Nonlinear Controller Design of Power Electronics and Electric Machines with *Fast and Slow* Dynamics

IEEE PEAL Dayton 2020

Luis Herrera
Assistant Professor
Department of Electrical Engineering
University at Buffalo

University at Buffalo The State University of New York

Outline

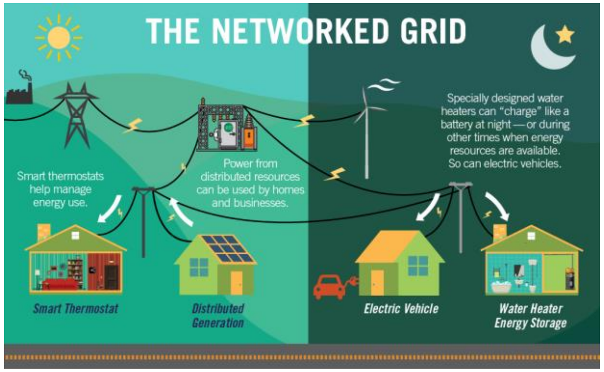
- Introduction and Motivation
- Proposed Controller Design
- Application to IPMSG in DC Microgrids
- Simulation Results
- Conclusion

Recent Trends in Electrification

- The rise in renewables and clean energy concepts have been enabled in part by:
  - Power electronics
  - Electric machines
  - Control theory
  - …

https://technology.nasa.gov/patent/LEW-TOPS-104

https://insideevs.com/features/343599/2021-electric-vehicles-the-future-generation-of-evs/

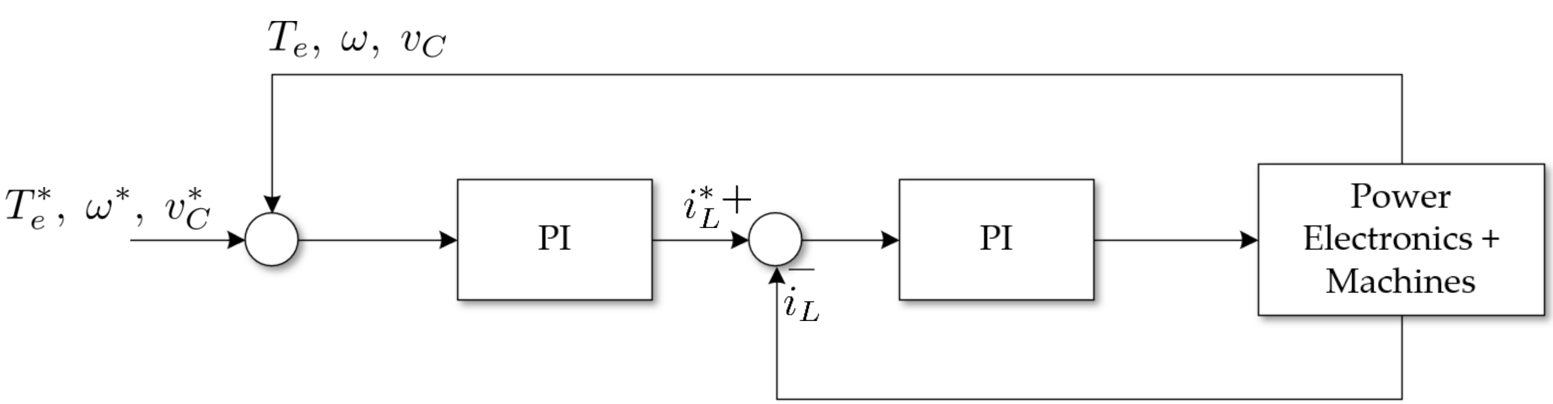


https://www.carolinacountry.com/departments/more-power-to-you/the-grid-will-connect-us-to-our-energy-future

Power Electronics + Machines + Control

- Control techniques are able to command the power electronics and machines to regulate necessary variables such as:
  - Voltage, current
  - Active and reactive power
  - Torque and speed
  - …

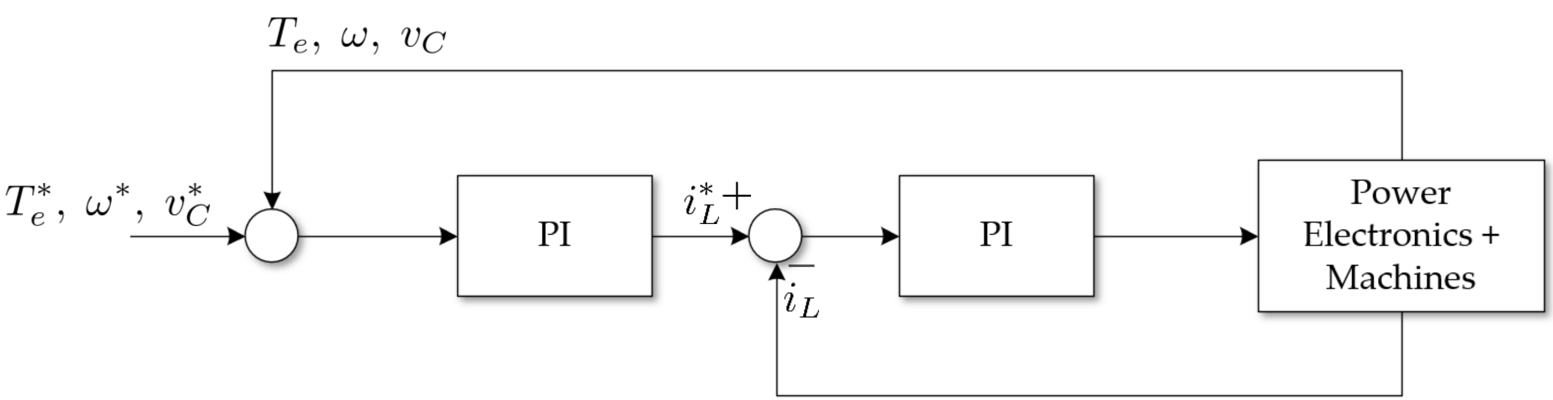
- In the majority of applications, the control structure to accomplish this is generally as follows



Overview and Goals

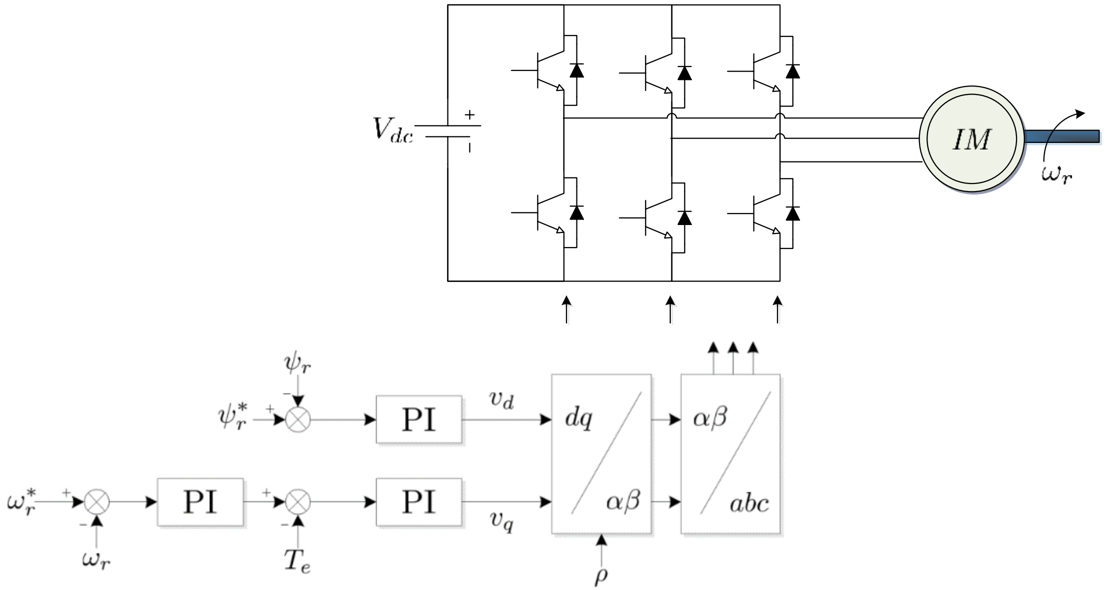
- Why does this controller structure work?

