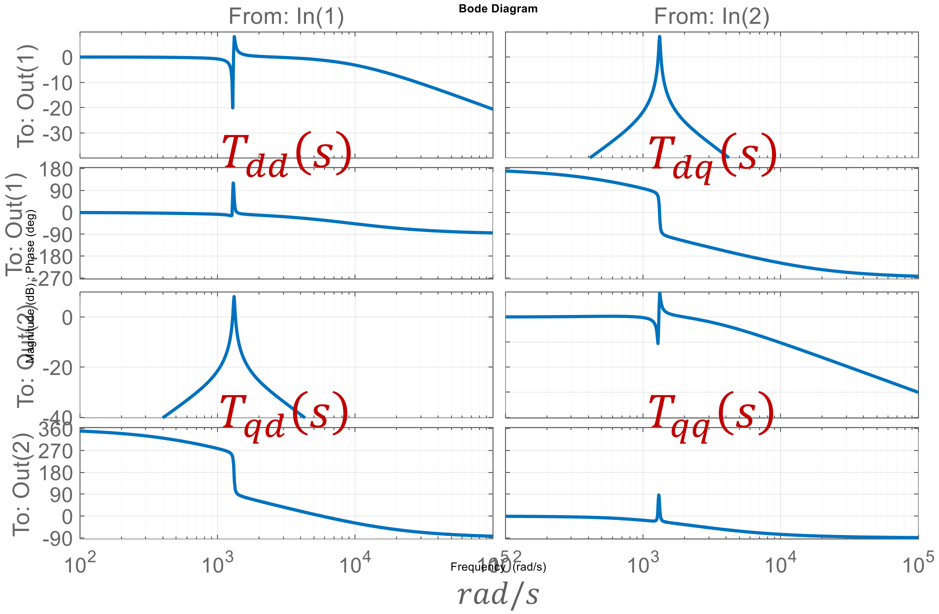
Closed-loop transfer function: **parameters uncertainty**

$$\begin{bmatrix}\tilde{\imath}_d \\ \tilde{\imath}_q\end{bmatrix} = \begin{bmatrix}T_{dd}(s) & T_{dq}(s) \\ T_{qd}(s) & T_{qq}(s)\end{bmatrix} \cdot \begin{bmatrix}\tilde{\imath}_{dref} \\ \tilde{\imath}_{qref}\end{bmatrix}$$

PI + **feedback decoupling**:



PI + **feedforward decoupling**:



Complex Vector Current Control: Design

Current controller transfer function:

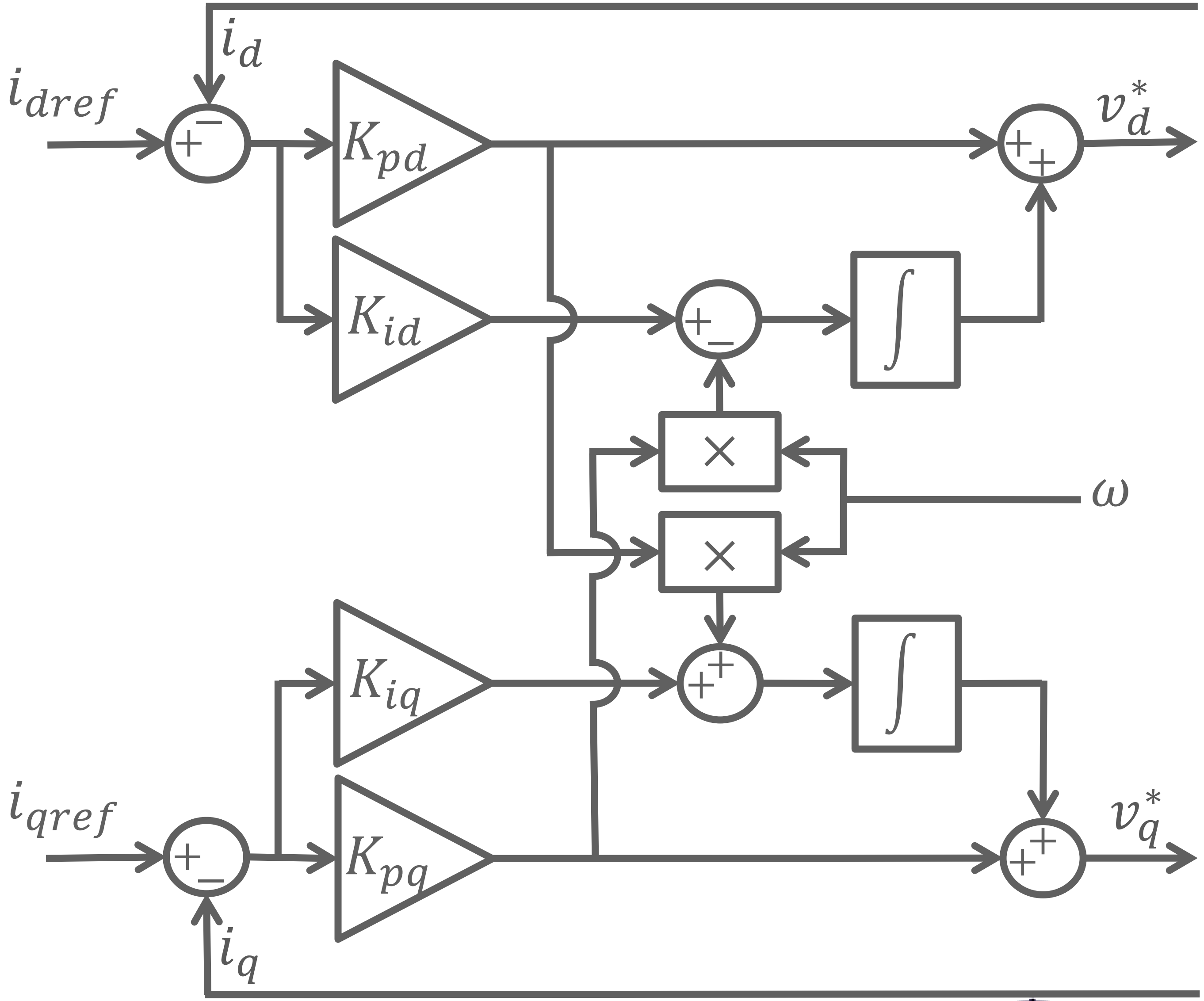
$$\begin{bmatrix}\tilde{v}_d^* \\ \tilde{v}_q^*\end{bmatrix} = C(s)\cdot\left\{\begin{bmatrix}\tilde{i}_{dref} \\ \tilde{i}_{qref}\end{bmatrix} - \begin{bmatrix}\tilde{i}_d \\ \tilde{i}_q\end{bmatrix}\right\}$$

$$K_{pd} = \ell_d \cdot \omega_{BWd} \qquad K_{pq} = \ell_q \cdot \omega_{BWq}$$

$$K_{id} = R_s \cdot \omega_{BWd} \qquad K_{iq} = R_s \cdot \omega_{BWq}$$

Transfer function of **complex vector current controller**:

$$C(s) = \begin{bmatrix} K_{pd}\dfrac{1+\tau_{id}\cdot s}{\tau_{id}\cdot s} & \dfrac{-K_{pq}\cdot\omega}{s} \\ \dfrac{K_{pd}\cdot\omega}{s} & K_{pq}\dfrac{1+\tau_{iq}\cdot s}{\tau_{iq}\cdot s} \end{bmatrix}$$

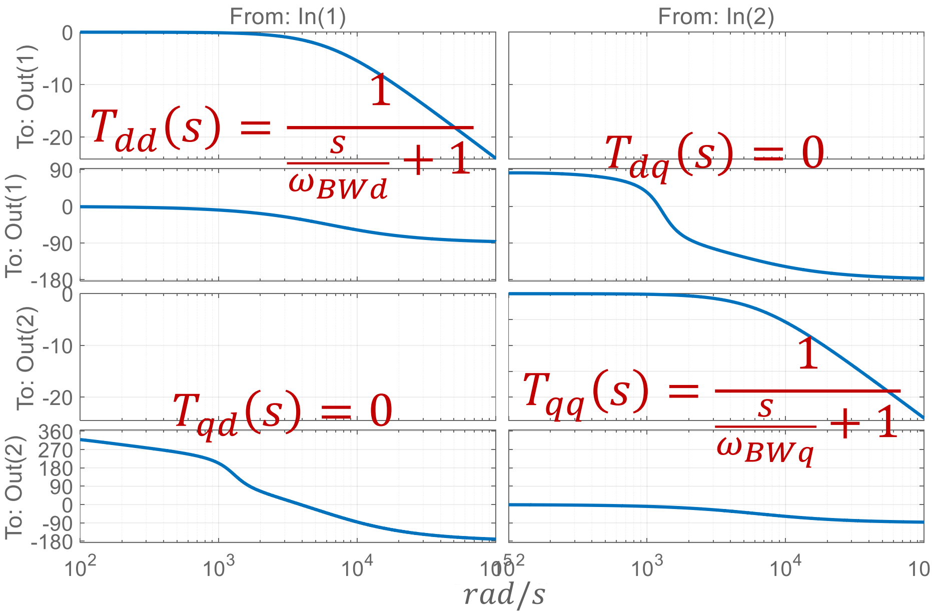


Complex Vector Current Control: Design

Improved PI controller: inherent decoupling

$$\begin{bmatrix}\tilde{i}_d\\ \tilde{i}_q\end{bmatrix}=\begin{bmatrix}T_{dd}(s) & T_{dq}(s)\\ T_{qd}(s) & T_{qq}(s)\end{bmatrix}\cdot\begin{bmatrix}\tilde{i}_{dref}\\ \tilde{i}_{qref}\end{bmatrix}$$

known parameters



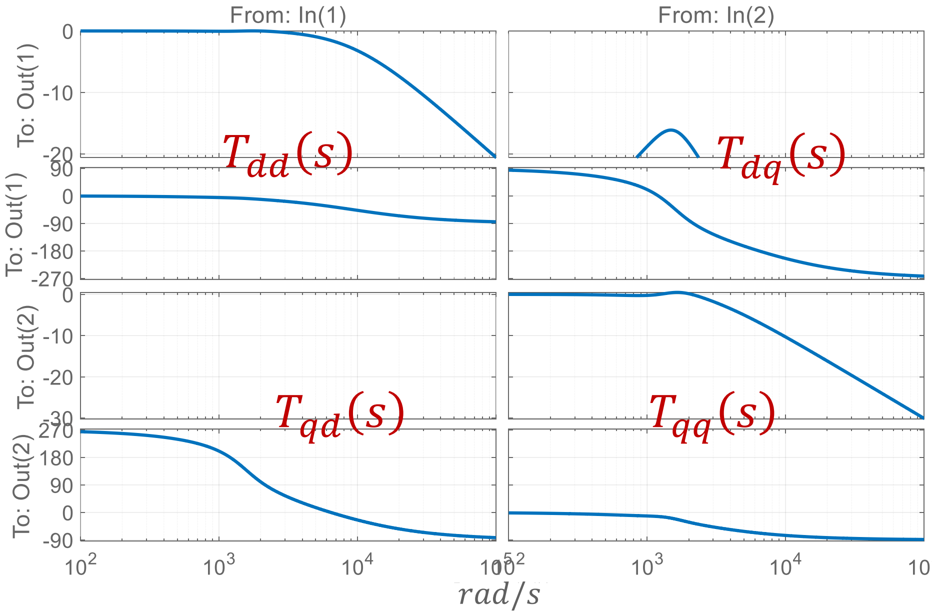
$$T_{dd}(s)=\frac{1}{\frac{s}{\omega_{BWd}}+1}$$

