



VEA

VEHICLE ELECTRONICS AND ARCHITECTURE

HIGH PERFORMANCE CONTROLLERS BASED ON REAL PARAMETERS TO ACCOUNT FOR PARAMETER VARIATIONS DUE TO IRON SATURATION

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Outline

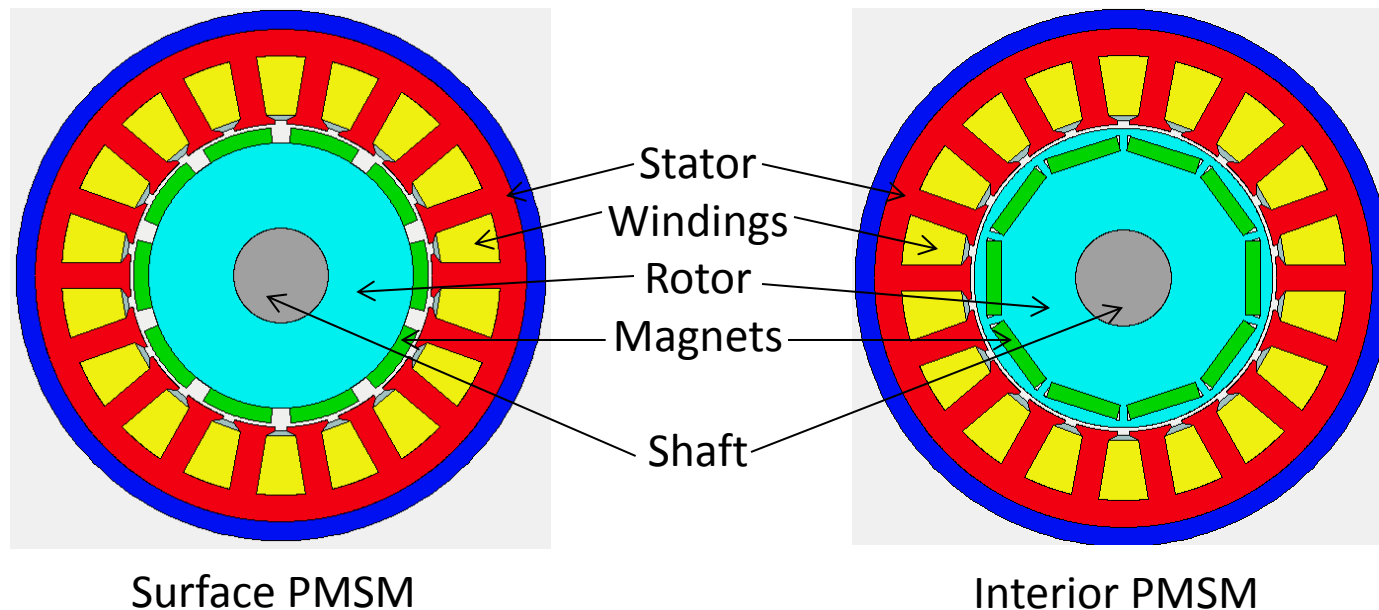
- Motivation
- Problem Statement
 - Experimental and FEA results comparison
- Proposed method
 - Linear Approximation Methods
- Performance Simulation
 - Based on experimental data.
 - Controllers based on different parametric data
- Conclusion

Motivation

- There is an increasing demand for high performance motor controllers.
 - Military ground vehicles
 - On-board vehicle power (125-160kW)
 - Electrification of vehicle loads (cooling fan, HVAC, etc...)
 - Transportation
 - Automotive industry
 - Mass transportation drives, etc.
 - Better energy generation and utilization
 - Smart Grid
 - Renewable energy
- The efficiency of a motor drive is dependent on the parameters used in the motor controller.

Motor Model

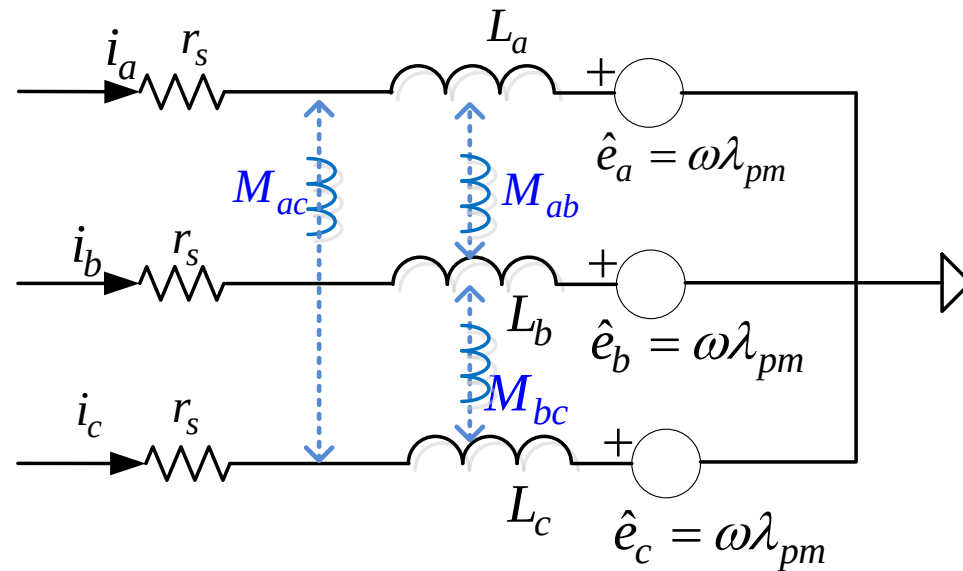
- Motor Types, (Surface PMSM and Interior PMSM)



- Windings are distributed in a balanced 3 phase configuration.
- Rotor magnets, induce a balanced 3 phase back EMF.