- The goals of this presentation will be to
  1. Explain why this control structure has been used widely
  2. Develop new controller design techniques to improve performance
  3. Present an example based on an IPMSG with active rectifier



Physical System Based Motivation

- One of the reasons this control structure has appeared is the ***time scales*** that exists in these systems:
  - **Current has a faster decay ratio (small inductance)**
  - **Voltage/speed is slower (larger capacitance/inertia)**
- Some examples can be seen in electric machines and dc/dc converters



https://www.tesla.com/models?redirect=no

- **The inner loop quickly regulates the current while the outer loop controls the speed/torque**

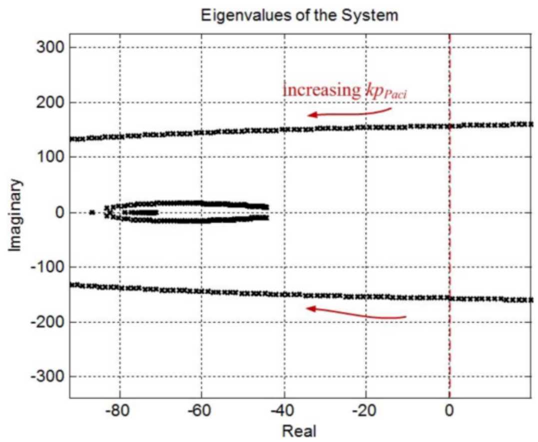
General Controller Design

- Controller design and gain selection does not exploit these fast/slow time scales
- These dynamical systems can be decomposed as follows:

$$\dot{x} = f(x,\ z,\ u,\ d) \qquad \text{Slow states}$$

$$\dot{z} = g(x,\ z,\ u,\ d) \qquad \text{Fast states}$$

- Typical controller design linearizes the **entire** system
- Stability is thus analyzed locally
- PI gains can be tuned/obtained using Routh-Locus techniques or bode plots



- **What advantages can we gain from separating the fast/slow states?**

Main Assumptions

- Control designs for these systems generally falls under singular perturbation techniques

$$\dot{x} = f(x,\ z,\ u,\ d) \qquad \text{Slow states}$$

$$\epsilon\dot{z} = g(x,\ z,\ u,\ d) \qquad \text{Fast states}$$

where $0 < \epsilon \ll 1$

- **Assumption 1:** The slow modes are relatively **constant** when seen through the fast dynamics

$$\epsilon\dot{z} = g(\bar{x},\ z,\ u,\ d) = \tilde{g}(z,\ u,\ d)$$

- **Assumption 2:** The fast modes are **instantaneous** when analyzing the slow states:

$$\dot{x} = f(x,\ z,\ u,\ d)$$

$$0 = g(x,\ z,\ u,\ d)$$

Outline

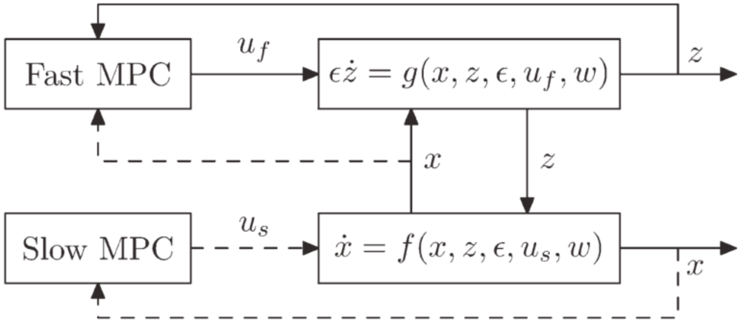
- Introduction and Motivation
- **Proposed Controller Design**
- Application to IPMSG in DC Microgrids
- Simulation Results
- Conclusion

Controller Design Using Singular Perturbation

- Based on the previous two assumptions, one of the most common controllers used for these systems is of the following form [1]:

$$\begin{aligned} \dot{x} &= f(x,\ z,\ u,\ d) \\ \epsilon \dot{z} &= g(x,\ z,\ u,\ d) \end{aligned}, \qquad u_c(x,\ z) = \underbrace{\mu_s(x)}_{\text{slow}} + \underbrace{\mu_f(z)}_{\text{fast}}$$

- The idea is to design the control law as a summation of two components, slow and fast



Chen, Xianzhong, et al. "Composite fast-slow MPC design for nonlinear singularly perturbed systems." *AIChE Journal* 58.6 (2012): 1802-1811.

- However, **this loses the typical** inner/outer loop control of structure used in power applications

[1] J. Chow and P. Kokotovic, "A decomposition of near-optimum regulators for systems with slow and fast modes," in *IEEE Transactions on Automatic Control*, vol. 21, no. 5, pp. 701-705, October 1976, doi: 10.1109/TAC.1976.1101342.

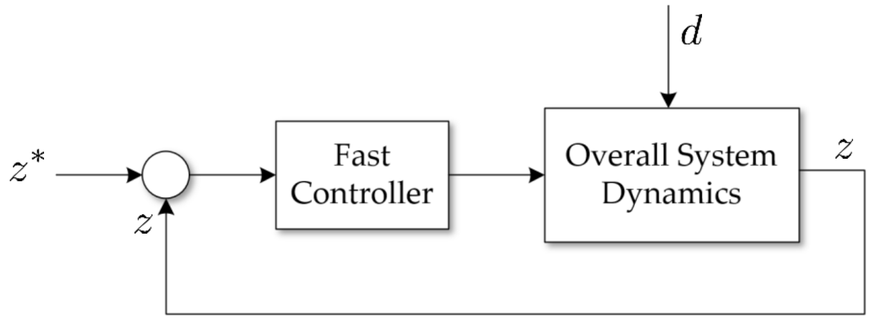
Proposed Controller Design

- The proposed controller design considers the same assumptions, but maintains the inner/outer loop loops

$$\begin{aligned} \dot{x} &= f(x,\ z,\ u,\ d) \\ \epsilon \dot{z} &= g(x,\ z,\ u,\ d) \end{aligned}$$

- **Step 1:** Design inner current control to track a reference, z^*, through u. Recall (assumption 1):

$$\epsilon \dot{z} = g(\underbrace{\bar{x}}_{\text{constant}},\ z,\ u,\ d) = \tilde{g}(z,\ u,\ d)$$



Proposed Controller Design (cont'd)

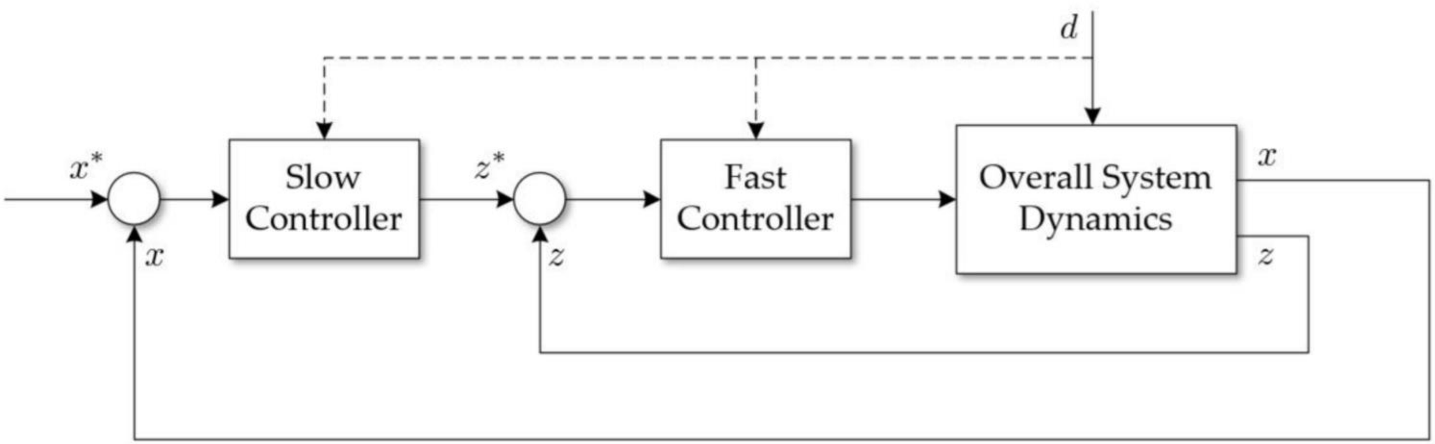
- The proposed controller design considers the same assumptions, but maintains the inner/outer loop loops

$$
\begin{aligned}
\dot{x} &= f(x,\ z,\ u,\ d) \\
\epsilon \dot{z} &= g(x,\ z,\ u,\ d)
\end{aligned}
$$

- **Step 1:** Design inner current control to track a reference, z^*, through u. Recall: $\dot{z} = \tilde{g}(z,\ u,\ d)$ (assumption 1)

- **Step 2:** From $0 = g(x,\ z,\ u,\ d)$, let $u = p(x,\ z,\ d)$ (assumption 2).