$$T_{dq}(s)=0$$

$$T_{qd}(s)=0$$

$$T_{qq}(s)=\frac{1}{\frac{s}{\omega_{BWq}}+1}$$

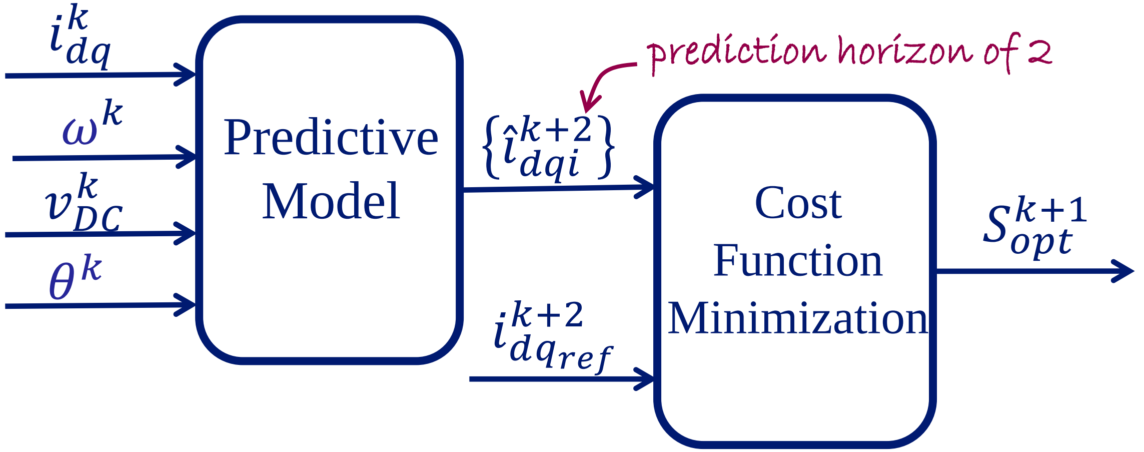
parameters uncertainty



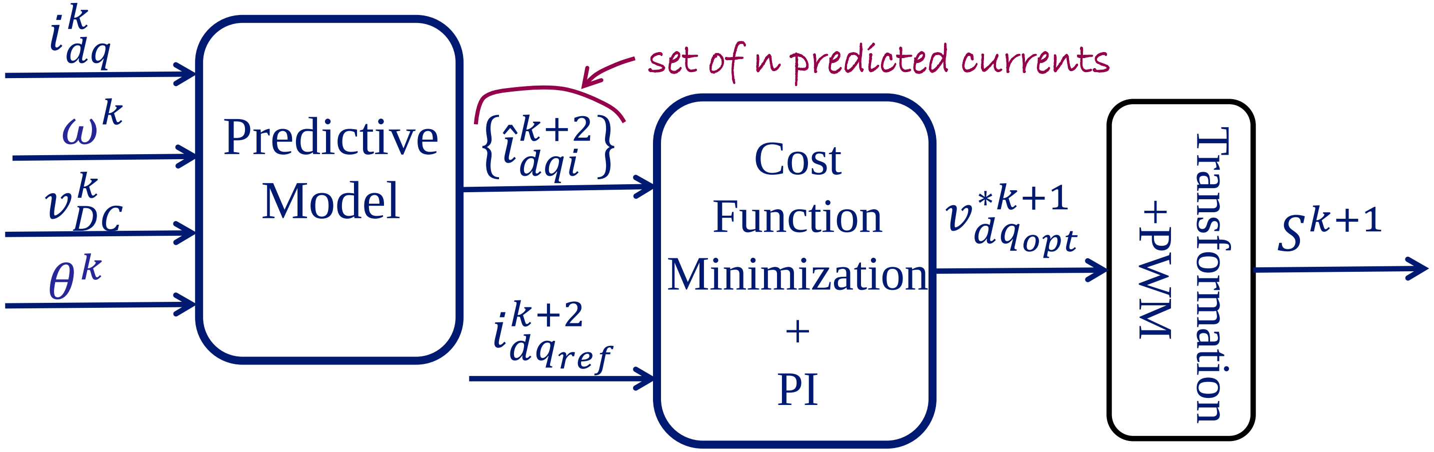
$T_{dd}(s)$ $T_{dq}(s)$ $T_{qd}(s)$ $T_{qq}(s)$

Model-Predictive Current Control: Design

Finite Control Set MPC (FCS-MPC):



Continuous Control Set MPC (CCS-MPC):



Predictive model using Euler discretization:

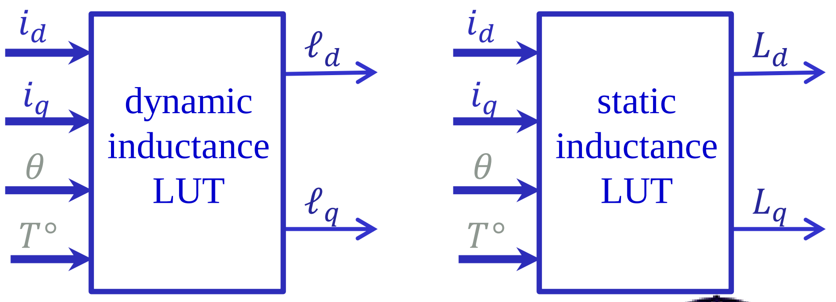
i^{th} predicted currents:

$$i_{di}^{k+1} = i_d^k + \frac{T_s}{\ell_d^k}\left(v_{di}^{*k} - R_s i_d^k + \omega^k L_q^k i_q^k - \Delta V f_d(\theta^k)\right)$$

$$i_{qi}^{k+1} = i_q^k + \frac{T_s}{\ell_q^k}\left(v_{qi}^{*k} - R_s i_q^k - \omega^k\left(L_d^k i_d^k + \Psi_f\right) - \Delta V f_q(\theta^k)\right)$$

with:

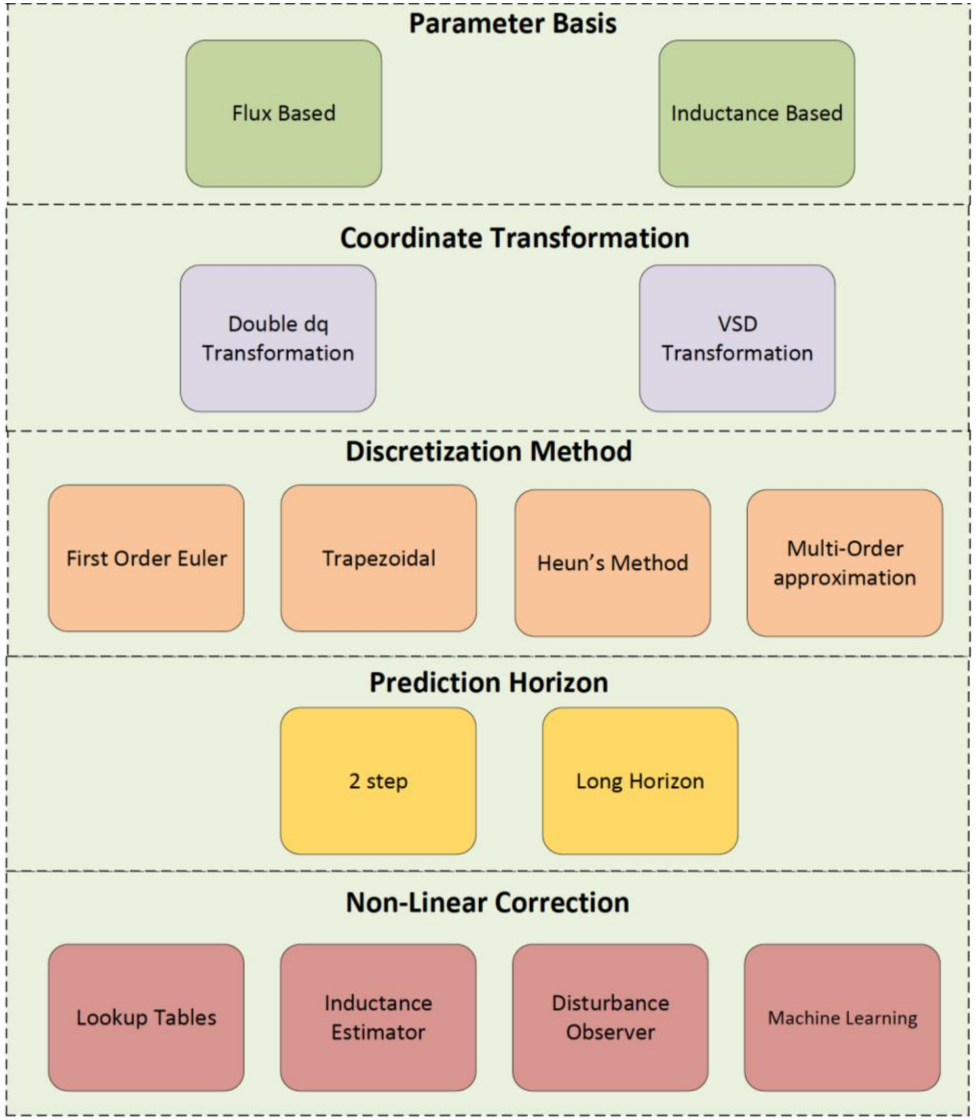
$$\begin{bmatrix} v_{di}^* \\ v_{qi}^* \end{bmatrix} = \underbrace{P(-\theta) \cdot C_{32}^{-1}}_{\text{Park and Clarke transformation matrices}} \cdot \underbrace{\begin{bmatrix} S_{ai} \\ S_{bi} \\ S_{ci} \end{bmatrix}}_{i^{th}\text{ switching state}} \cdot v_{DC}$$



Note- x^k: variable at instant k

Model-Predictive Current Control: Design

Choices for predictive model:



Parameter Basis
- Flux Based
- Inductance Based

Coordinate Transformation
- Double dq Transformation
- VSD Transformation

Discretization Method
- First Order Euler
- Trapezoidal
- Heun's Method
- Multi-Order approximation

Prediction Horizon
- 2 step
- Long Horizon

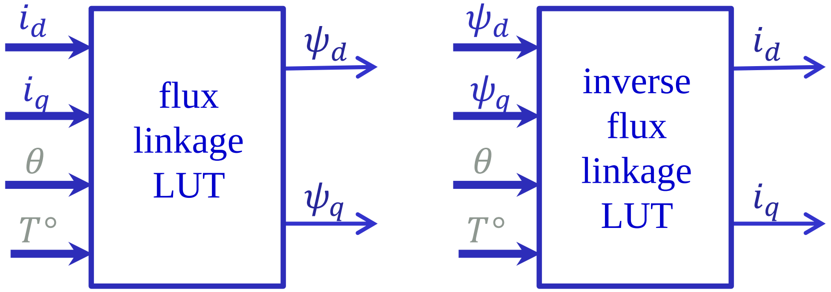
Non-Linear Correction
- Lookup Tables
- Inductance Estimator
- Disturbance Observer
- Machine Learning

Predictive model using Euler discretization:

i^{th} predicted flux linkages:

$$\psi_{di}^{k+1} = \psi_d^k + T_s\left(v_{di}^{*k} - R_s i_d^k + \omega^k \psi_q^k - \Delta V f_d(\theta^k)\right)$$
$$\psi_{qi}^{k+1} = \psi_q^k + T_s\left(v_{qi}^{*k} - R_s i_q^k - \omega^k \psi_d^k - \Delta V f_q(\theta^k)\right)$$

with:



Choices for cost function:

$$g_i = \left(i_{dref} - \hat{i}_d^{k+2}\right)^2 + \lambda_q\left(i_{qref} - \hat{i}_q^{k+2}\right)^2$$
$$g_{is} = \left(i_{dref} - \hat{i}_d^{k+2}\right)^2 + \lambda_q\left(i_{qref} - \hat{i}_q^{k+2}\right)^2 + \lambda_S n_S$$

with: $n_S = \sum_{i=1}^{n} \left|S_i^{k+1} - S_i^k\right|$

McMas University

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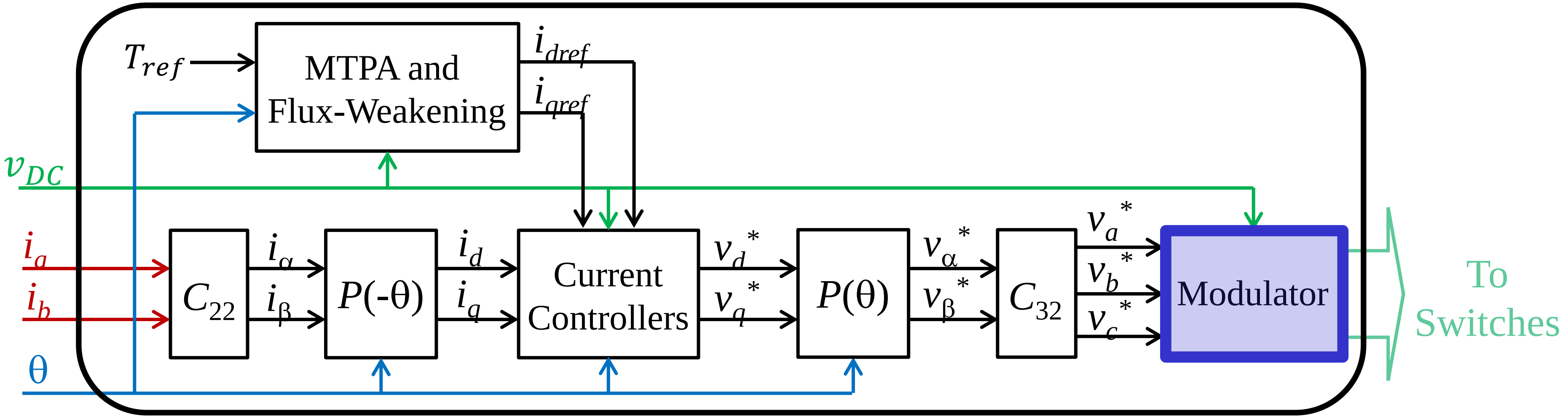
Electric Motor Torque Control for Electrified Transportation Systems

Current Control: Control of dq −currents for indirect torque control

- **Techniques:** many linear and nonlinear current controllers
- **Challenges:** accurate model, online parameter estimation, robustness, current sensorless control
- **Requirements:** phase current sensors and rotor angle sensor, DC-link voltage sensor (optional), current controllers, modulator (recommended)