Three phase model

- Electrical model:



- Back EMF voltages, $e_{a,b,c}$, are produced by rotational magnetic induction.

Transformation into the dq axis model

- Using Park's transformation matrix:

$$P = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}$$

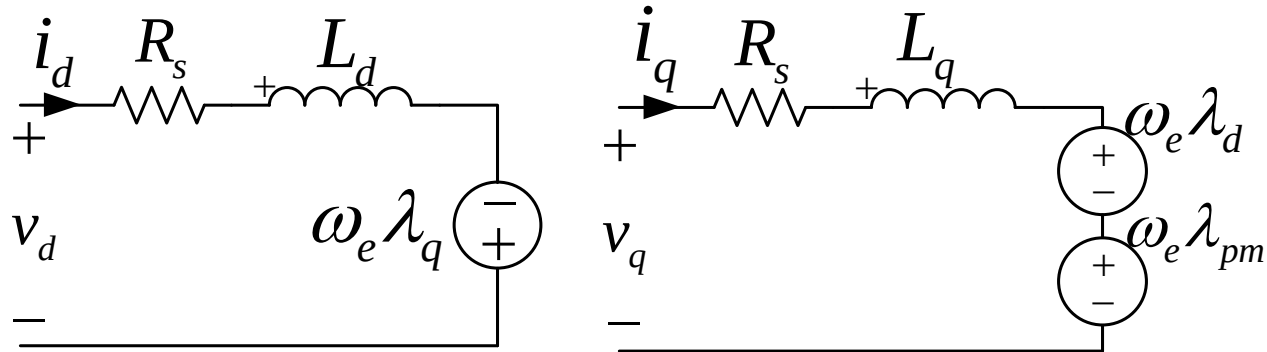
- To transform from 3 phase *abc* to 3 equivalent axes *dq0*:

$$x_{dq0} = P \cdot x_{abc}$$

- Under balanced condition zero sequence quantities are nullified.

dq motor Model

- The motor model:



$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_{pm}$$

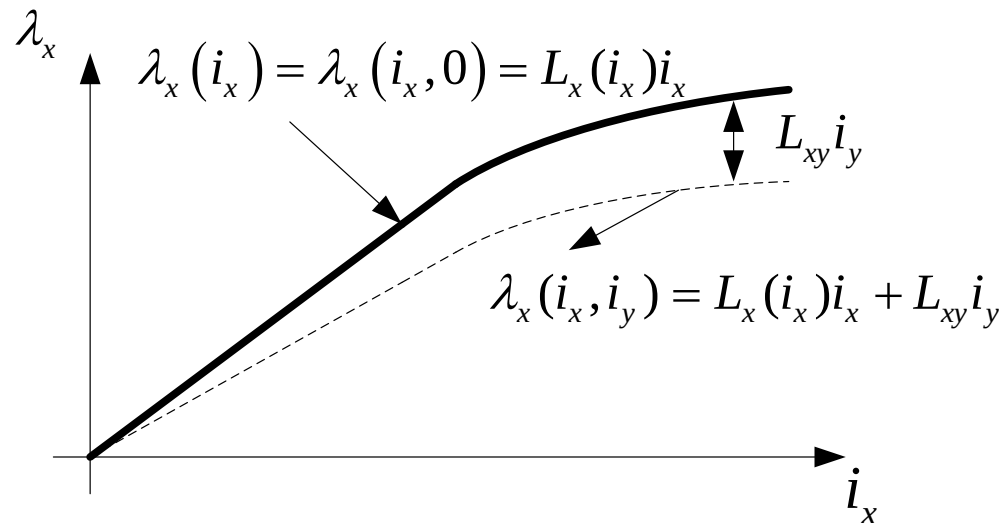
$$\lambda_d = L_d i_d + \lambda_{pm}$$

$$\lambda_q = L_q i_q$$

$$T = \frac{3P}{4} \{ \lambda_d i_q - \lambda_q i_d \}$$

Problem Statement

- The real situation, saturation:



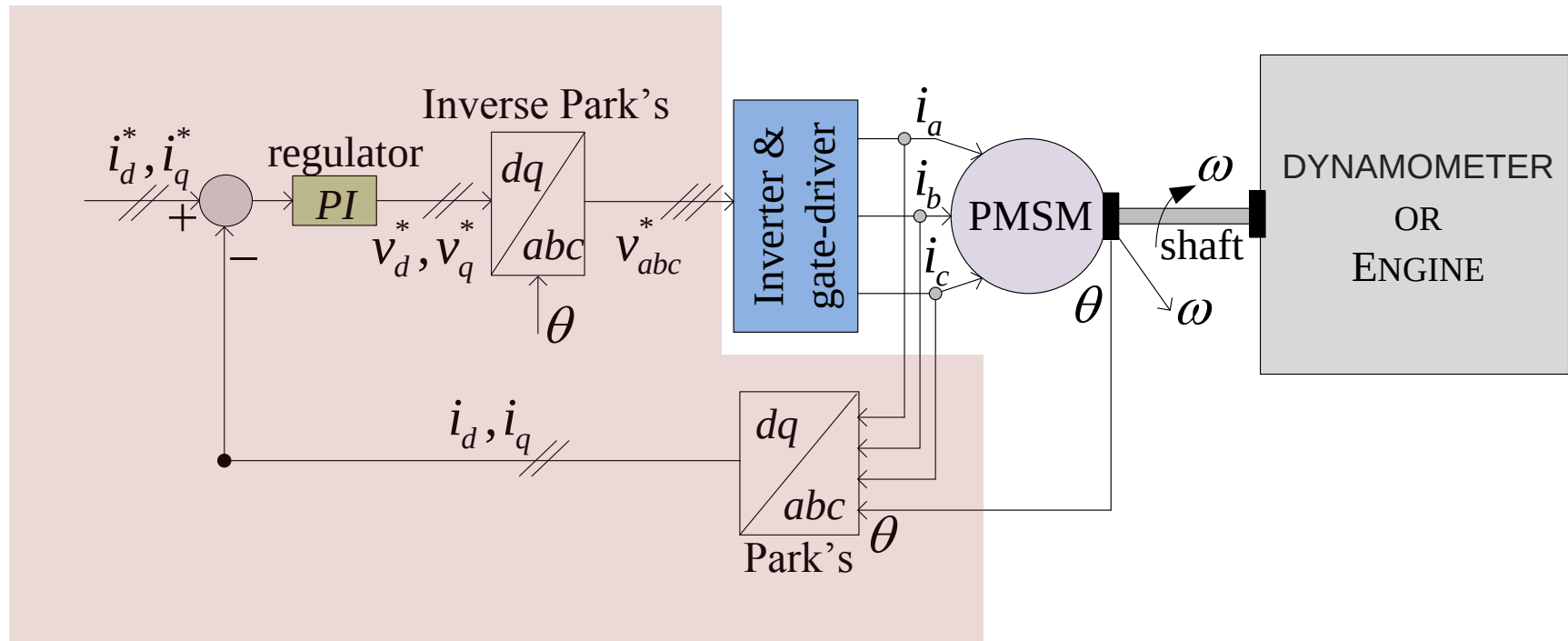
$$\lambda_d(i_d, i_q) = L_d(i_d)i_d + L_{dq}(i_d, i_q)i_q + \lambda_{pm}$$