  This implies that $\dot{x} = \tilde{f}(x,\ z^*,\ d)$. Control $x \to x^*$ through z^*



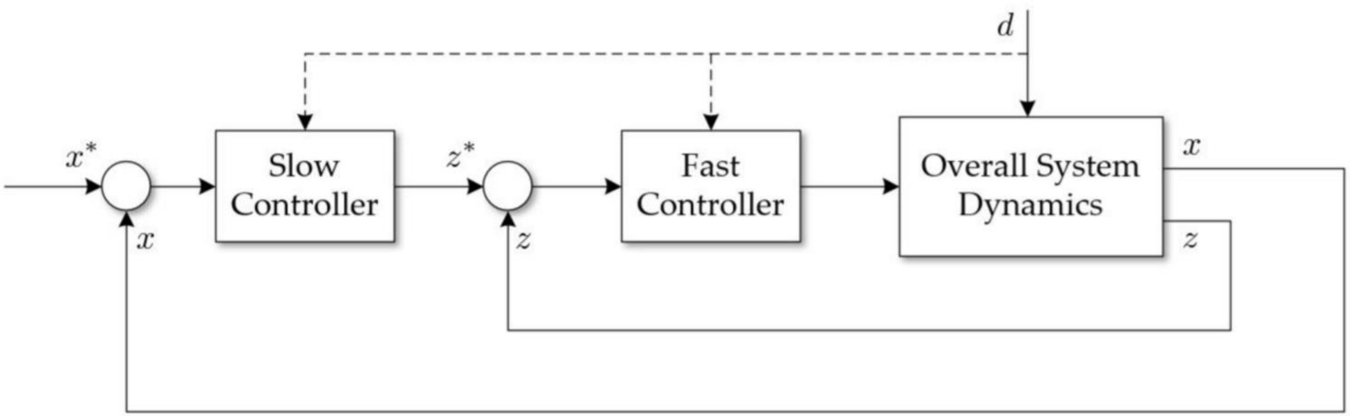
Remarks

Advantages

- The proposed controller design maintains the typical inner/outer loop structure
- Helpful in applications where it is desired to track the slow states (voltage, speed, etc.)

Disadvantages

- The fast controller design must ensure its closed loop system is still fast, such that it can be considered **instantaneous** by the outer loop system



Outline

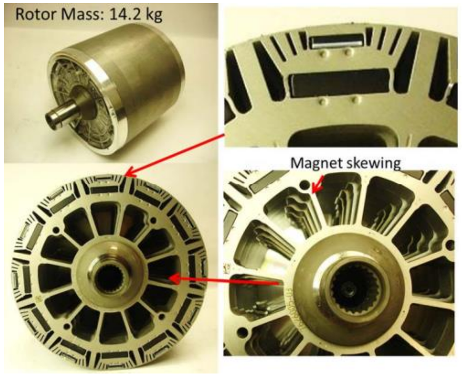
- Introduction and Motivation
- Proposed Controller Design
- **Application to IPMSG in DC Microgrids**
- Simulation Results
- Conclusion

IPMSG Based DC Source

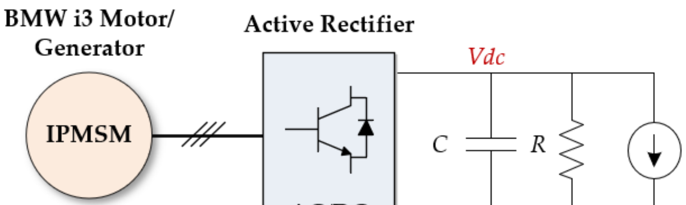
- The BMW i3 has as primary electric machine an Interior Permanent Magnet Synchronous Machine (IPMSM)
- This machine is primarily used as a motor in an EV

- Consider the use of this machine as a main generator in a dc microgrid (e.g. MEA, electric ships, etc.)
- ***Main Goal:*** regulate the dc bus voltage – active rectification

https://www.truecar.com/prices-new/bmw/i3-pricing/

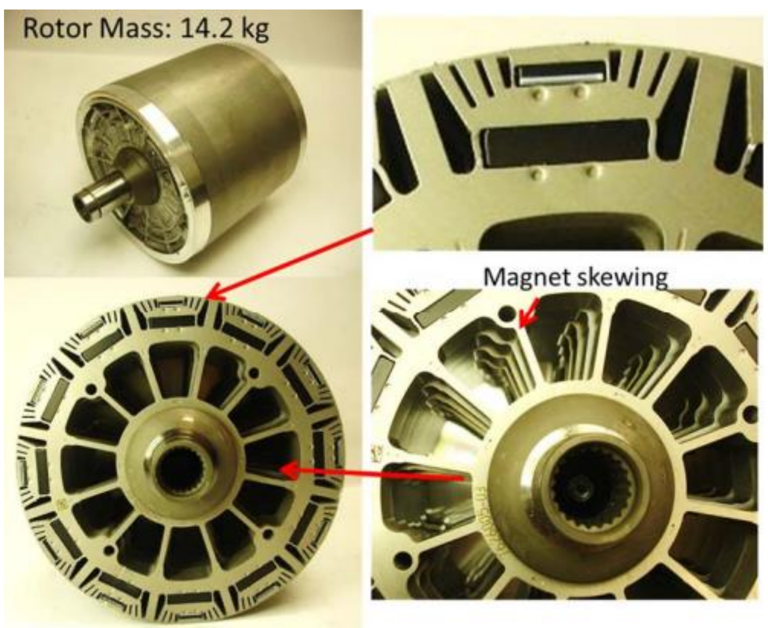


Source: ORNL annual progress report for the electric drive technologies program, 2016.

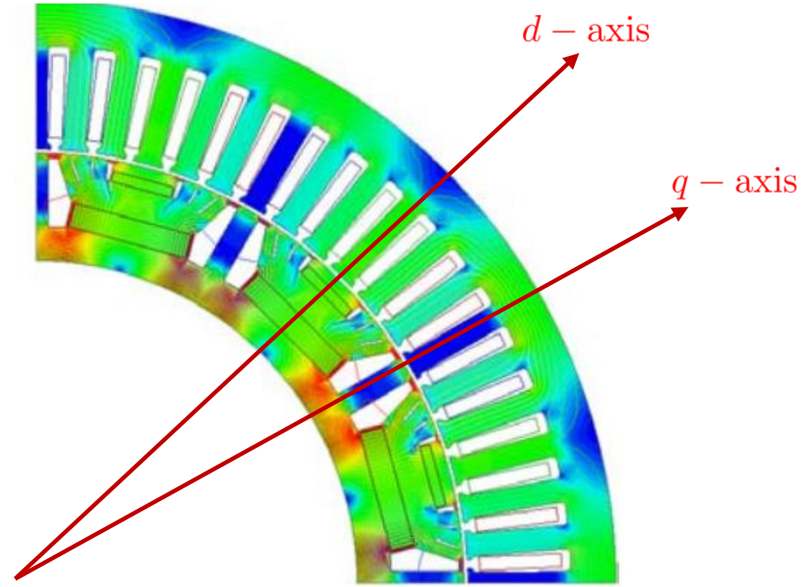


BMW i3 IPMSM Overview

- The BMW i3 motor/generator design is based on an interior permanent magnet synchronous machine (IPMSM)
- IPMSM take advantage of saliency in the rotor in order to add a reluctance torque which helps to further increase available torque



Source: ORNL annual progress report for the electric drive technologies program, 2016.



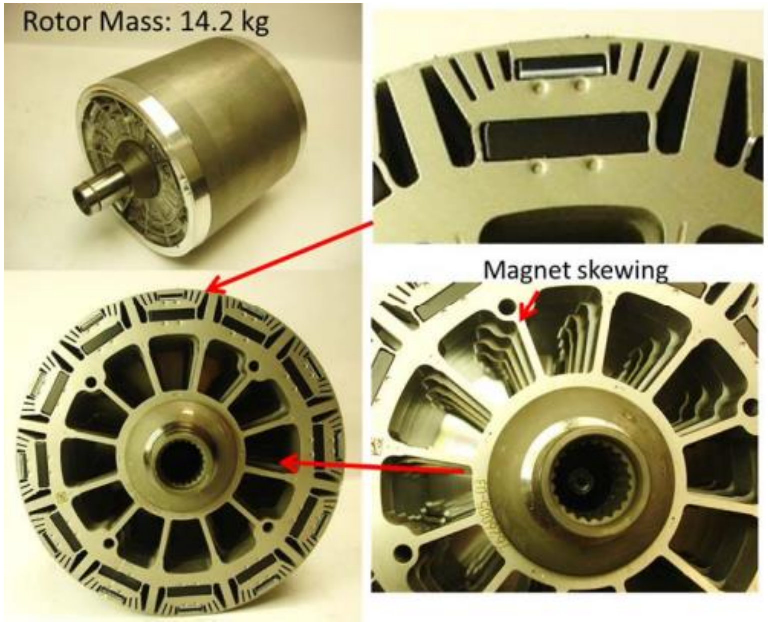
Source: Dajaku, G., et al. "Novel Rotor Design with Reduced Rare-Earth Material for PM Machines." 2019 IEEE International Electric Machines & Drives Conference (IEMDC). IEEE, 2019.