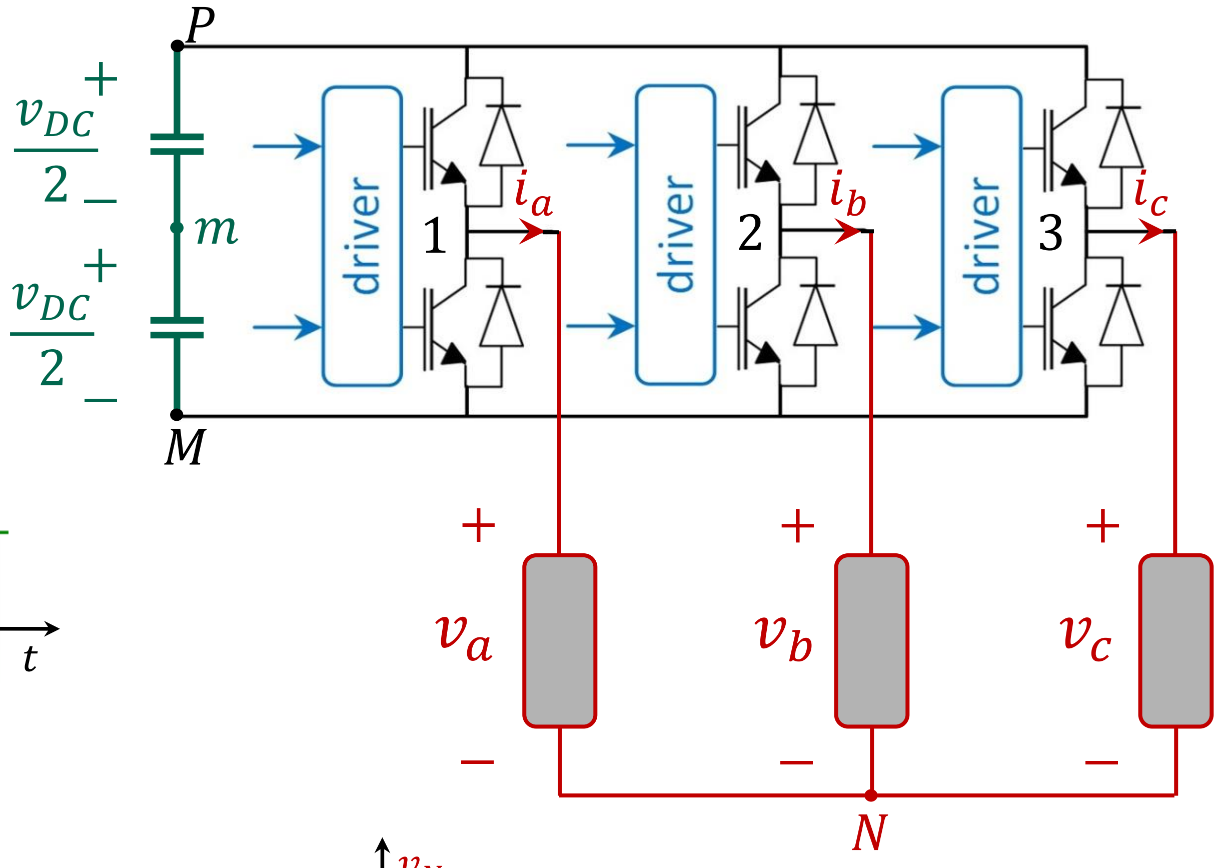


Pulse-Width Modulator

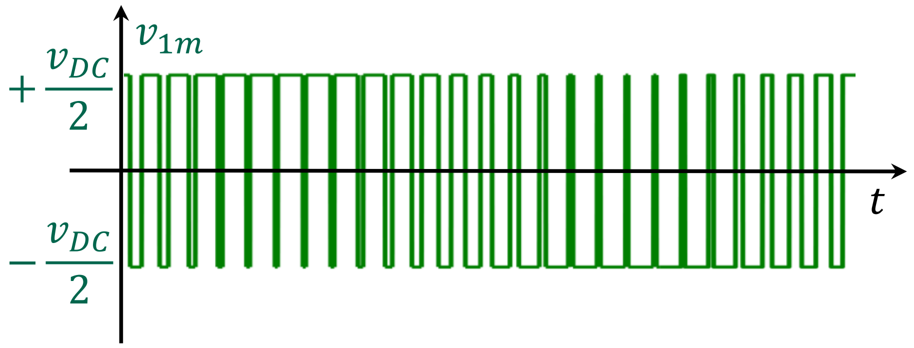
Modulator: Pulse-Width Modulation (PWM)

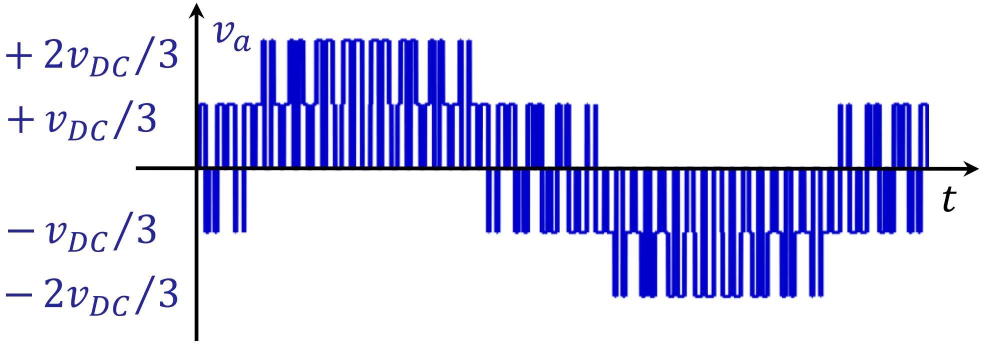
Phase voltages:

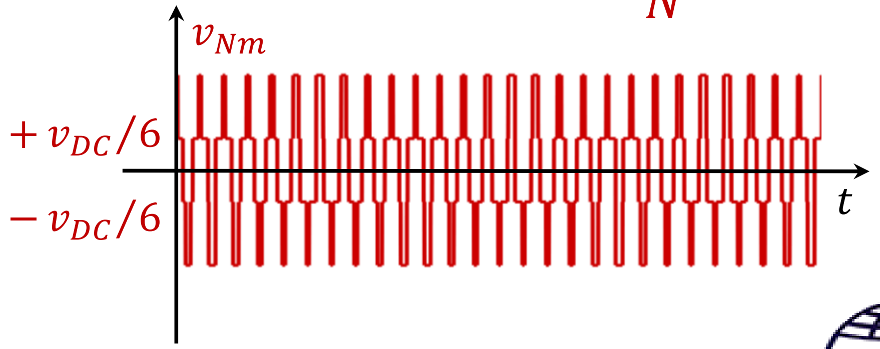
$$v_a = v_{1m} - v_{Nm}$$
$$v_b = v_{2m} - v_{Nm}$$
$$v_c = v_{3m} - v_{Nm}$$



Voltage waveforms:





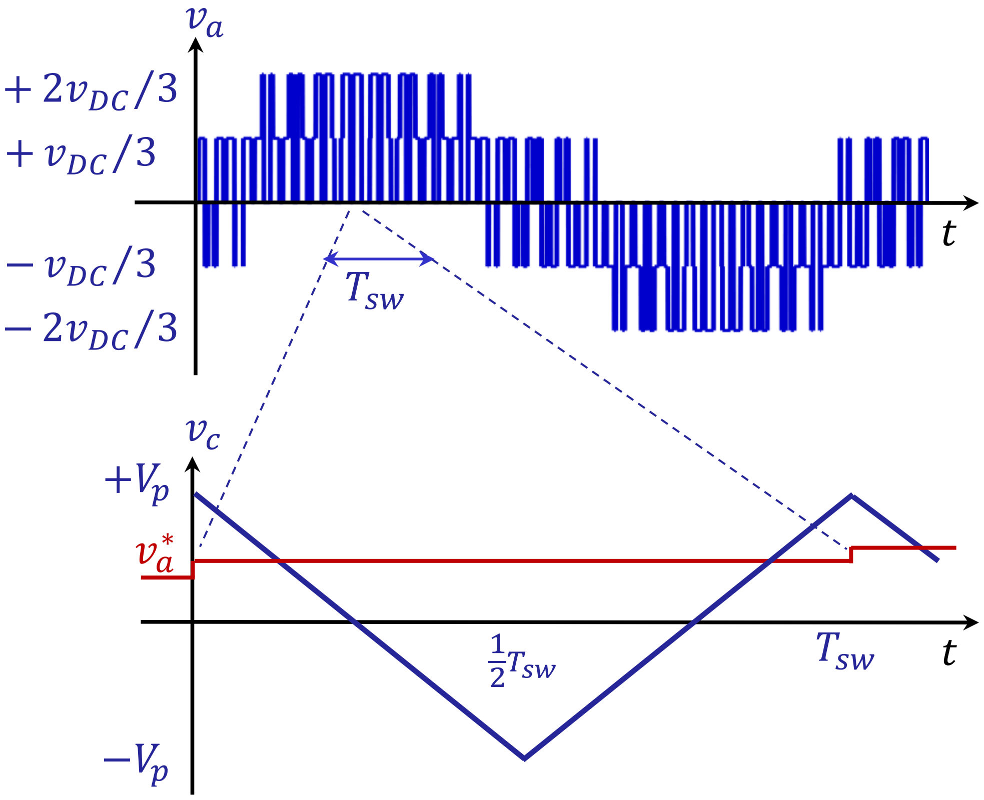


Sinusoidal PWM (SPWM): DC-Link Voltage Utilization

Linear modulation:

Fundamental of $v_{abc} = G_{VSI} \cdot v_{abc}^{*}$

$\Rightarrow$ VSI being modeled as a gain



Condition for linear modulation:

$$|v_a^*| \leq V_p = \frac{v_{DC}}{2}$$

Therefore:

$$\|v_{abc}^*\| = \sqrt{v_a^{*2} + v_b^{*2} + v_c^{*2}} = \sqrt{\frac{3}{2}}\, V_m^* < \sqrt{\frac{3}{2}}\, \frac{v_{DC}}{2} \cong 0.612\, v_{DC}$$

SVM *vs* SPWM: DC-Link Voltage Utilization

Maximum voltage vector magnitude:

Space-Vector Modulation (SVM) *vs* SPWM

Comparison in abc frame:

$$\|v_{abc}\|_{SPWM} \le \sqrt{\frac{3}{2}}\frac{v_{DC}}{2}$$

+15%

$$\|v_{abc}\|_{SVM} \le \frac{v_{DC}}{\sqrt{2}}$$

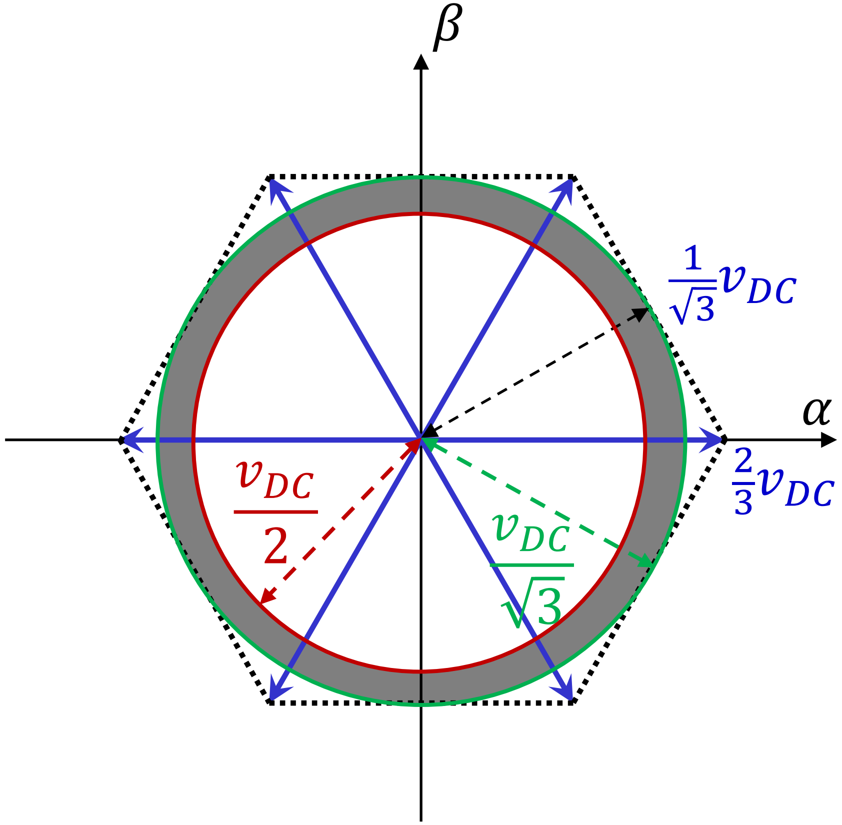
Comparison in $\alpha\beta$ frame:

(Clarke transformation)

$$\left\|v_{\alpha\beta}\right\|_{SPWM} \le \frac{v_{DC}}{2}$$

+15%

$$\left\|v_{\alpha\beta}\right\|_{SVM} \le \frac{v_{DC}}{\sqrt{3}}$$



$\alpha\beta$ –Clarke

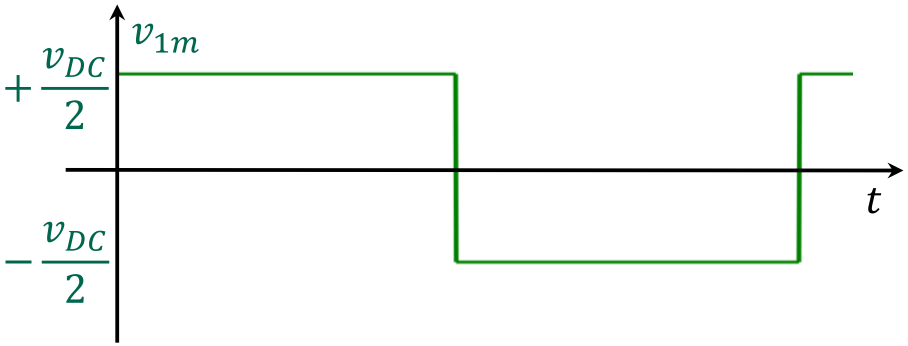
Six-Step Operation (SSO): DC-Link Voltage Utilization