$$\lambda_q(i_d, i_q) = L_q(i_q)i_q + L_{qd}(i_d, i_q)i_d$$

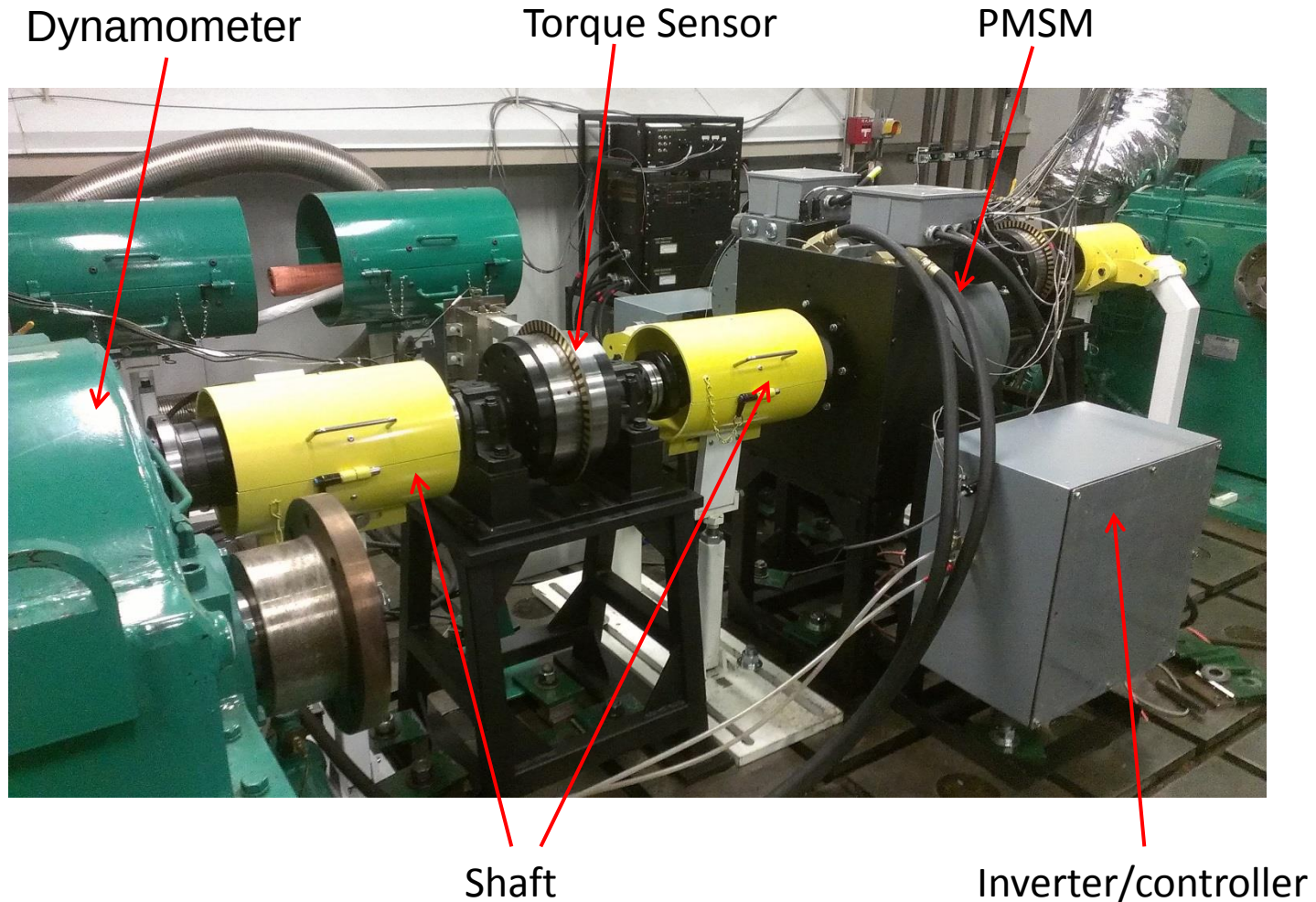
Experimental Setup

- Schematic diagram

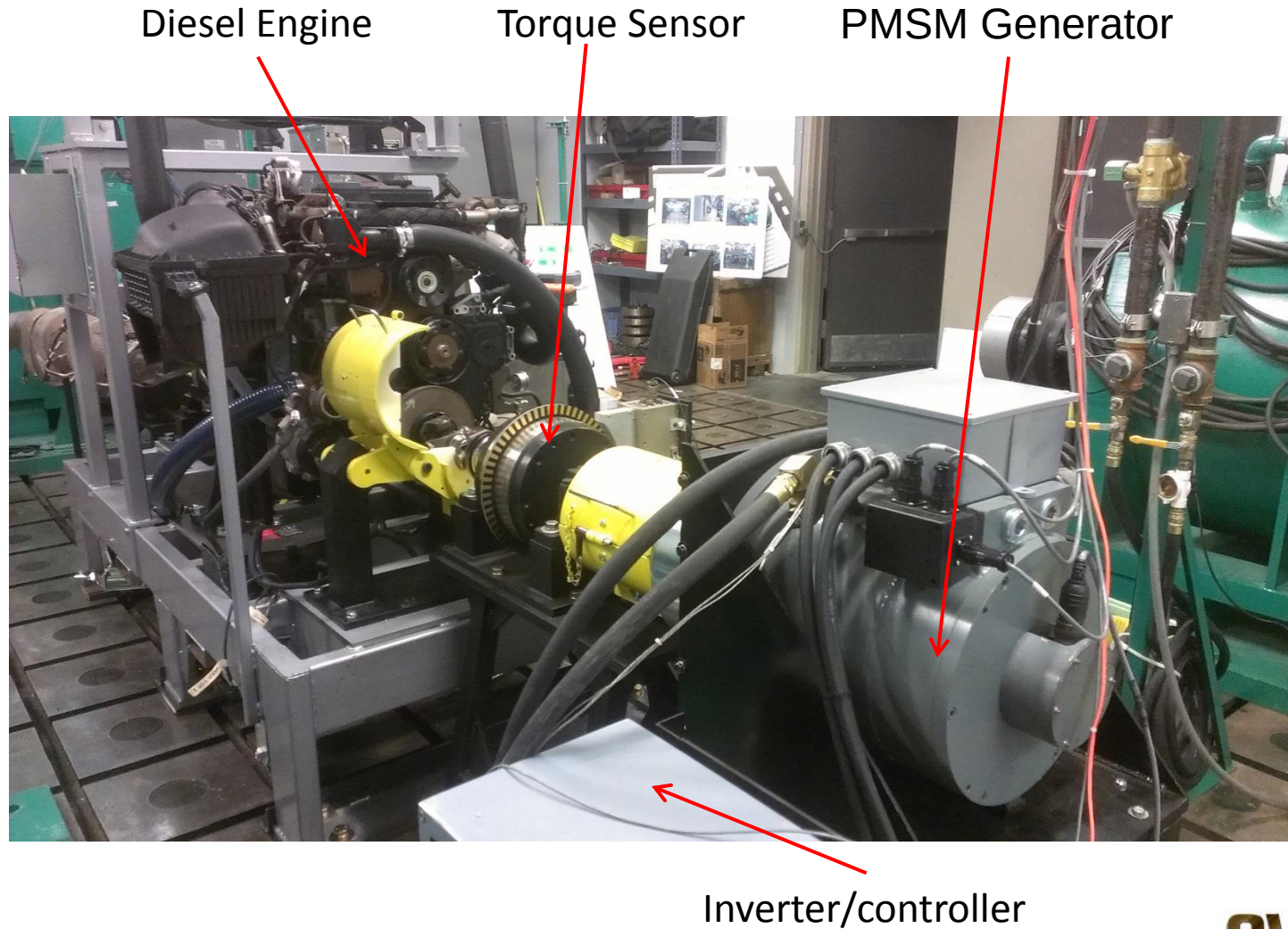
Controller



Experimental Setup with Dynamometer

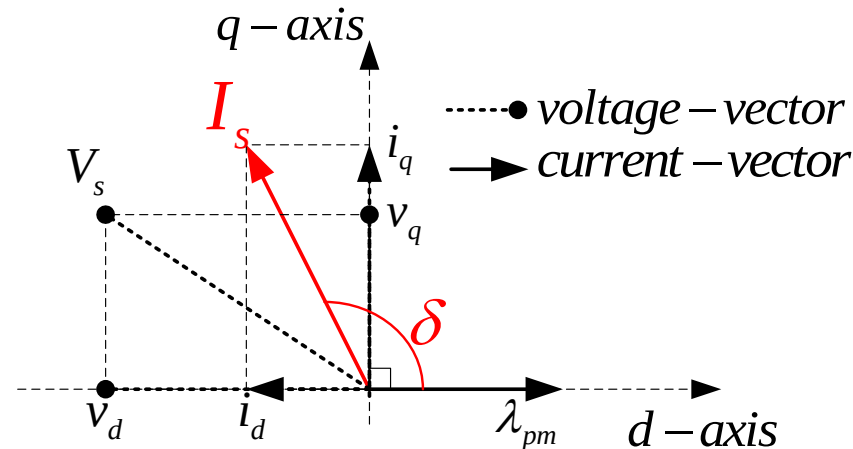


Experimental Setup with Engine