BMW i3 Electric Machine Rating Values

- The BMW i3 motor/generator design is based on an interior permanent magnet synchronous machine (IPMSM)
- The ratings and baseline parameters are as follows:

BMW i3 Motor Specifications	
Maximum Torque (Nm)	250
Maximum Speed (rpm)	11400
Voltage Range (V)	250 – 400
Max phase current (A)	400
Total Poles	12
Open circuit voltage @ 11400 rpm (Vpeak - LN)	275
Peak Power (kW)	125

Source: J. Hendershot, BMW i3 E-traction drive presentation, 2017



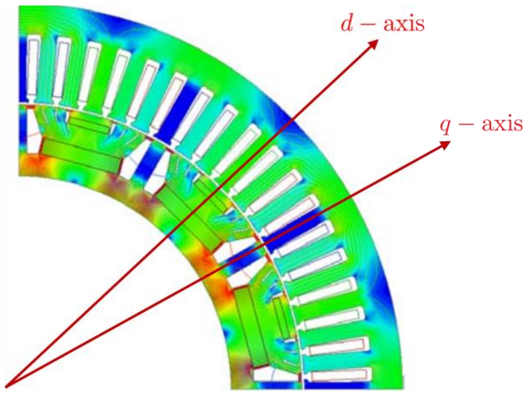
Source: ORNL annual progress report for the electric drive technologies program, 2016.

IPMSM vs SPMSM

- Permanent Magnet Synchronous Machines (PMSM) can be categorized into two types:
  - Surface (mounted) PMSM (SPMSM)
  - Interior PMSMS

- **IPSMS can product torque through both its permanent magnets and the saliency of the rotor (reluctance torque)**
- Therefore, the following applies:
  - SPMSM: $L_d = L_q$ since the magnetic paths are approximately equal
  - IPMSM: $L_q \geq L_d$ since the d axis reluctance is higher

$$L \triangleq \frac{N^2}{\mathcal{R}}$$



Source: Dajaku, G., et al. "Novel Rotor Design with Reduced Rare-Earth Material for PM Machines." 2019 IEEE International Electric Machines & Drives Conference (IEMDC). IEEE, 2019.

Dynamic Equations for an Active Rectifier

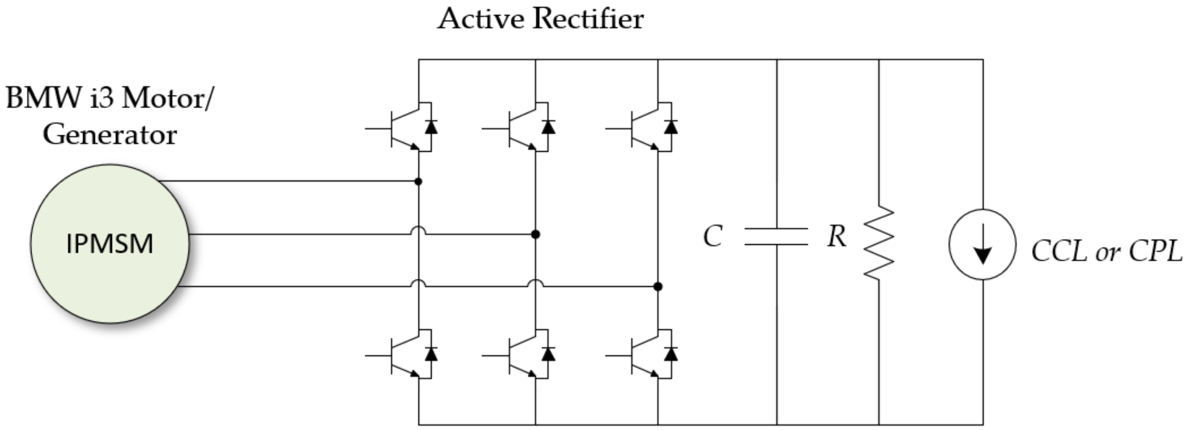
- Consider the active rectifier shown below
- The dynamic equations are as follows:

$$\text{(dc)} \left\{ \dot{v}_{dc} = -\frac{1}{RC}v_{dc} + \frac{3}{2C}\frac{1}{v_{dc}}\left(v_d i_d + v_q i_q\right) - \frac{1}{C}i_L \right. \qquad \text{(Slow state)}$$

$$\text{(ac)} \left\{ \begin{aligned} \dot{i}_d &= \frac{-R_s}{L_d}i_d + \omega_r \frac{L_q}{L_d}i_q + \frac{1}{L_d}v_d \\ \dot{i}_q &= \frac{-R_s}{L_q}i_q - \omega_r \frac{L_d}{L_q}i_d - \frac{\omega_r}{L_q}\lambda_m + \frac{1}{L_q}v_q \end{aligned} \right. \qquad \text{(Fast states)}$$

Table 1: PMSM parameters based on the BMW i3 motor/generator [1-2].

L_d	0.090 mH	L_q	0.255 mH	λ_m	0.0385 Vs
r_s	5.3 mΩ	$n_{\max}$	11400 rpm	Poles	12
$T_{\max}$	250 Nm	$P_{\max}$	125 kW	$I_{\text{phase-peak}}$	400 A



[1] J. Hendershot, BMW i3 E-traction drive presentation, 2017
[2] Dajaku, G., et al. "Novel Rotor Design with Reduced Rare-Earth Material for PM Machines." 2019 IEEE International Electric Machines & Drives Conference (IEMDC). IEEE, 2019.

Inner Loop: Current Regulator Design

- **Step 1:** Design inner current control to track a reference, z^*, through u. Recall: $\dot{z} = \tilde{g}(z,\ u,\ d)$ (assumption 1)

$$
\text{(ac)} \begin{cases} \dot{i}_d &= \frac{-R_s}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q + \frac{1}{L_d} v_d \\ \dot{i}_q &= \frac{-R_s}{L_q} i_q - \omega_r \frac{L_d}{L_q} i_d - \frac{\omega_r}{L_q}\lambda_m + \frac{1}{L_q} v_q \end{cases}
\qquad
\begin{aligned} v_d &= d_d \frac{v_{dc}}{2} \\ v_q &= d_q \frac{v_{dc}}{2} \end{aligned}
\quad \Rightarrow \quad v_x = d_x \frac{\bar{v}_{dc}}{2}
$$

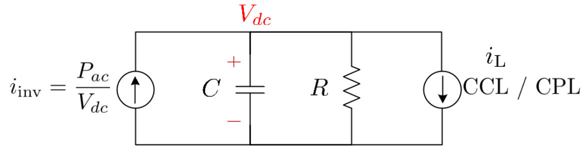
- The fast current dynamics use an average value of $\bar{v}_{dc}$
- Standard PI control + decoupling techniques can be used
- Used output regulation techniques [1]

[1] Herrera, Luis, Chad Miller, and Bang-Hung Tsao. "Nonlinear Model Predictive Control of Permanent Magnet Synchronous Generators in DC Microgrids." *arXiv preprint arXiv:2010.04069* (2020).c

Outer Loop: DC Bus Voltage Tracking

- **Step 2:** From $0 = g(x,\ z,\ u,\ d)$, let $u = p(x,\ z,\ d)$. This implies that $x = \tilde{f}(x,\ z^*,\ d)$. Control $x \to x^*$ through z^*

$$(\mathrm{dc}) \left\{ \begin{aligned} \dot{v}_{dc} &= -\tfrac{1}{RC} v_{dc} + \tfrac{3}{2C} \tfrac{1}{v_{dc}} (v_d i_d + v_q i_q) - \tfrac{1}{C} i_L \quad , \end{aligned} \right.$$