Maximum DC-link voltage utilization:

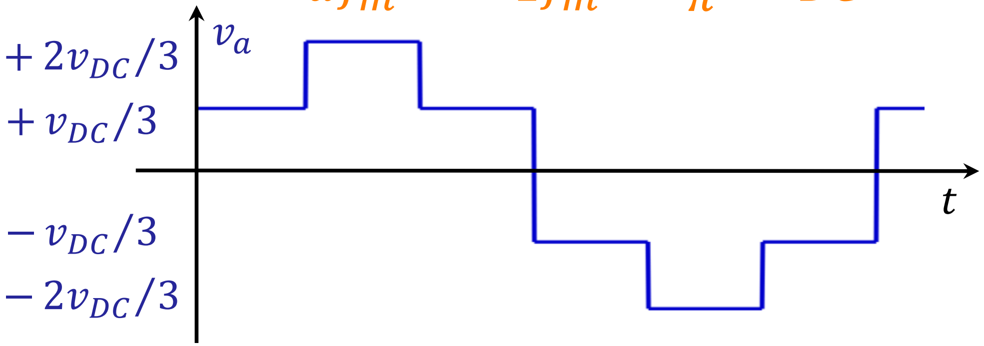
Six-step operation (SSO):

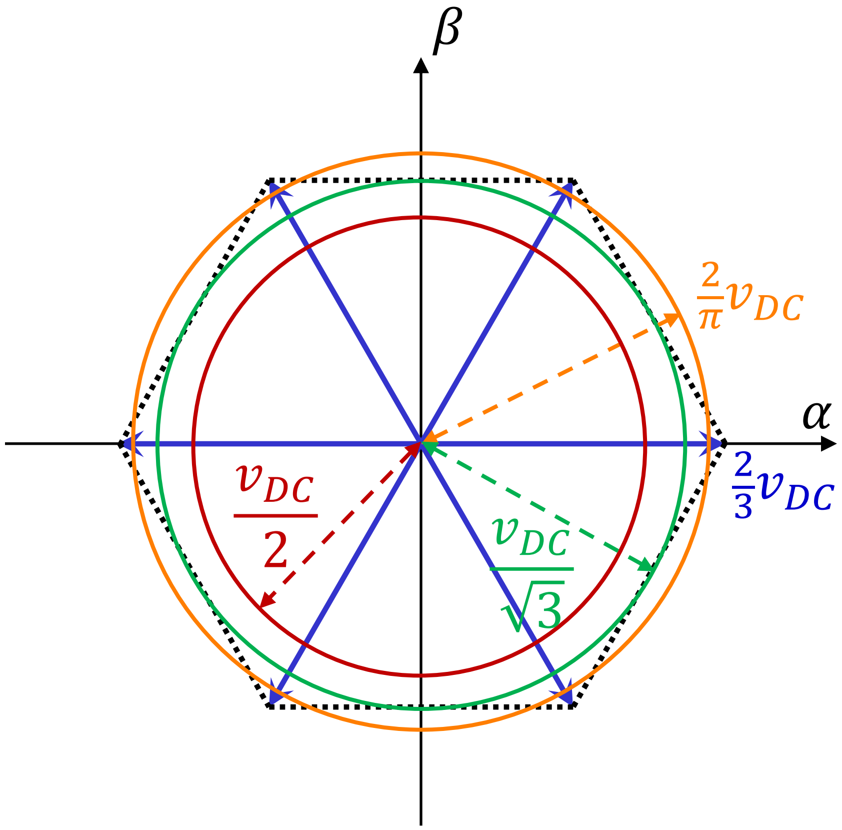
Amplitude of fundamental voltage:

$$V_{1f_m} = \frac{4}{\pi} \cdot \frac{v_{DC}}{2} = \frac{2}{\pi} \cdot v_{DC}$$



$$V_{af_m} = V_{1f_m} = \frac{2}{\pi} \cdot v_{DC}$$





$\alpha\beta$ –Clarke

Amplitude Modulation Index (MI)

Maximum DC-link voltage utilization:

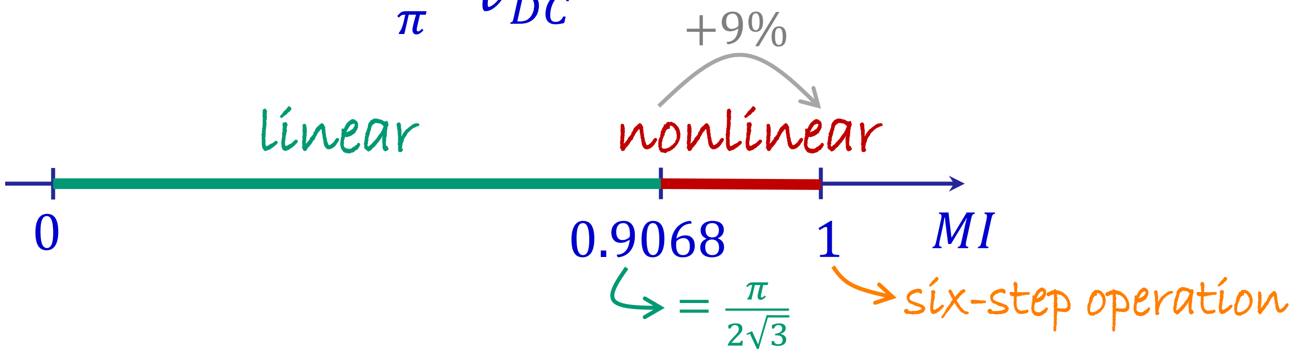
Nonlinear modulation region:

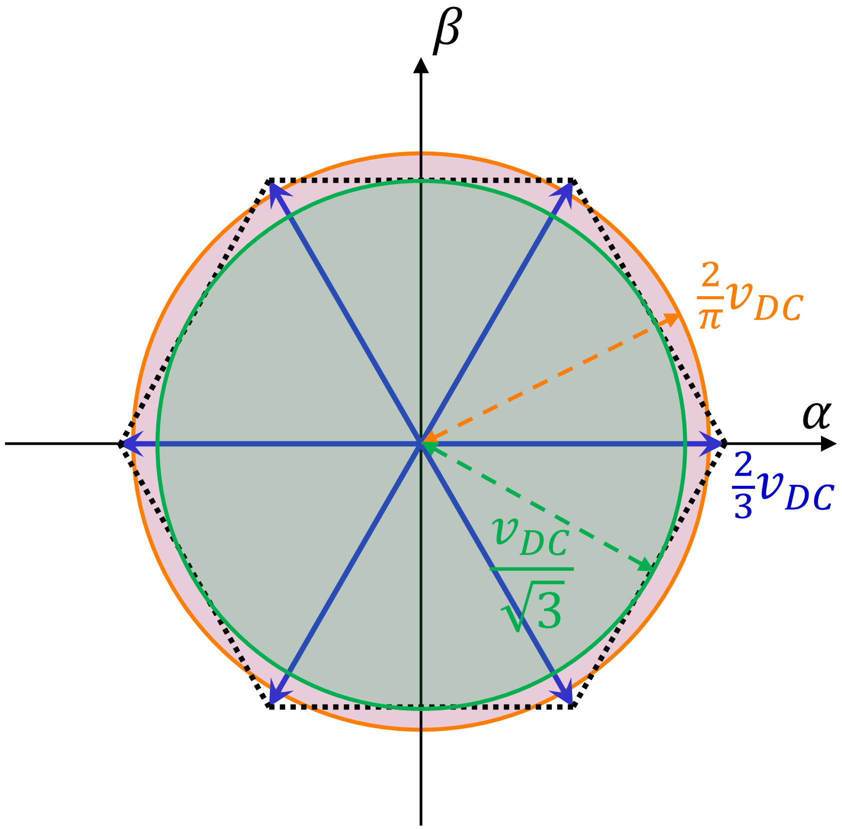
$\alpha\beta$ –Clarke:

$$\frac{1}{\sqrt{3}} \cdot v_{DC} < \left\| v_{\alpha\beta} \right\| < \frac{2}{\pi} \cdot v_{DC}$$

Modulation Index:

$$MI \triangleq \frac{\left\| v_{\alpha\beta} \right\|}{\frac{2}{\pi} \cdot v_{DC}}$$





$\alpha\beta$ –Clarke

Nonlinear Modulation: Overmodulation (OVM)

- MI^*: Modulation Index Reference

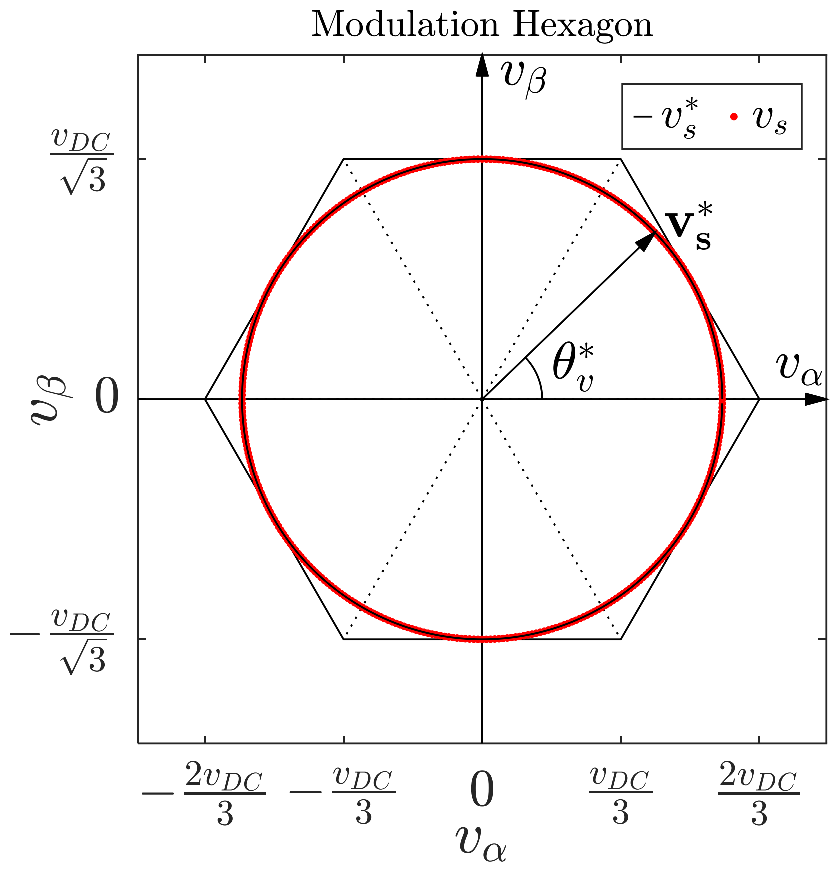
$$MI^* \triangleq \frac{\left\| v_{\alpha\beta}^* \right\|}{\frac{2}{\pi} \cdot v_{DC}}$$

- MI: Actual Modulation Index

$$MI \triangleq \frac{\left\| v_{\alpha\beta} \right\|}{\frac{2}{\pi} \cdot v_{DC}}$$

MI range:

- Linear modulation: $MI \in [0 \quad 0.9068]$
- Overmodulation: $MI \in (0.9068 \quad 1)$
- Six-step operation: $MI = 1$



	Magnitude	**Angle**
Input	v_s^*	θ_v^*
Output	v_s	θ_v

Nonlinear Modulation: Overmodulation (OVM)

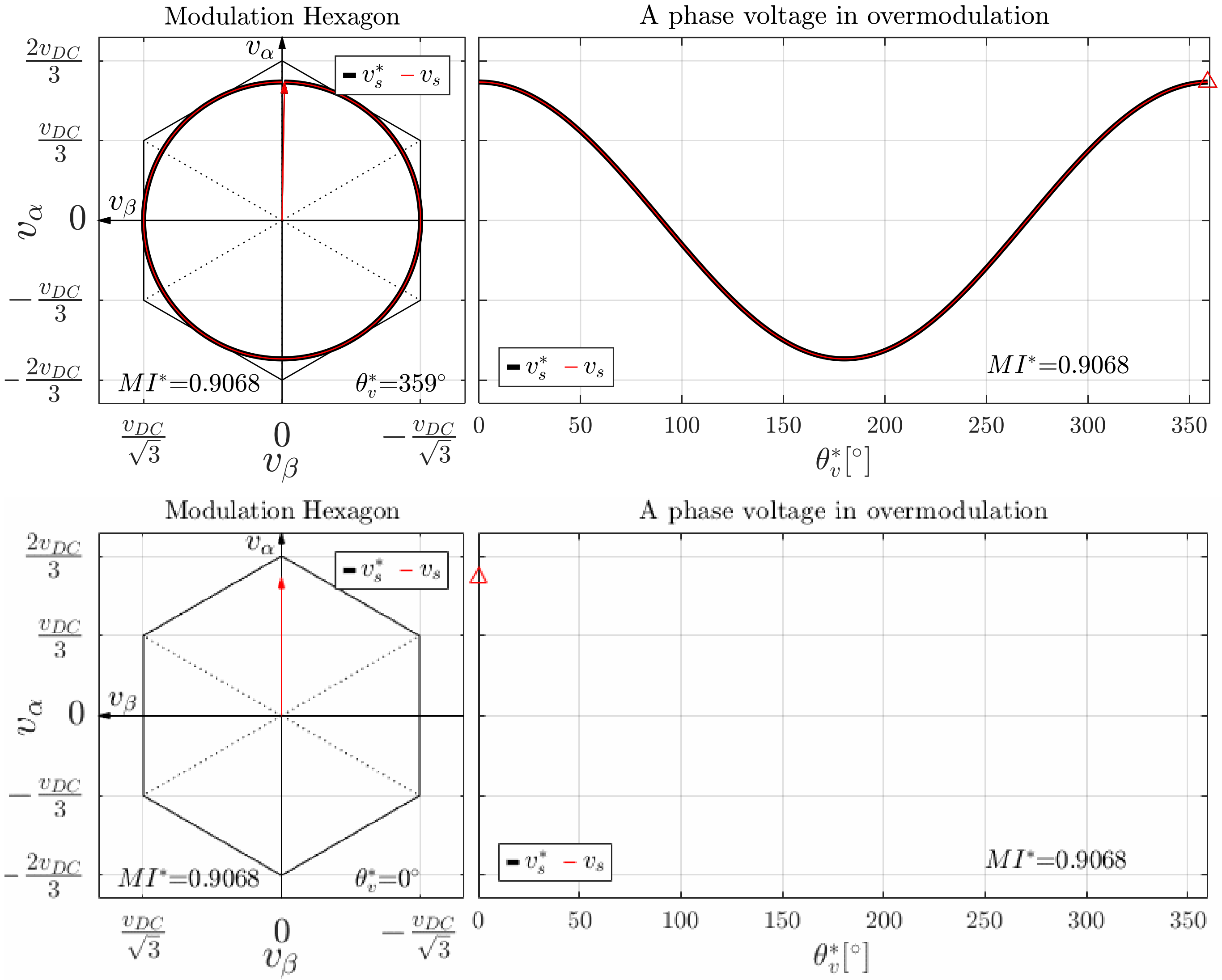
Linear modulation:

$$MI = MI^*$$

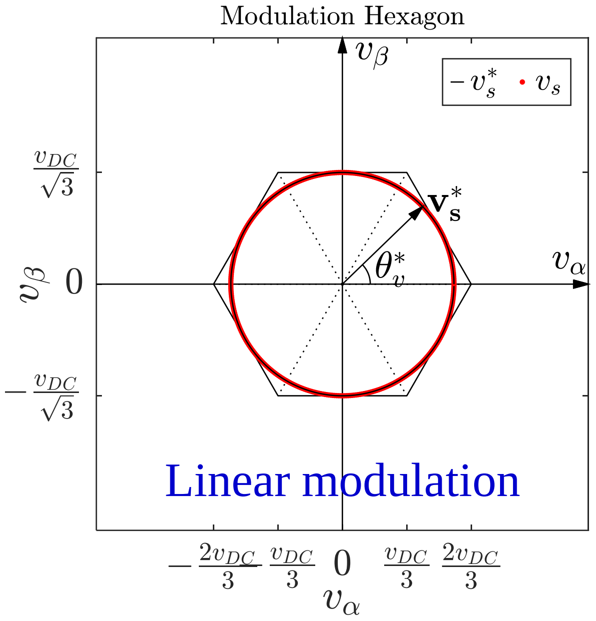
Recall:

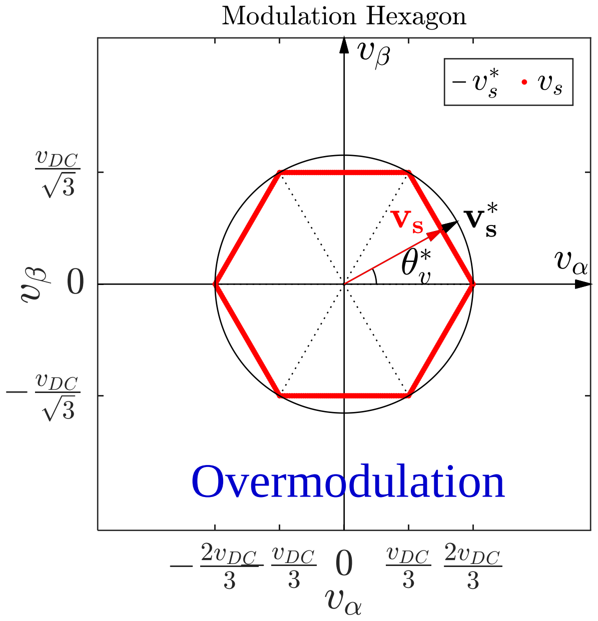
$$0 \leq MI \leq 0.9068$$

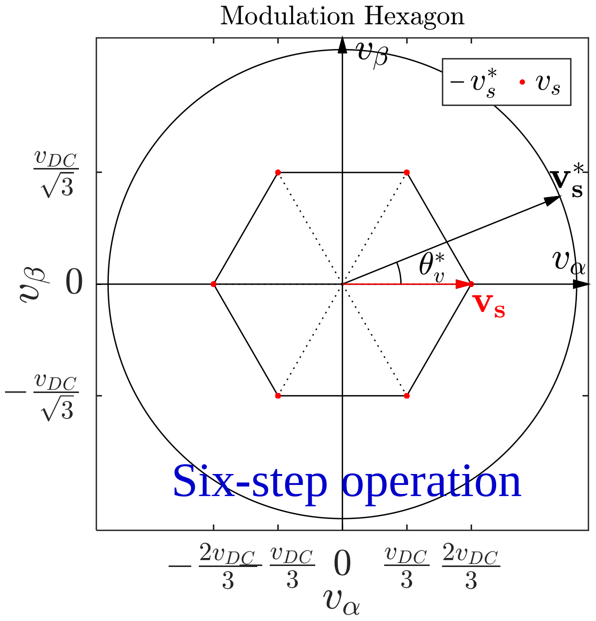
Modulation hexagon **Fundamental phase voltage**



From Linear Modulation to Overmodulation and Six-Step Operation





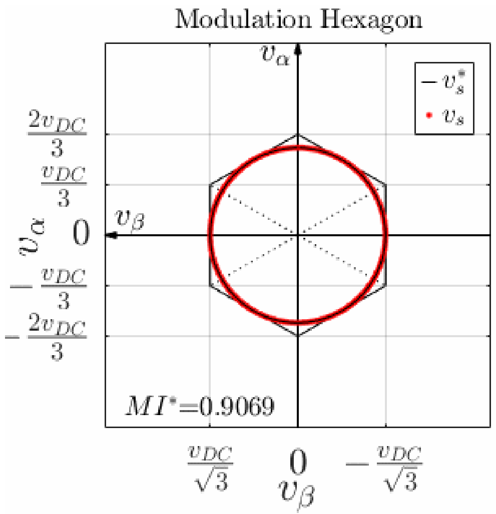


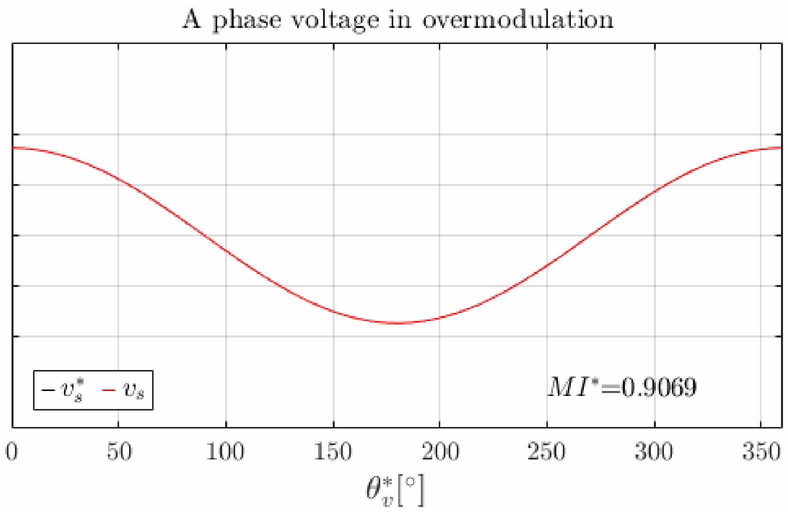
Overmodulation:

$$MI \neq MI^*$$

Recall:

$$0.9068 < MI < 1$$

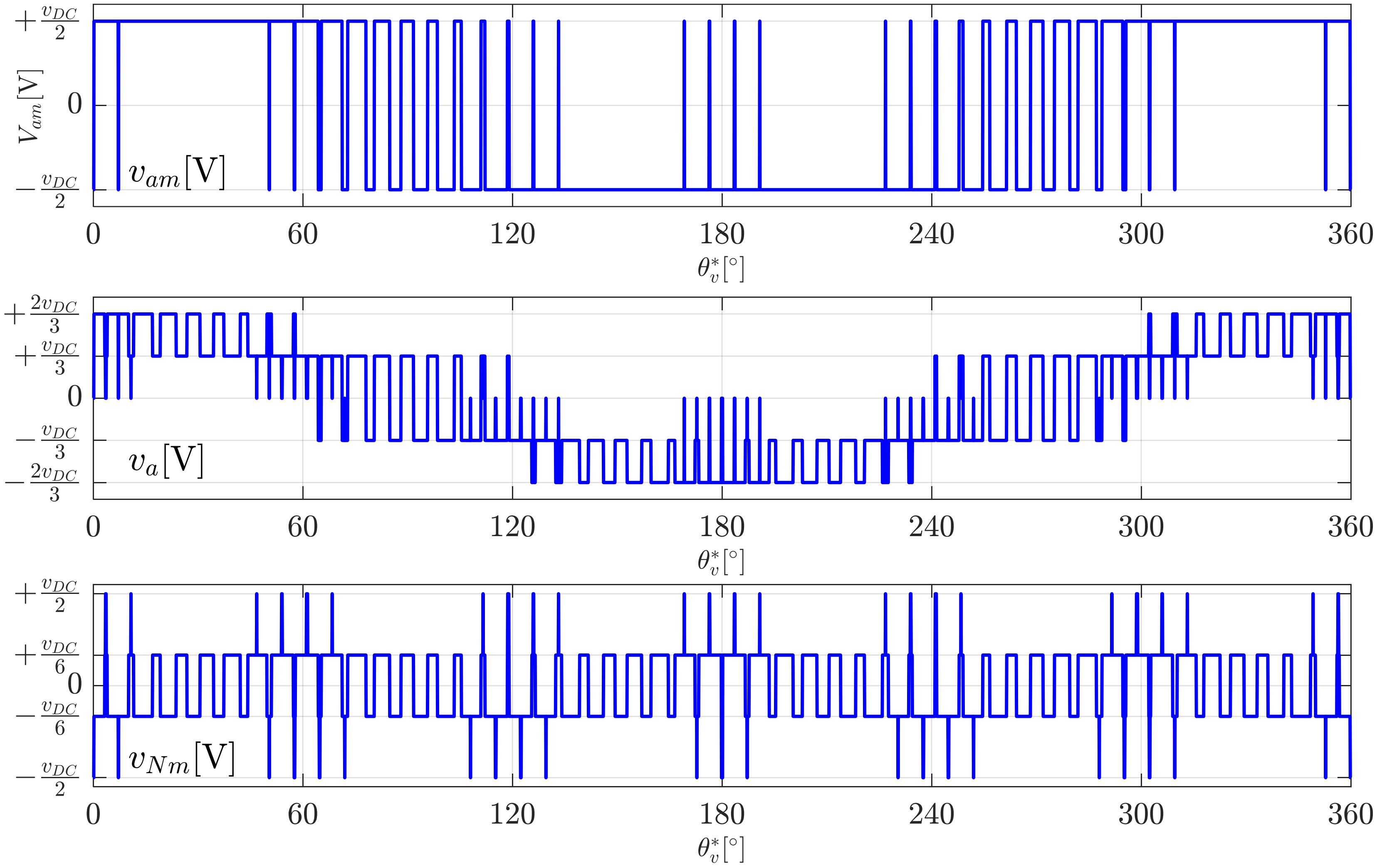




Linear modulation ≫ Overmodulation ≫ Six-step operation

Overmodulation (OVM): Waveforms

Overmodulation: $MI^* = 0.94$, $M_f = f_{sw}/f_1 = 50$



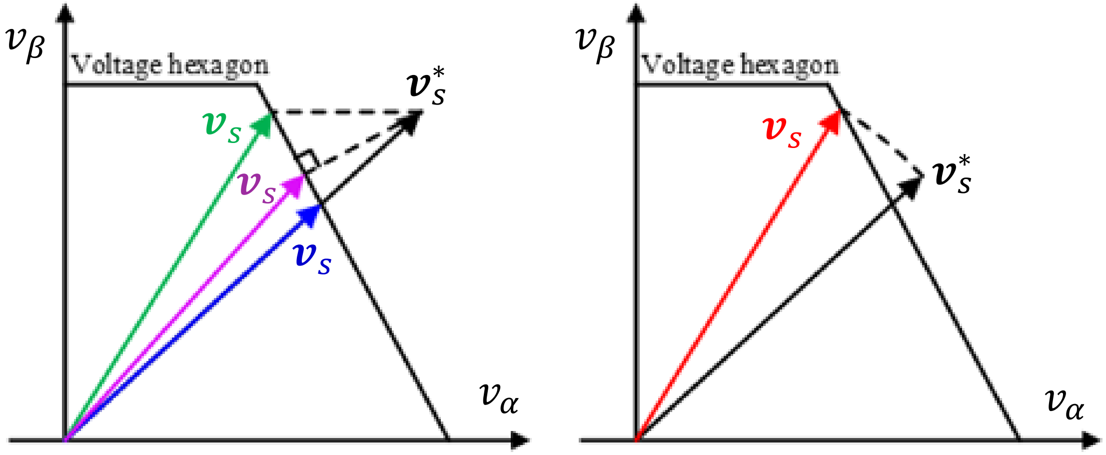
Overmodulation (OVM) Techniques

1. Minimum Phase Error (MPE)
   - $\theta_v^* = \theta_v$: Phase error is **ZERO**

2. Minimum Distance Error (MDE)
   - $\min(|\boldsymbol{v}_s^* - \boldsymbol{v}_s|)$: Vector error is minimized

3. Keeping Switching State (SS)
   - Hold on v_α^* or v_β^*

4. Minimum Magnitude Error (MME)
   - $v_s^* = v_s$: Magnitude error is **ZERO**



	Input	Output
Magnitude	v_s^*	v_s
Angle	θ_v^*	θ_v

Overmodulation (OVM) Techniques

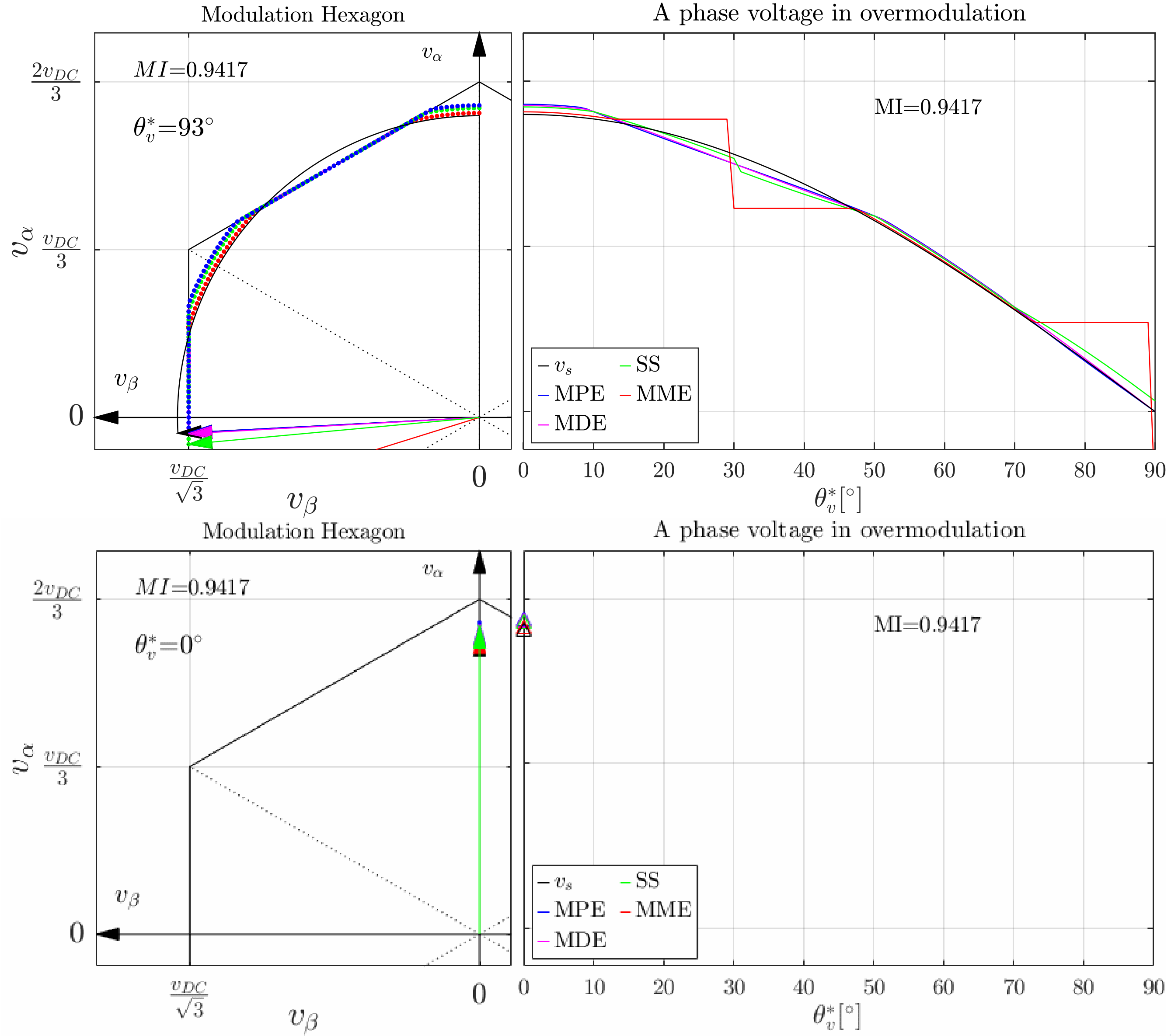
Comparison:

Minimum Phase Error (MPE)

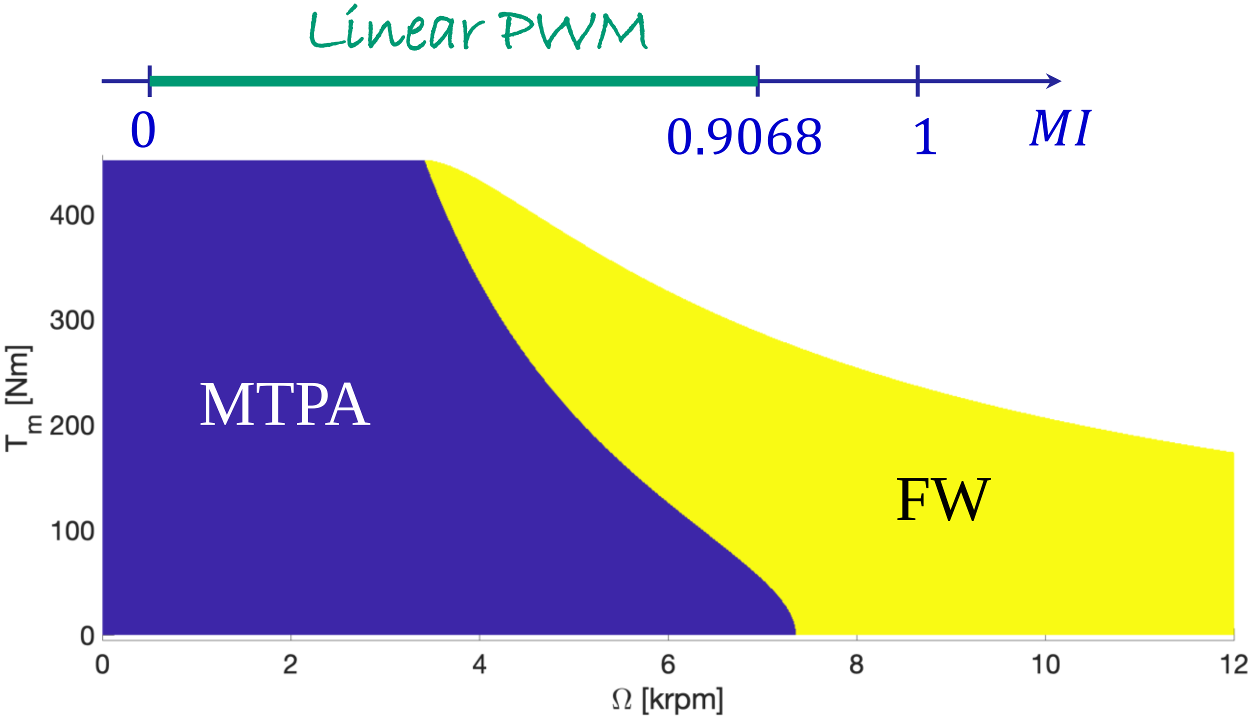
Minimum Distance Error (MDE)

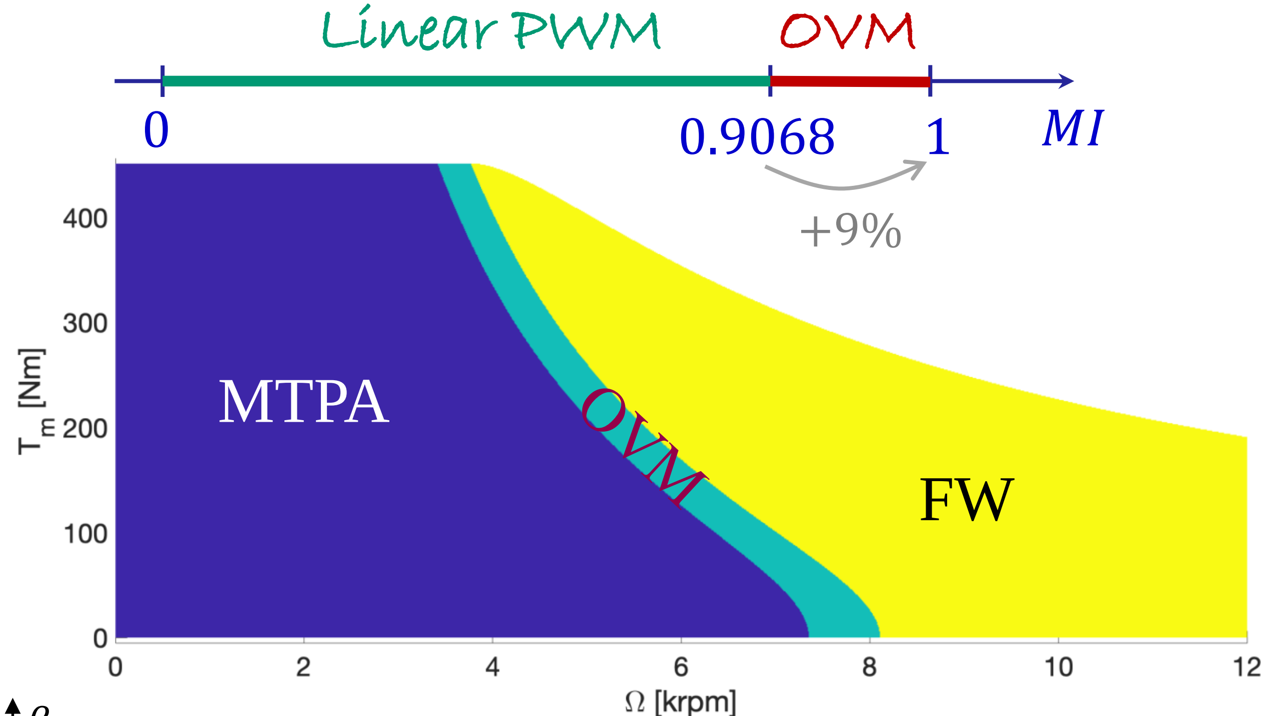
Keeping Switching State (SS)

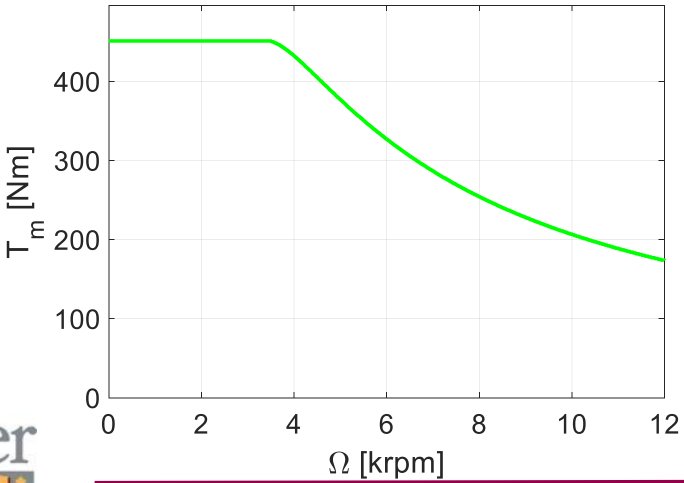
Minimum Magnitude Error (MME)

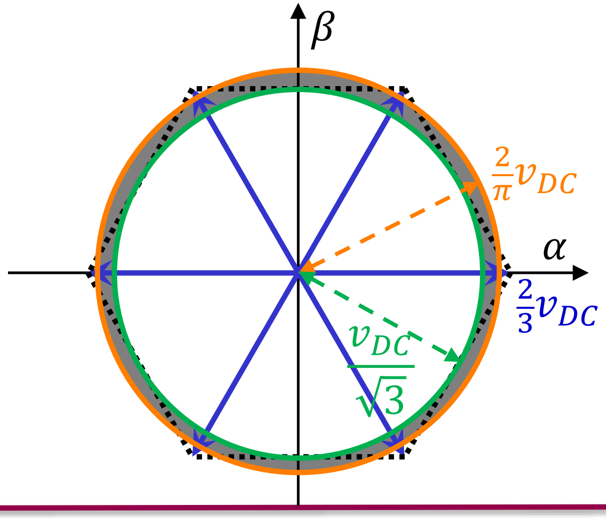


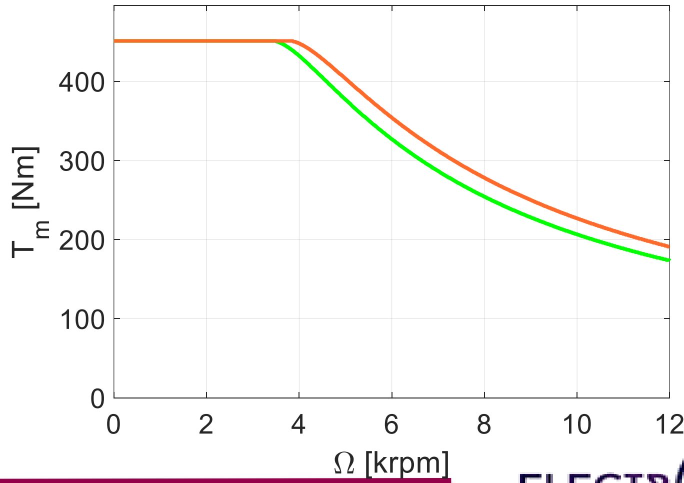
Maximization of DC-link Voltage Utilization