Experimental Characterization

- Data collection:
- The current space vector is swept in the region of interest.



- Flux calculation from measured data:

$$\lambda_d(i_d, i_q) = \frac{v_q - i_q R_s}{\omega_e}$$

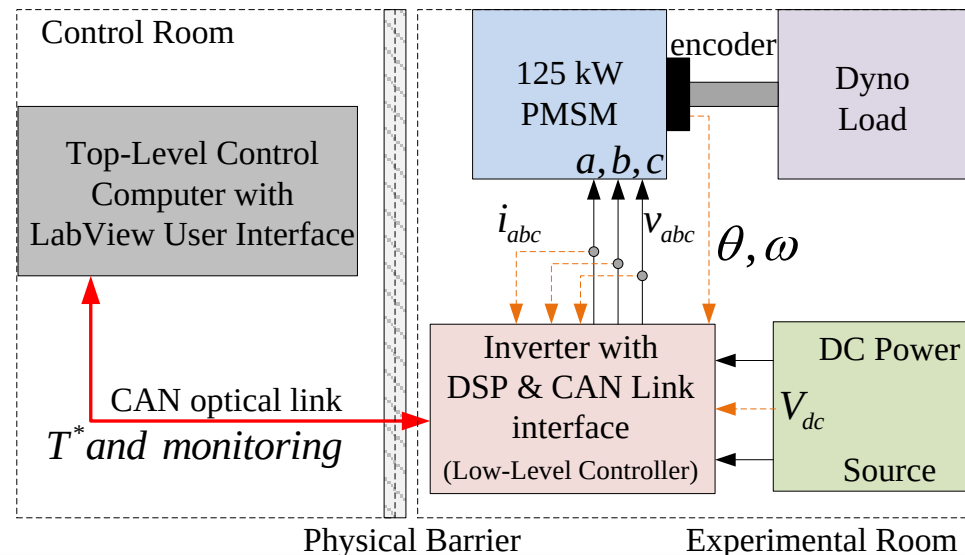
$$\lambda_q(i_d, i_q) = \frac{i_d R_s - v_d}{\omega_e}$$