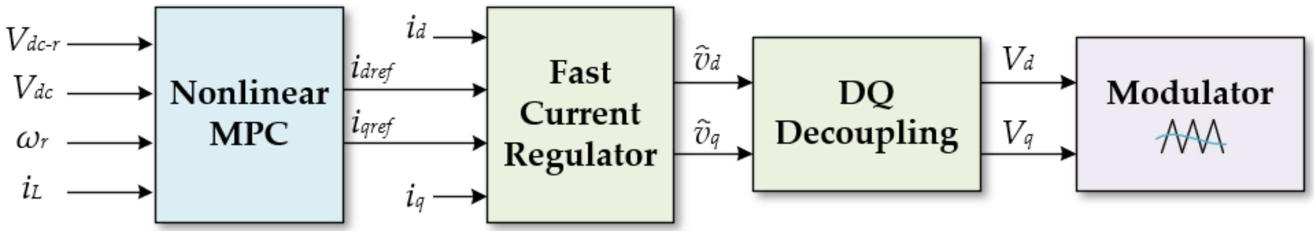


$$\begin{aligned} v_d &= -r_s i_d + \omega_r L_q i_q \\ v_q &= -r_s i_q - \omega_r L_d i_d - \omega_r \lambda_m \end{aligned}$$

$$\Rightarrow \dot{v}_{dc} = -\frac{1}{RC} v_{dc} - \frac{1}{C} i_L + \frac{3}{2C} \frac{1}{v_{dc}} \left(-r_s (i_d^2 + i_q^2) + \omega_r (L_q - L_d) i_q i_d - \omega_r \lambda_m i_q \right)$$

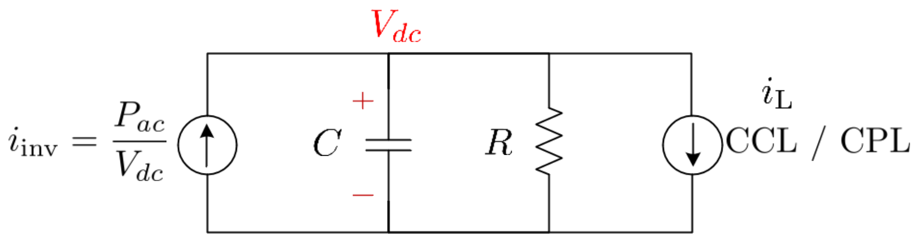
$$\dot{e}_{\text{int}} = -v_{\text{dc}} + v_{\text{dc}}^*$$

- The new inputs are then $i_d,\ i_q$ (become reference to inner loop)



Nonlinear Model Predictive Control Formulation

- The dynamic equation for the dc side voltage is **nonlinear**



- State: $x = V_{dc}$
- Inputs $u = [i_d,\ i_q]^T$
- Disturbance $d = i_L$

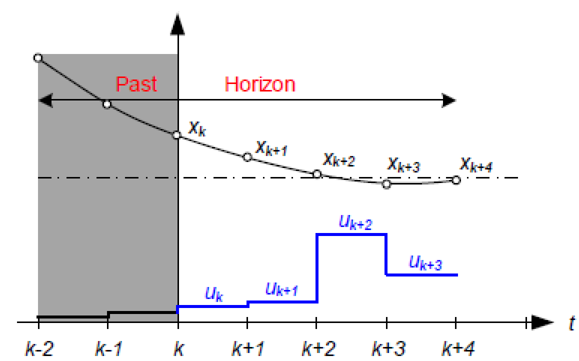
- Nonlinear Model Predictive Control goals:
  1. Regulate the dc side voltage to a desired reference
  2. Minimize the ac side current peak (minimize stator losses)

$$\min_{x_k,\, u_k} \sum_{k=0}^{N-1} (x_k - x_{\text{ref}})^T Q (x_k - x_{\text{ref}}) + u_k^T R u_k + (x_N - x_{\text{ref}}) Q (x_N - x_{\text{ref}})$$

s.t.

$$\begin{cases} x_{k+1} = f_d(x_k,\ u_k,\ d_k) \\ \|u_k\|_2^2 \le I_{\text{peak}}^2 \quad \text{for } k = 0,\ \ldots,\ N-1 \\ (\omega_r L_q u_{2,k})^2 + (\omega_r L_d u_{1,k} + \omega_r \lambda_m)^2 \le \left(\frac{x_{1,k}}{2}\right)^2 \end{cases}$$

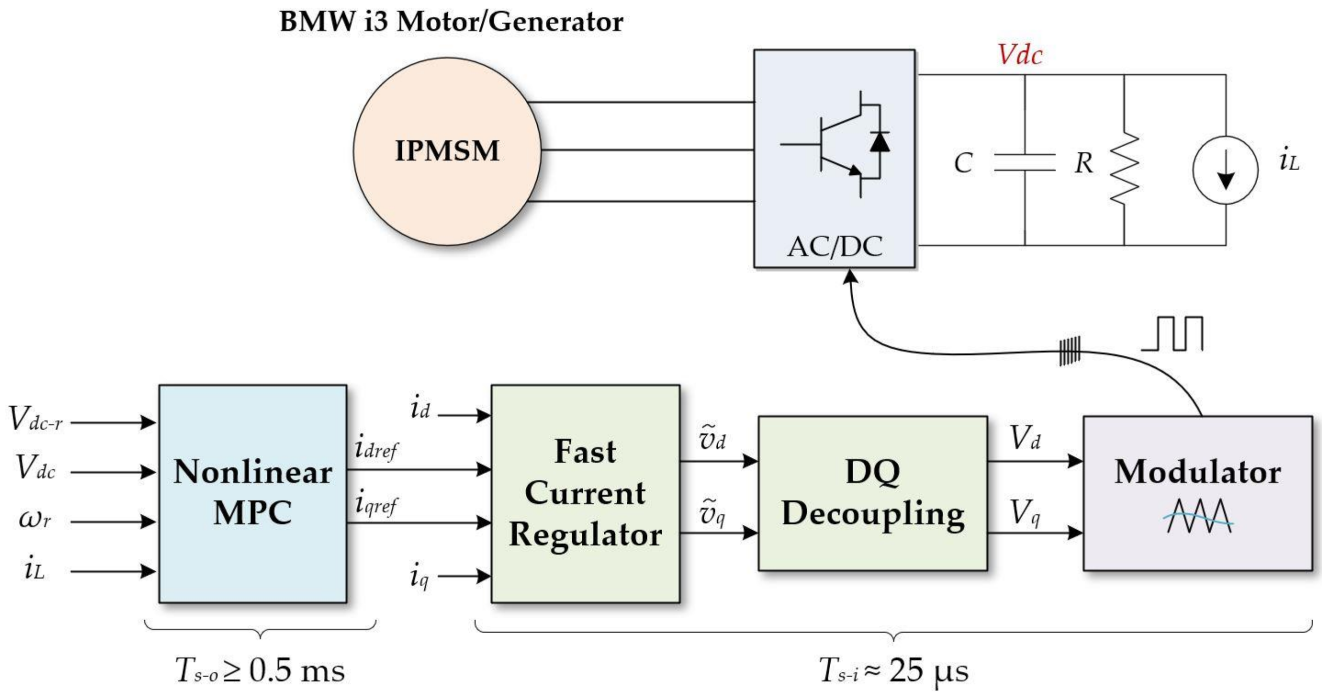
$$V_{\text{dc-min}} \le x_{1,k} \le V_{\text{dc-max}} \quad \text{for } k = 1,\ \ldots,\ N$$



Source: T. Geyer, MPC of high PE and drives, 2017.

Overall Control Structure using NMPC

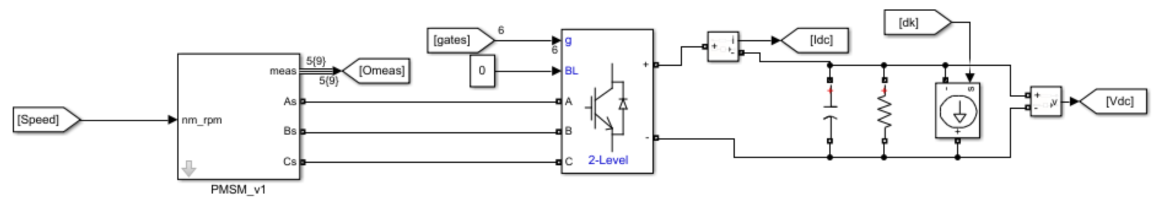
- The overall algorithm includes NMPC, current regulator, and modulator as shown below