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Overmodulation: Challenges

- Harmonics of control (reference) voltages
- Nonlinear modulation index
- Effect on THDv (and so THDi)
- Performance degradation at low frequency modulation index

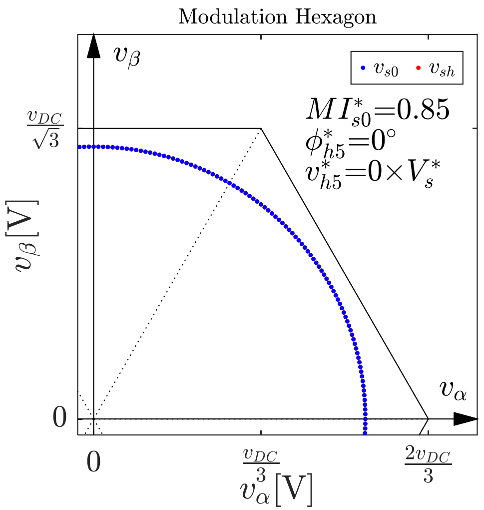
$$M_f = \frac{f_{sw}}{f_1}$$

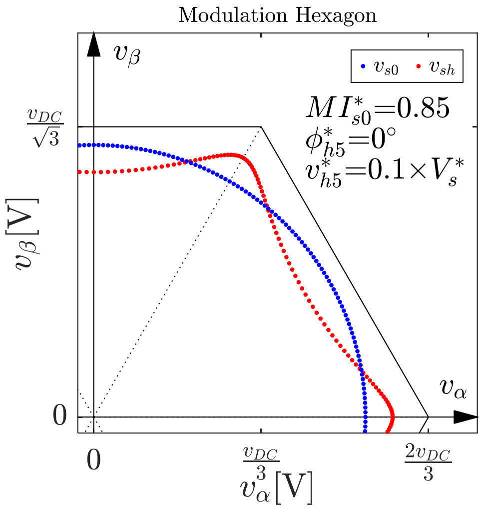
- Transition from OVM to SSO

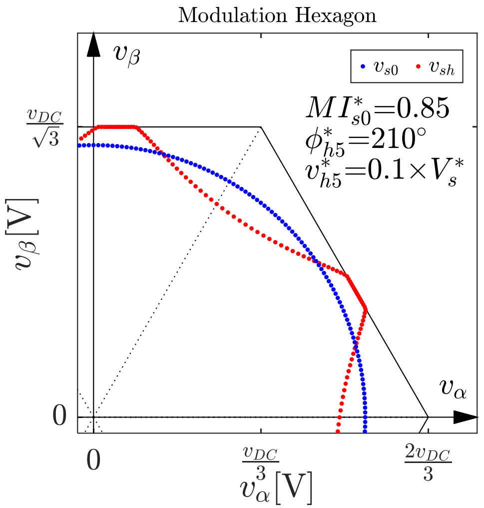
Overmodulation Challenges: Harmonics of Control Voltages

Example: effect of 5th-harmonic: $v_a^* = V_s^* \cos\theta_v^* + V_{h5}^* \cos(5\theta_v^* + \phi_{h5}^*)$

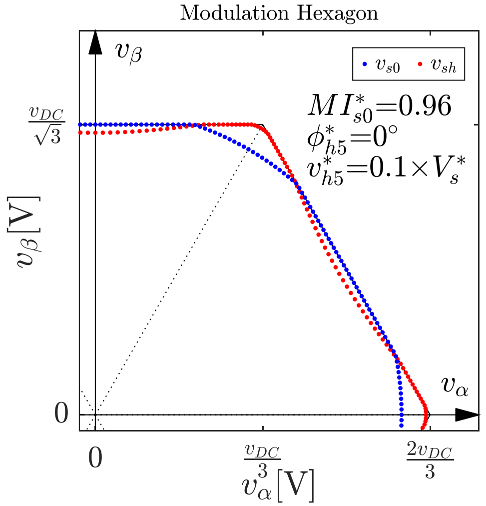
Linear modulation:

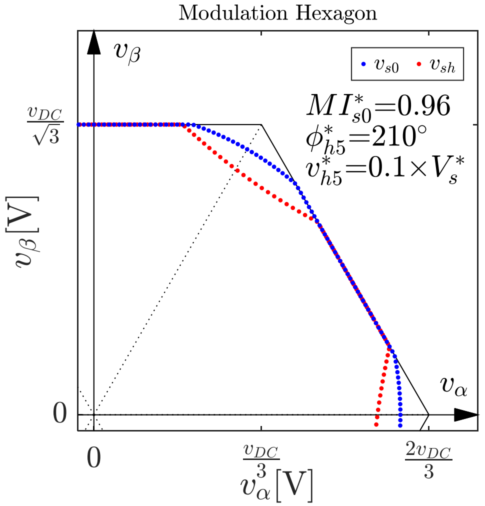






Overmodulation:



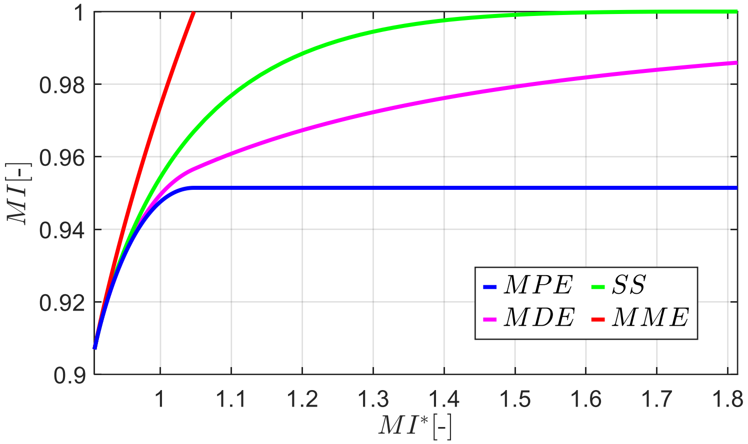


Observation:

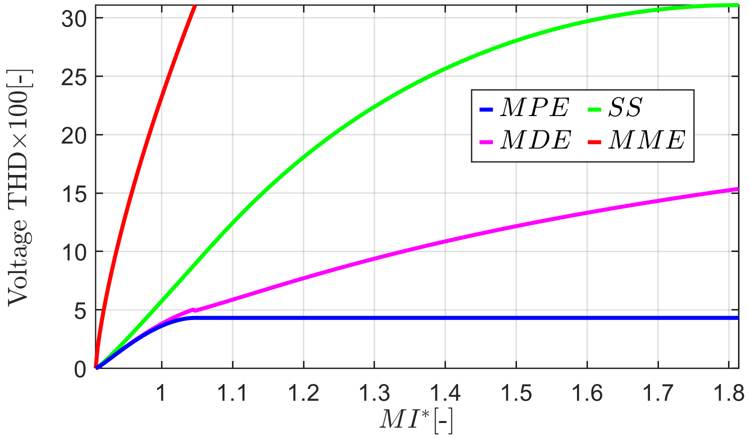
1. V_h^* : THDv ↑
2. ϕ_h^* : MI ? (=, ↑, ↓)

Overmodulation Challenges: Nonlinear Modulation Index

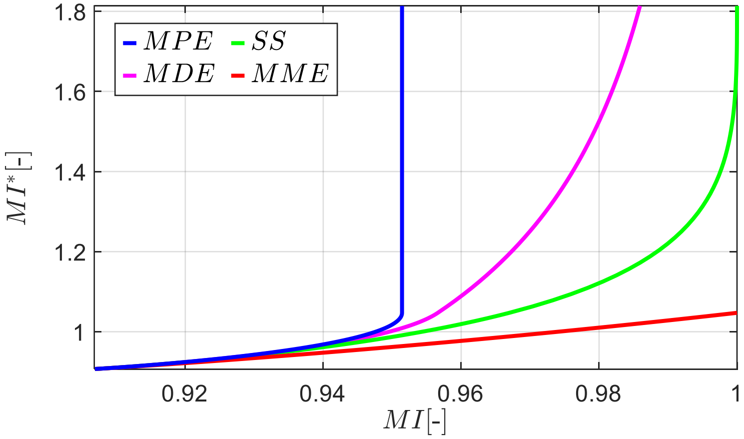
Nonlinearity due to OVM: $< v_{abc} > \neq G_{VSI} \cdot v^*_{abc}$



Effect of OVM on THDv:



Modulation Index Linearization (MIL):



Problem: $MI^* \rightarrow OVM \rightarrow MI$, then $MI^* \neq MI$

MI linearization: $MI^* \rightarrow MI^{**} \rightarrow OVM \rightarrow MI$

Objective: $MI^* = MI$

Method: $MI^{**} = f_{OVM}(MI)$

1. Polynomial function
2. LUT

Electric Motor Torque Control for Electrified Transportation Systems

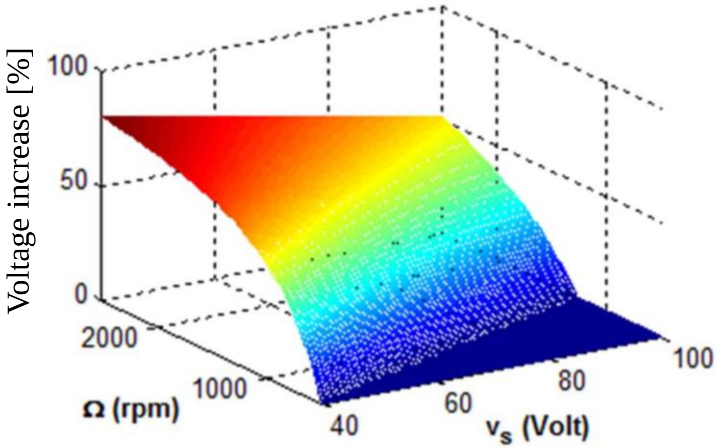
Modulator: Generate command signals from continuous control voltages

- **Advantage of linear PWM:** constant switching frequency
- **Advantage of overmodulation:** maximization of DC-link voltage utilization ⇒ extension of speed range
- **Challenges:** harmonics of control voltages, THDv and THDi, smooth transition to six-step operation, instabilities/disturbances at low frequency modulation index
- **Other techniques:** Selected Harmonic Elimination (SHE), Selected Harmonic Mitigation (SHM), Hybrid PWM, Optimal Pulse Patterns
- **Other solutions to extend speed range:** variable DC-link voltage, Current-Source Inverter (CSI), sinus-inverter

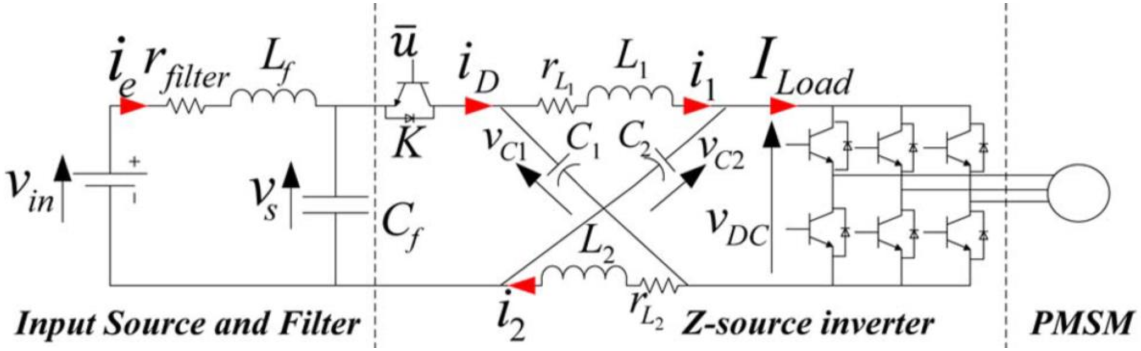
Motor Drives

Motor Drives for Speed Range Extension

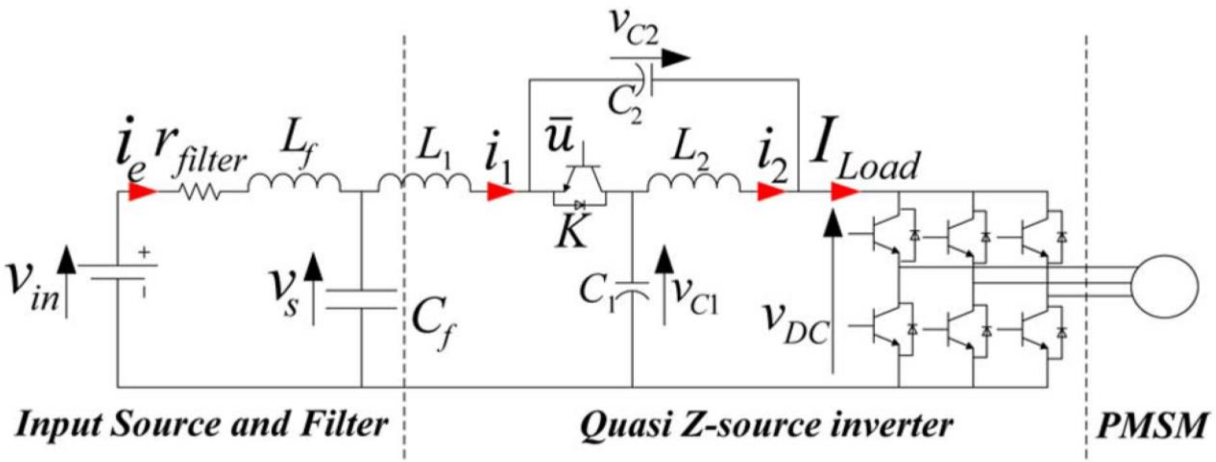
DC-link voltage adaptation for speed range extension:



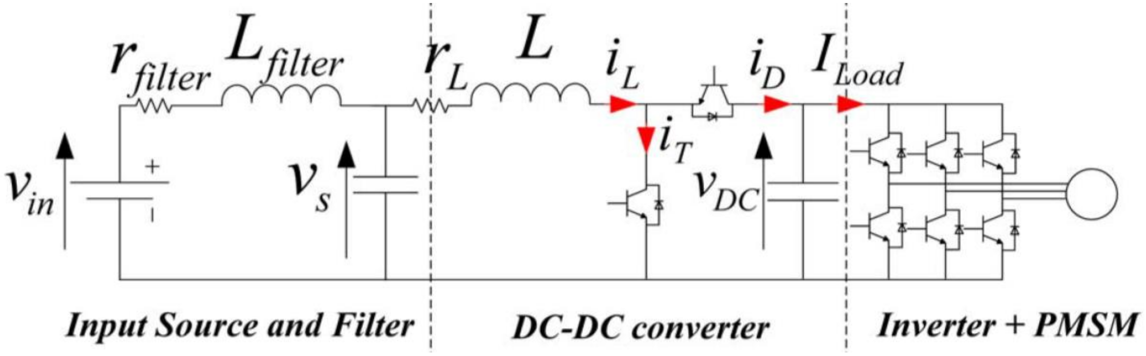
Z-source inverter



Quasi Z-source inverter



Boost + VSI

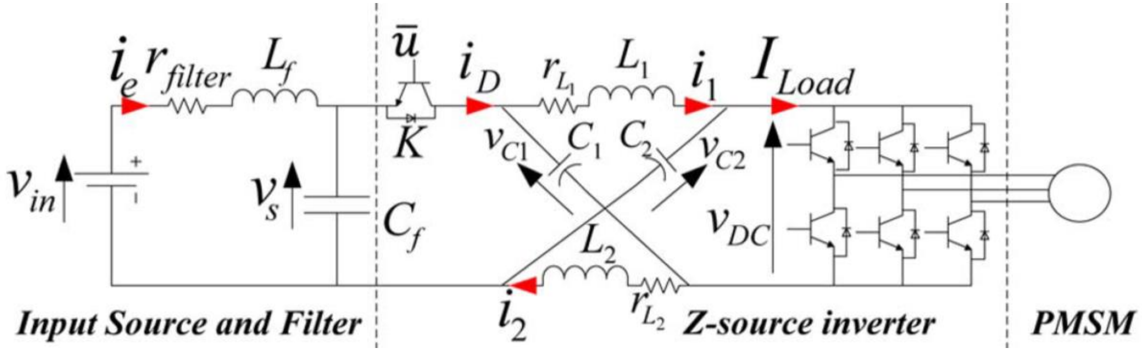


A. Battiston *et al.*, "A Control Strategy for Electric Traction Systems Using a PM-Motor Fed by a Bidirectional Z-Source Inverter," *IEEE Trans. on Vehicular Technology*, Vol. 63, No. 9, pp. 4178-4191, Nov. 2014.

Motor Drives for Speed Range Extension

DC-link voltage adaptation for speed range extension:

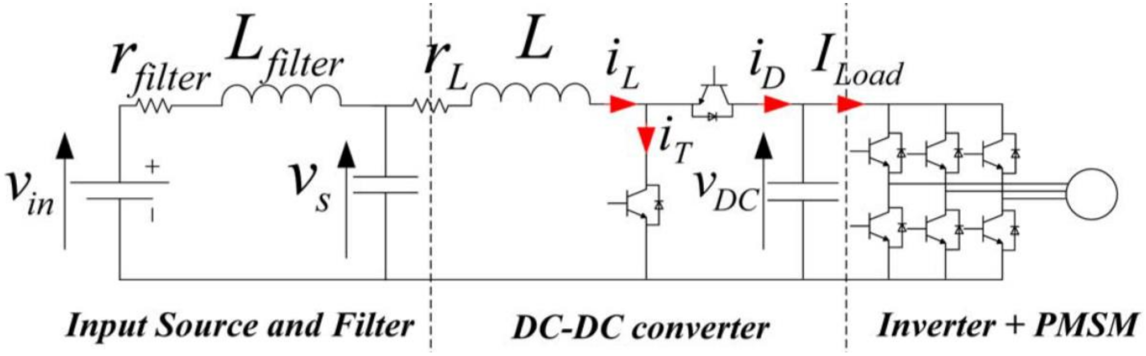
Z-source inverter



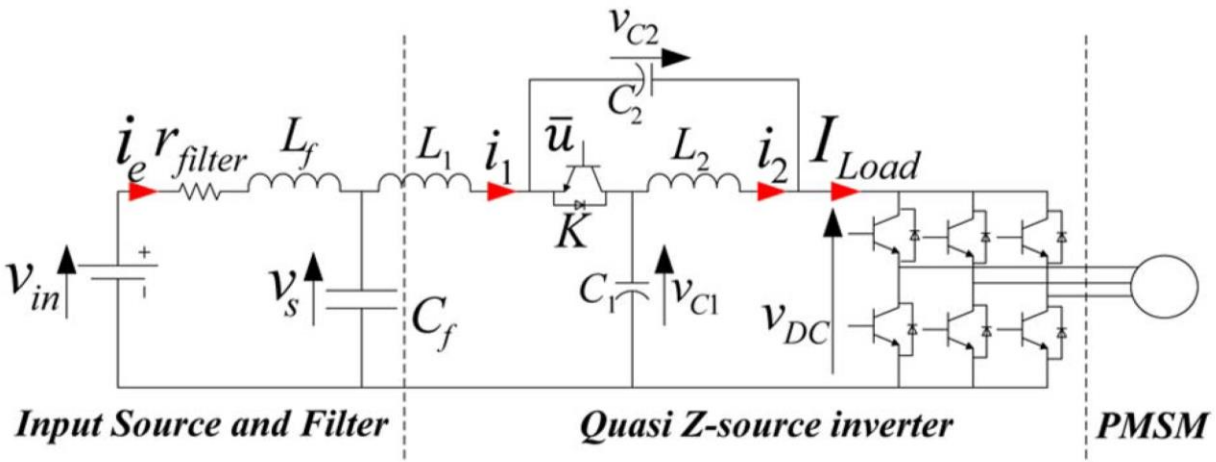
Drawbacks:

- High stress on components
- Limited voltage stepping-up due to efficiency
- Power density

Boost + VSI



Quasi Z-source inverter



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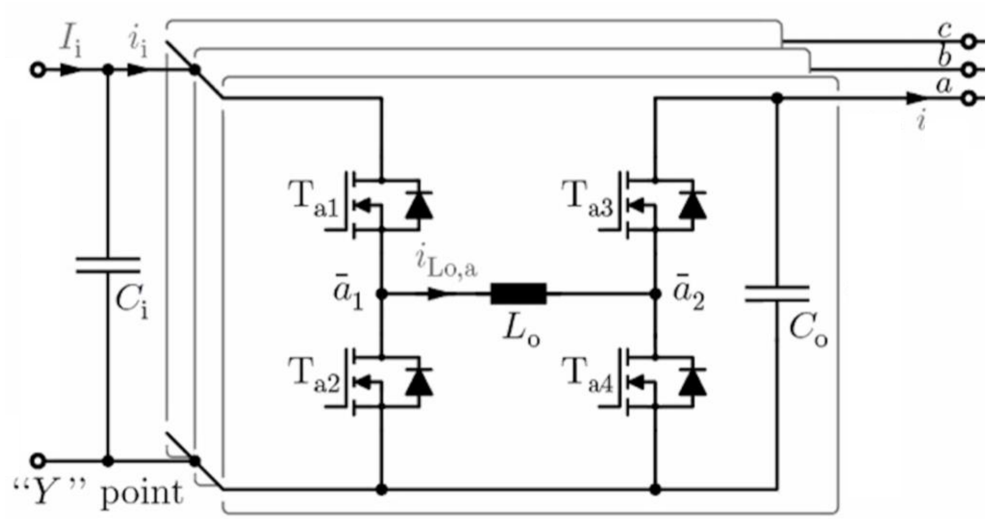
Motor Drives: New Topologies

Y-inverter:



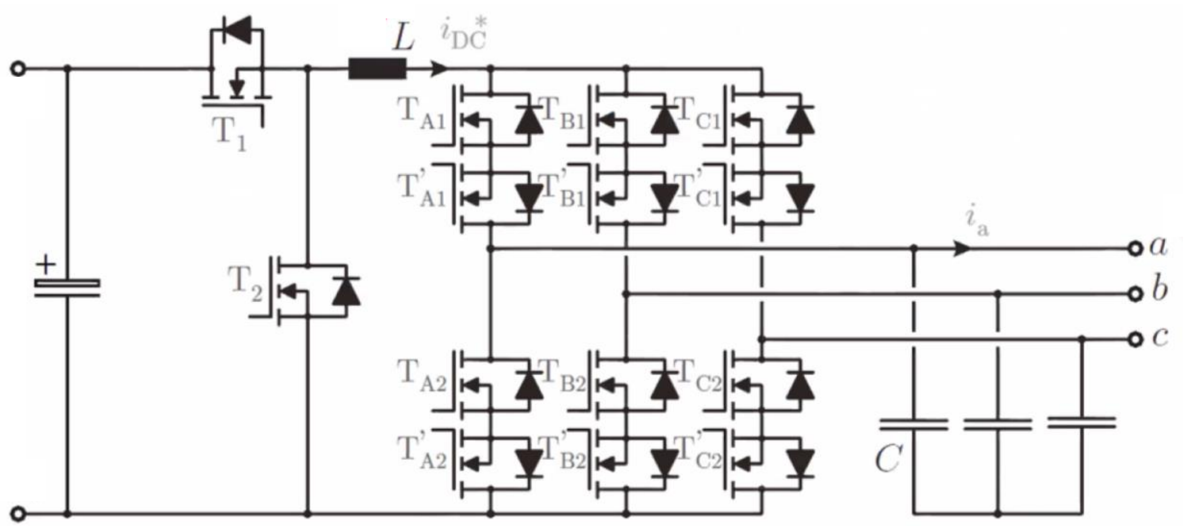
Features:

- Buck-boost conversion
- Sinusoidal output voltage
- Off-the-shelf legs or bridges

Challenges:

- Complex control: three-cascaded loops
- Power density

Current-Source Inverter (CSI):



Features:

- Single inductor
- Current control for buck stage output current
- Monolithic Bidirectional GaN switches

Challenges:

- Off-the-shelf legs/inverter
- Motor torque control over wide speed range

J. Kolar and J. Huber, "Next Generation Three-Phase Variable Speed Drive SiC/GaN PWM Inverter Concepts," PEMC 2020, Apr. 2021.

Motor Drives: Trends and Challenges

- **Multi-level inverters:** higher voltage motors
- **Sinus-inverter:** low high frequency components, longer useful lifetime, lower losses in motor, wide voltage and frequency range
- **Smaller/lighter inverters and Motor-integrated inverters**
- **Challenges with WBG devices (SiC and GaN):** packaging, EMI, motor insulation, shaft (bearing) currents
- **Challenges at high-power motor drives:** parallel interleaving for large currents sharing
- **Challenges with EMI filters:** higher influence of parasitic elements, couplings between components
- **Effect of long cables:** output filter to be added

Conclusion

Motor Control for Electrified Transportation: Trends and Challenges

- **Wide speed range operation:** maintaining the control over wide range variation of speed with a given DC voltage (maximum DC-link voltage utilization)
- **Efficiency:** high efficiency operation over wide speed range (extension of battery range)
- **Optimal design of ASD:** impact of control on optimization of ASD (system level) in terms of weight and volume (power density in kg/kW and l/kW)
- **Reliability and maintenance:** improving reliability by design, partial/full parallel redundancy, fast/cost effective maintainability
- **Cost reduction:** reducing cost while improving/keeping same performances
- **Noise and vibration reduction:** reducing torque ripples, noise and vibration using more effective control laws
- **Accurate torque control:** torque estimation, adaptive MTPA, effect of temperature

Motor Control for Electrified Transportation: Trends and Challenges

- **Current control under OVM and SSO:** THDi reduction under OVM, torque ripple reduction, smooth transition between OVM and SSO
- **Fault-tolerant capability:** fault diagnosis and prognosis, health-monitoring, remaining useful lifetime (RUL) estimation, fault-tolerant control
- **Multi-phase motors:** power and torque splitting under normal and fault conditions, reducing current harmonics using either current controllers or tailored PWM techniques
- **Current control techniques:** development of control laws for new motor drives and multi-phase motors
- **Motor-integrated inverters:** high efficiency, high power density, better EMI immunity, “non-expert” installation

A good motor is one that can be forgotten!

Thank you!