Characterization Results

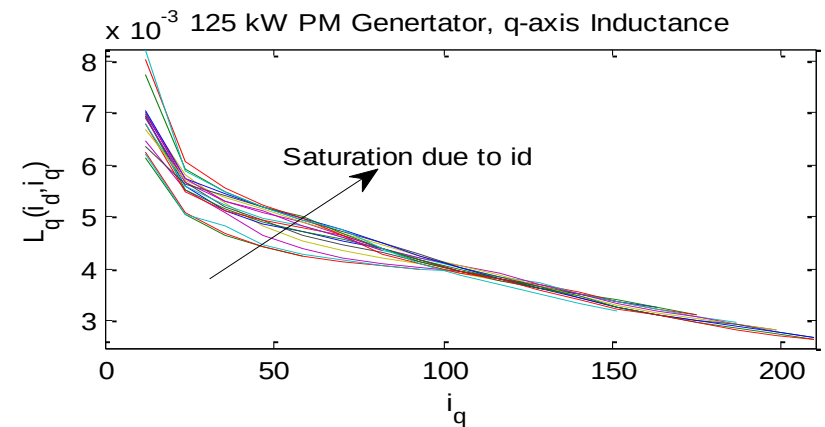
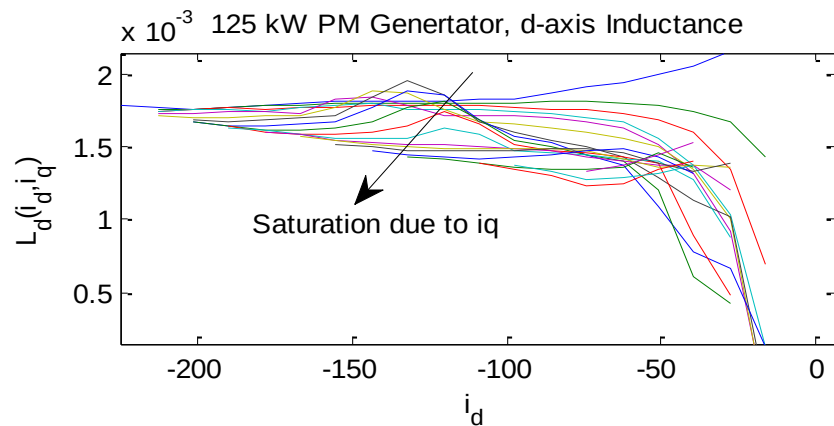
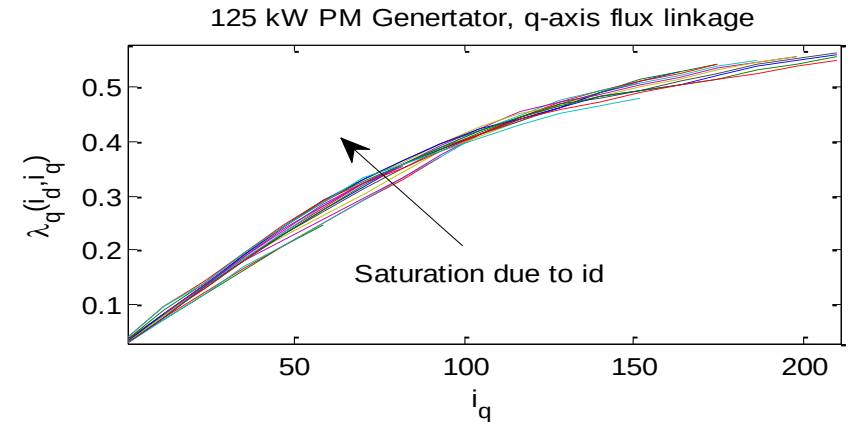
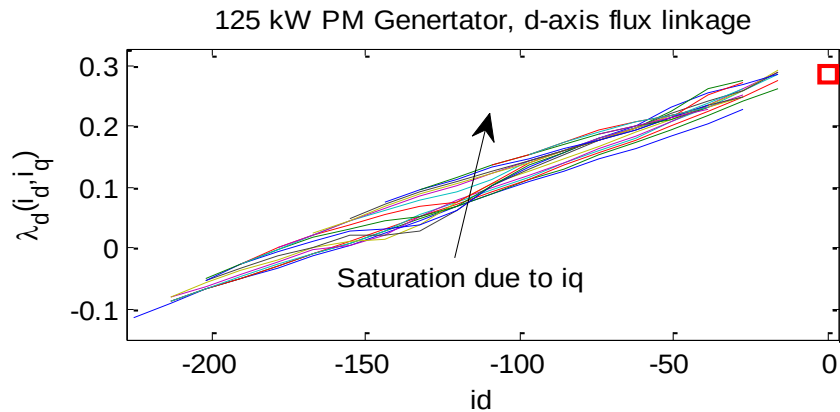
- PMSM specifications:

Parameters	Motor	Generator
Rated power	125 kW	125 kW
Rated speed	1500 RPM	1900 RPM
Max speed	5000 RPM	3000 RPM
Line voltage	$480 V_{LL}$	$480 V_{LL}$
Max current	$250 A_{peak}$	$250 A_{peak}$
No. poles	4	8