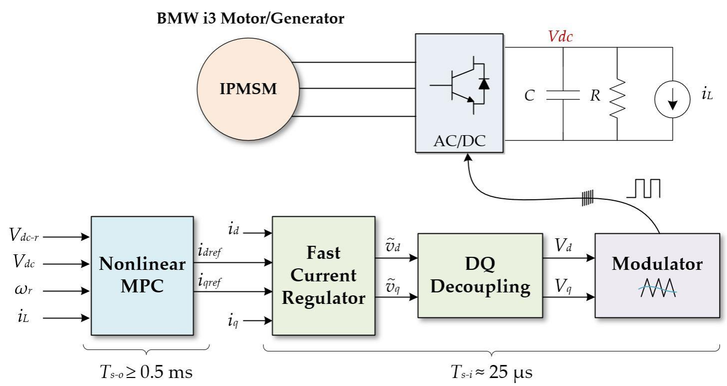


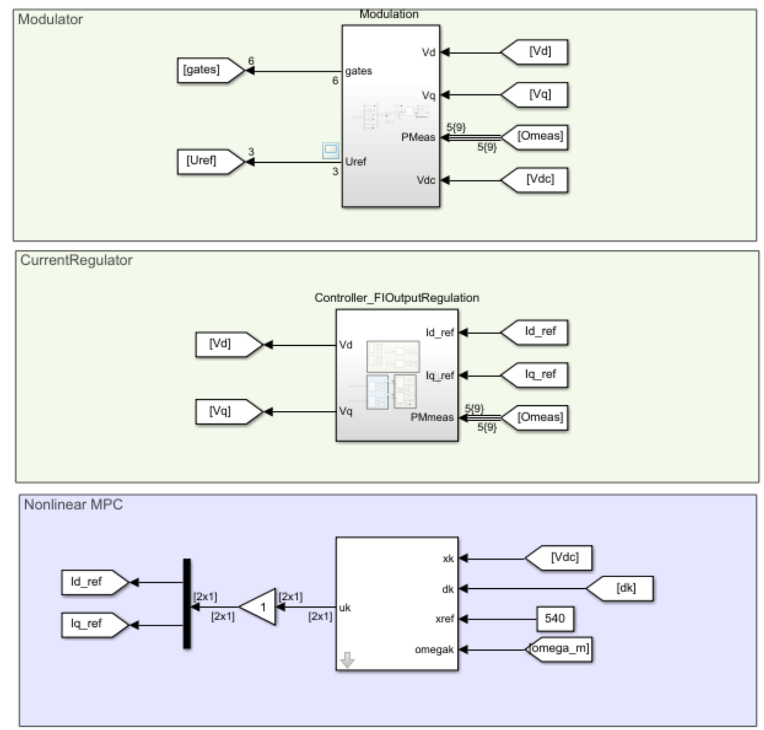
- The proposed analysis allows us to obtain a nonlinear model of the dc voltage in terms of currents

Matlab Simulation Model

- The PMSG based dc source is implemented in Matlab Simulink along with the proposed controller
- The discretization rates are set within each subsystem.

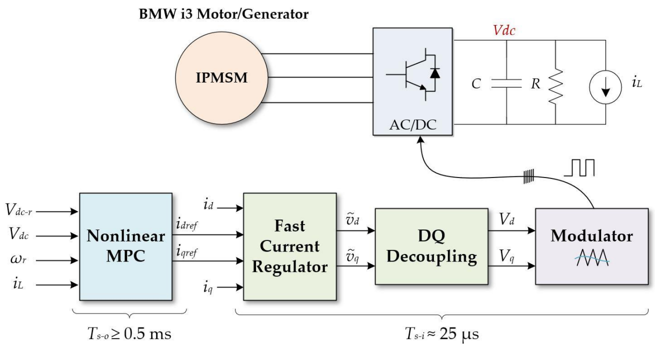






Optimal Operation of the IPMSG

- The optimal operation of the IPMSM in generation mode can be viewed as an optimization problem:



$$\min_{i_d,\, i_q} \quad i_d^2 + i_q^2 \longrightarrow \text{(peak ac current)}$$

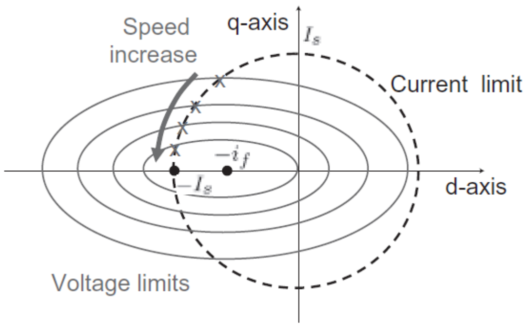
s.t.

$$\tfrac{3}{2}\omega_r\left(\lambda_m i_q + (L_d - L_q) i_q i_d\right) = P_e \longrightarrow (P_{\mathrm{ac}} = P_{\mathrm{dc}})$$

$$i_d^2 + i_q^2 \leq I_{\mathrm{peak}}^2 \longrightarrow \text{(current limit)}$$

$$(\omega_r L_q i_q)^2 + (\omega_r L_d i_d + \omega_r \lambda_m)^2 \leq \left(\tfrac{v_{\mathrm{dc}}}{2}\right)^2 \longrightarrow \text{(voltage limits)}$$

- It can be shown that the proposed NMPC operates at optimal point during steady state [1]



[1] Herrera, Luis, Chad Miller, and Bang-Hung Tsao. "Nonlinear Model Predictive Control of Permanent Magnet Synchronous Generators in DC Microgrids." *arXiv preprint arXiv:2010.04069* (2020)

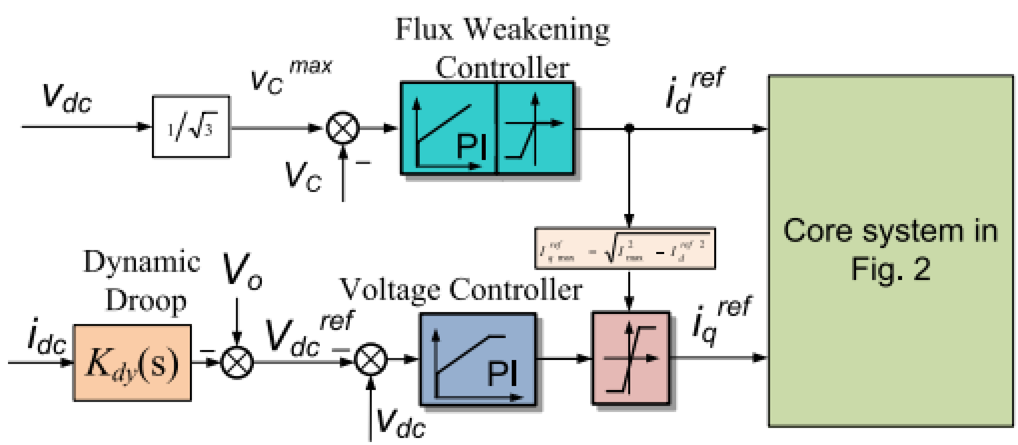
Outline

- Introduction and Motivation
- Proposed Controller Design
- Application to IPMSG in DC Microgrids
- **Simulation Results**
- Conclusion

Baseline Control Structure

- In available literature, the control schemes are typically decomposed into two parts:
  1. **Fast inner current regulator**
  2. **Outer loop controlling dc bus voltage**

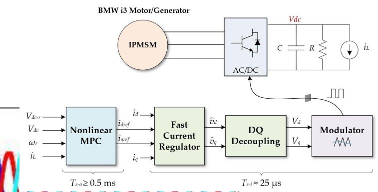
- The q-axis current regulates the dc bus voltage
- The d-axis current regulates the output ac bus voltage to be at maximum*

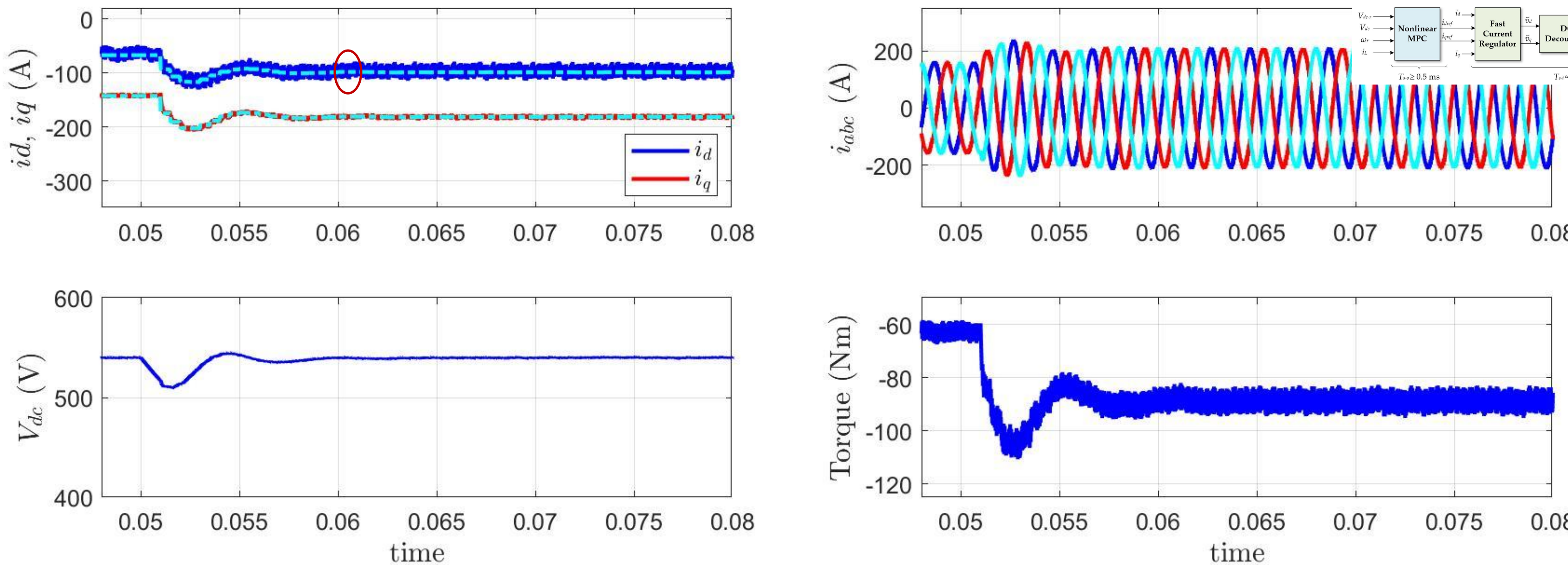


[1] Gao, Fei, et al. "Modal analysis of a PMSG-based DC electrical power system in the more electric aircraft using eigenvalues sensitivity." *IEEE Transactions on Transportation Electrification* 1.1 (2015): 65-76.
[2] Gao, Fei, and Serhiy Bozhko. "Modeling and impedance analysis of a single DC bus-based multiple-source multiple-load electrical power system." IEEE Transactions on Transportation Electrification 2.3 (2016): 335-346.

Case 1: NMPC Results for BMW i3 Generator – 540 Vdc

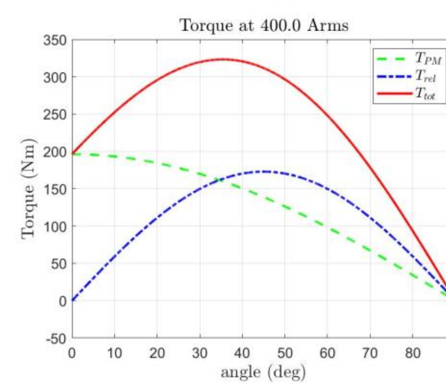
- Voltage regulation at 540 Vdc with a step load change of 33 kW to 47 kW
- **Mechanical speed** is 5000 rpm





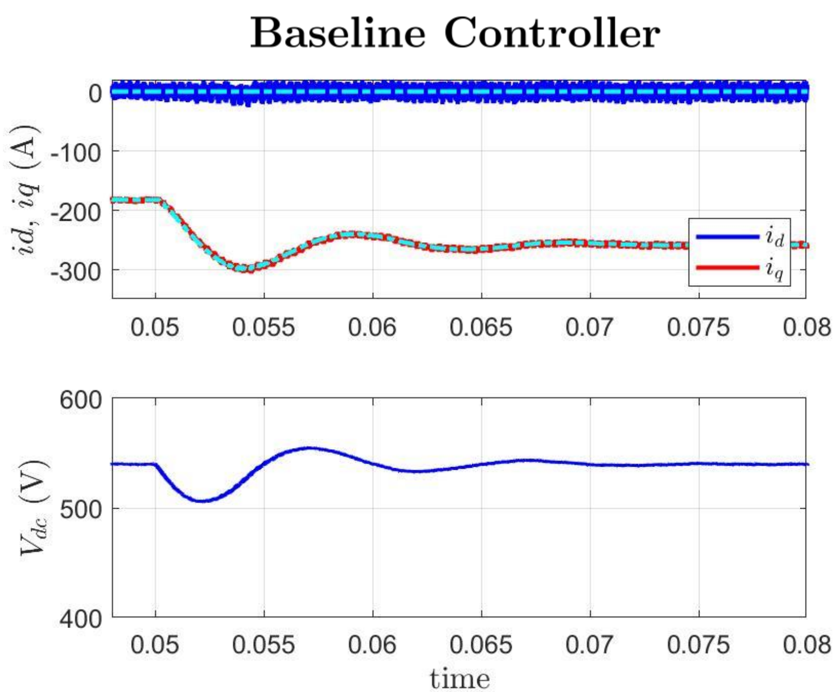
- Although flux weakening is not needed, it uses id current as well to regulate Vdc!
  (we are using PM + reluctance torque!)

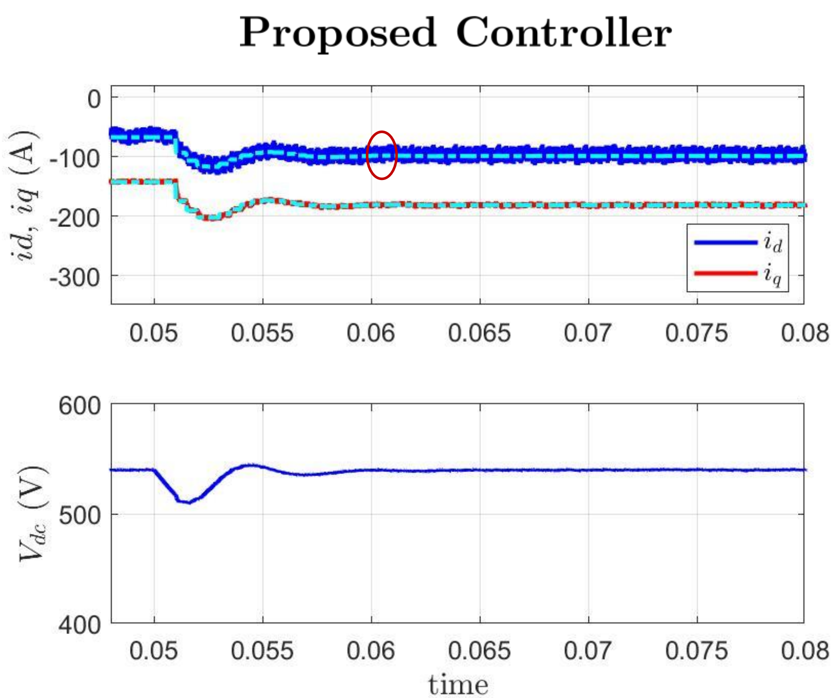
$$T = \left(\frac{3}{2}\frac{P}{2}\right)\left(\underbrace{\lambda_m i_q}_{\text{PM}} + \underbrace{(L_d - L_q) i_d i_q}_{\text{reluctance}}\right)$$



Case 1: NMPC comparison vs Baseline PI Controller

- Voltage regulation at 540 Vdc with a step load change of 33 kW to 47 kW
- **Mechanical speed** is 5000 rpm

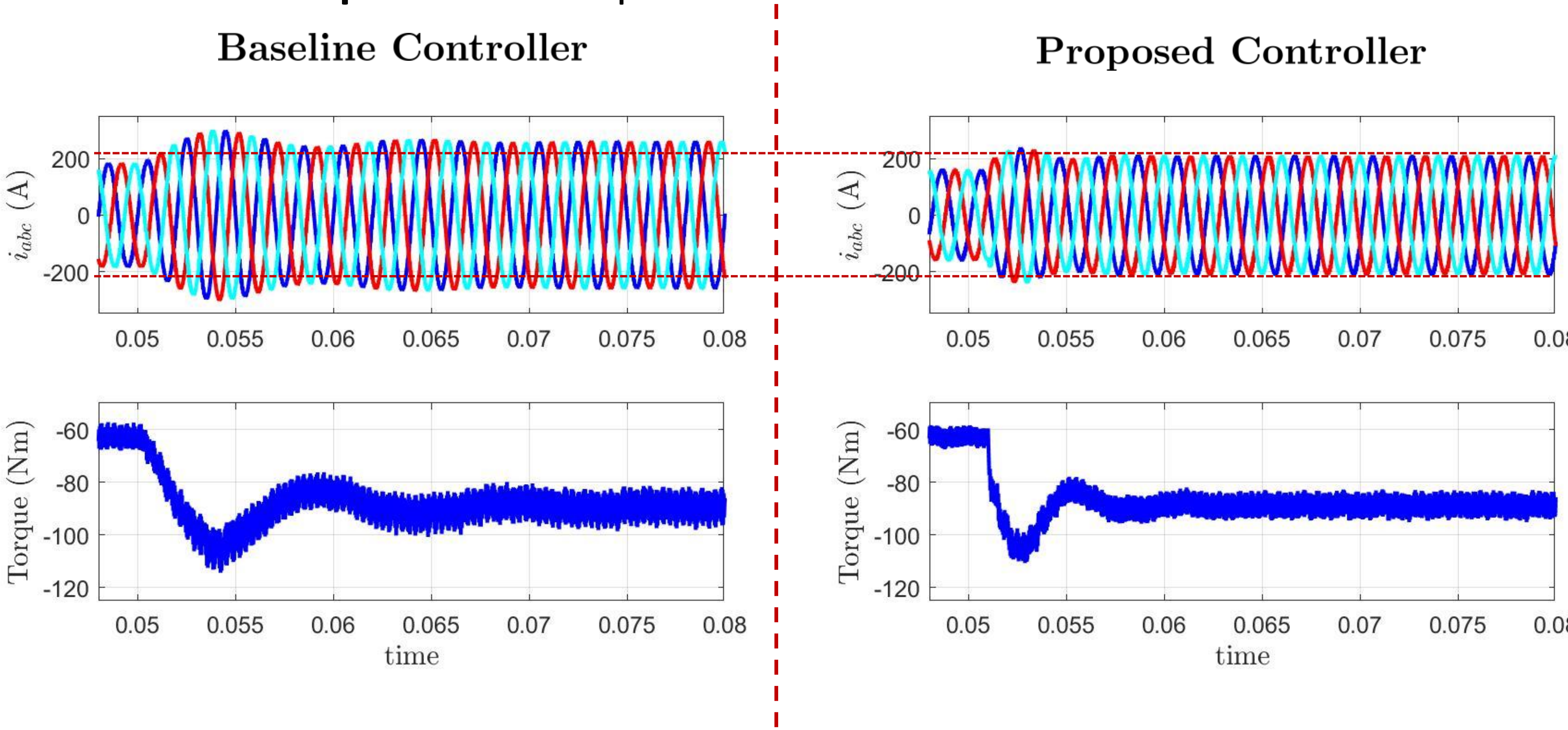




- Dynamically, the proposed controller can regulate Vdc very well
- Optimizes id and iq as well -> Ipk should be lower in proposed controller

Case 1: NMPC comparison vs Baseline PI Controller

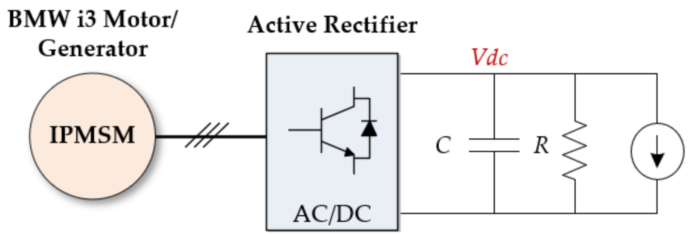
- Voltage regulation at 540 Vdc with a step load change of 33 kW to 47 kW
- **Mechanical speed** is 5000 rpm

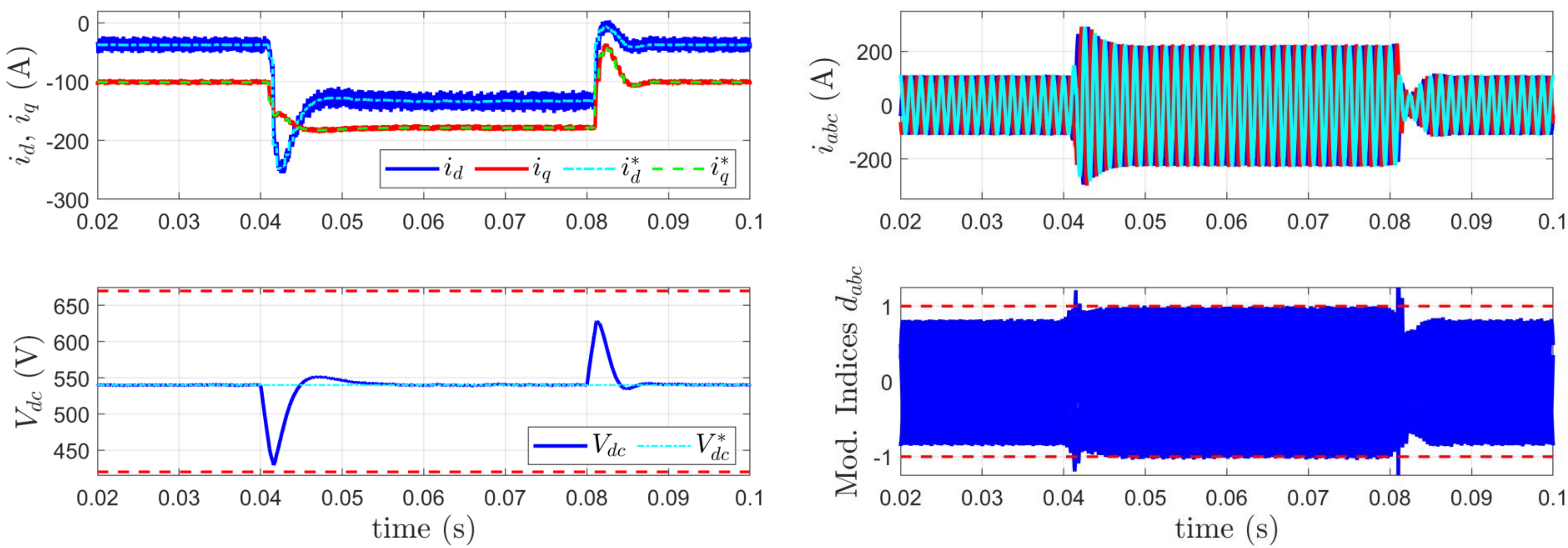


- **Proposed controller provides same torque with lower peak ac current!**
- Difference at 47 kW is around 50 A **(more efficient!)**

Case 2: Voltage Constrained Operation

- At higher speeds (more back emf), flux weakening may be needed
- NMPC is able to ensure operation at higher speeds while keeping voltage bounds
- In this case, *n* = 8000 rpm and pulsed load of 30 kW to 80 kW





Outline

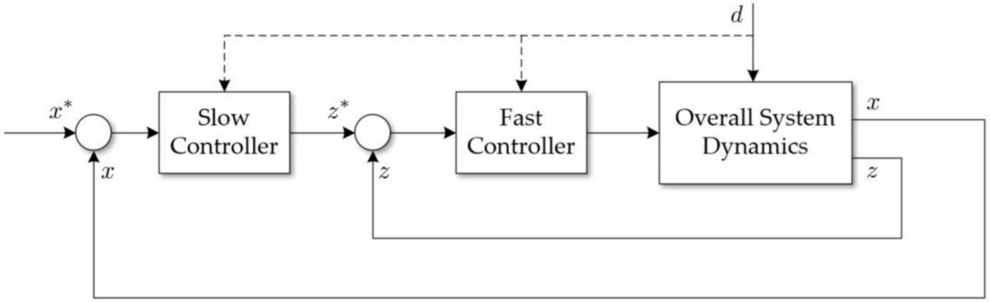
- Introduction and Motivation
- Proposed Controller Design
- Application to IPMSG in DC Microgrids
- Simulation Results
- **Conclusion**

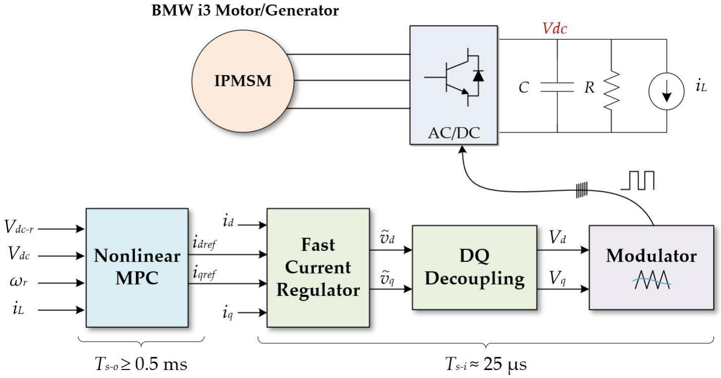
Conclusion

- Proposed a technique for the control of nonlinear systems with fast and slow states
- The proposed control maintains the conventional inner/outer loops used in power electronics and electric machines

----

- Developed a simulation model and control for a IPMSG based dc source with active rectification
- Proposed a Nonlinear MPC outer loop controller for Vdc regulation and optimization of id and iq (outer loop)
- The proposed controller is **optimal** at steady state





Thank you for your attention!