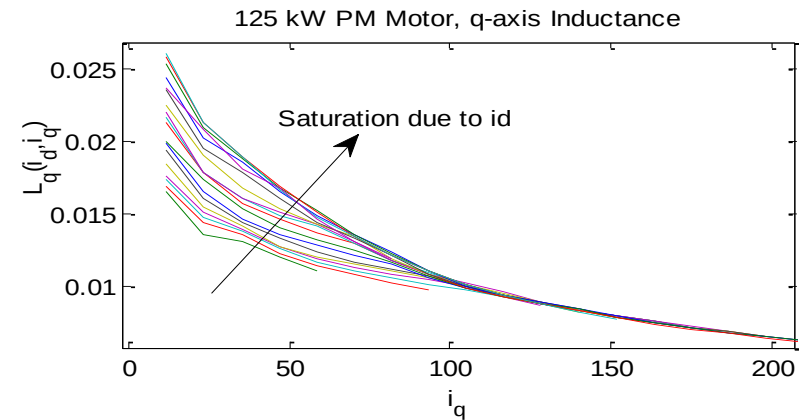
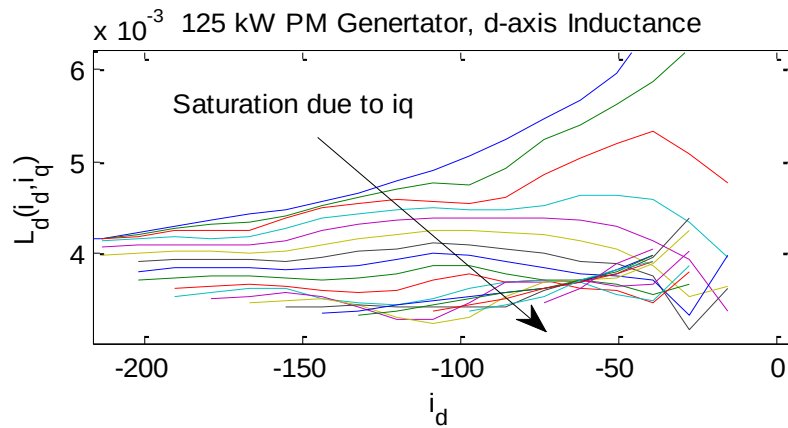
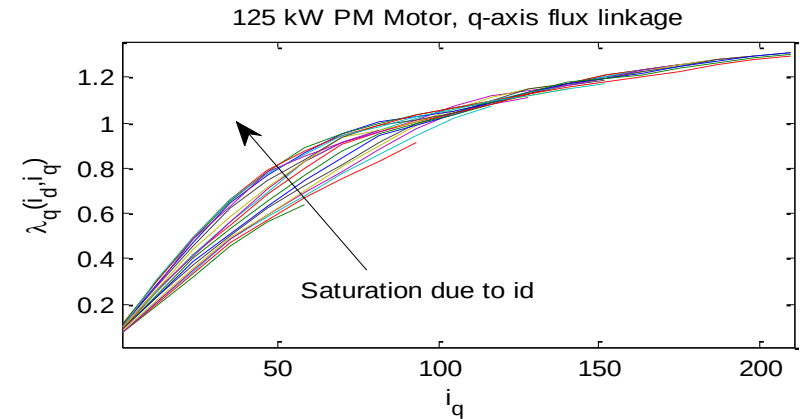
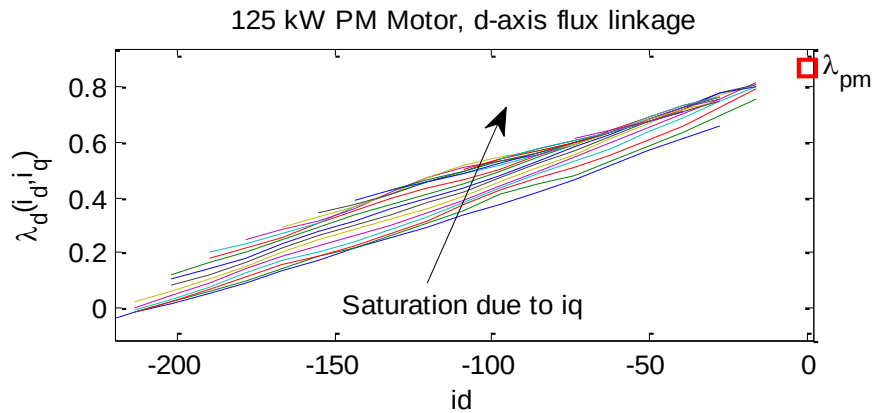
- Test Setup:



Generator, Experimental Results

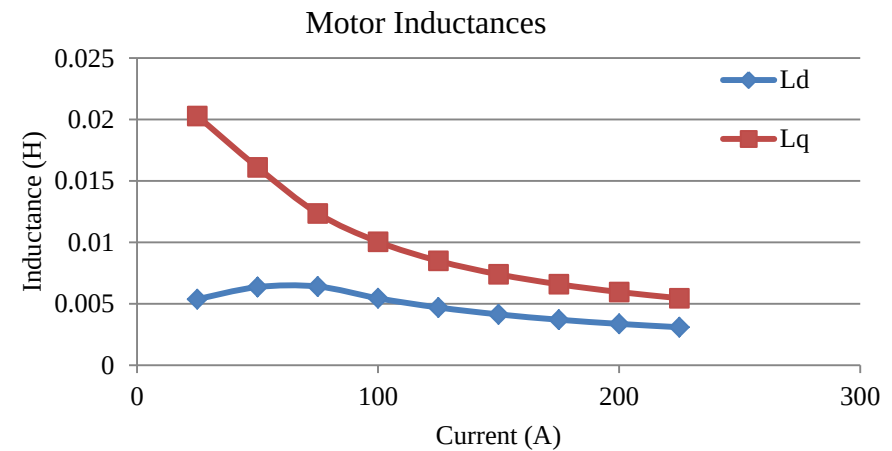
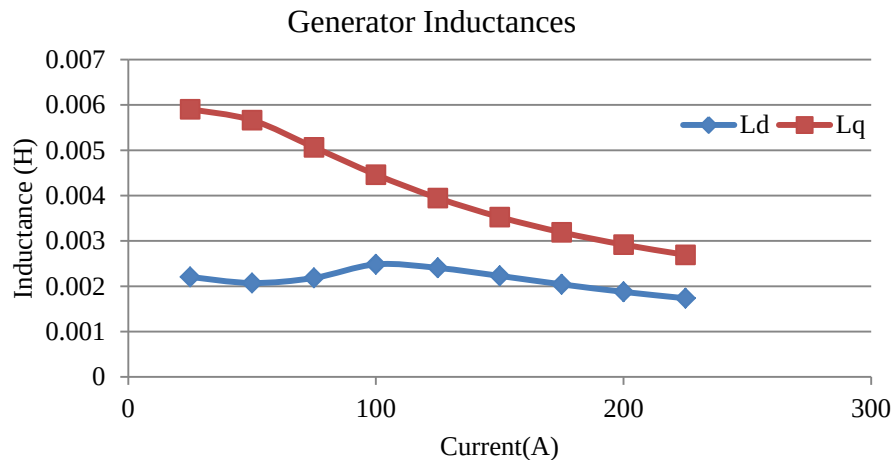


Motor, Experimental Results



FEA parametric results

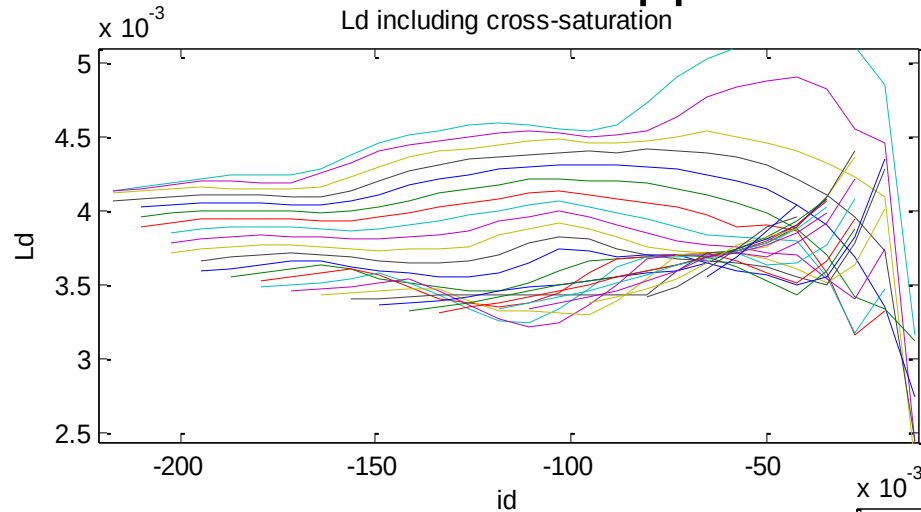
- Determined using a FEA magnetostatic simulation.



- This type of simulation was used, since it is considerably less time consuming than a full transient-magnetic simulation.

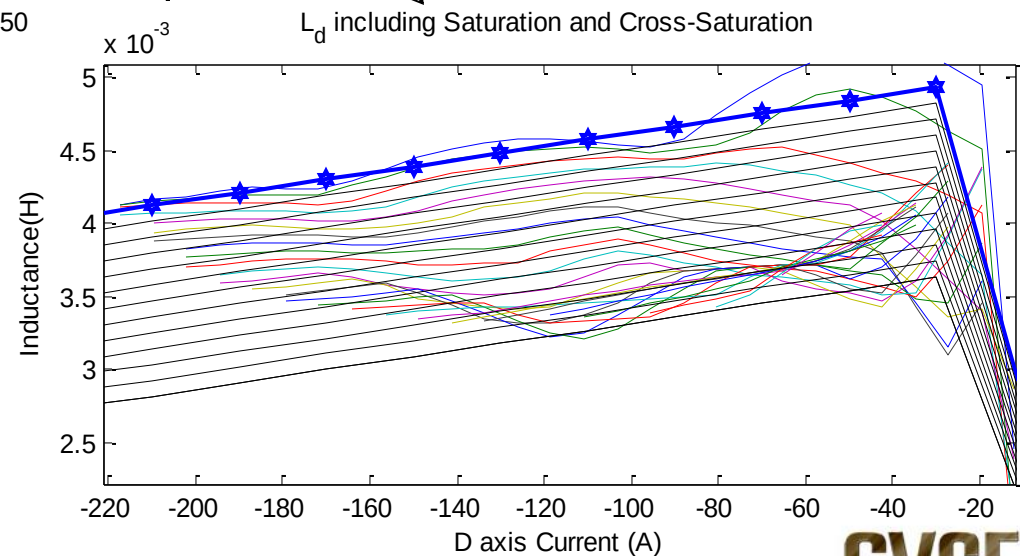
Proposed Linear approximation

- d-axis inductance approximation:



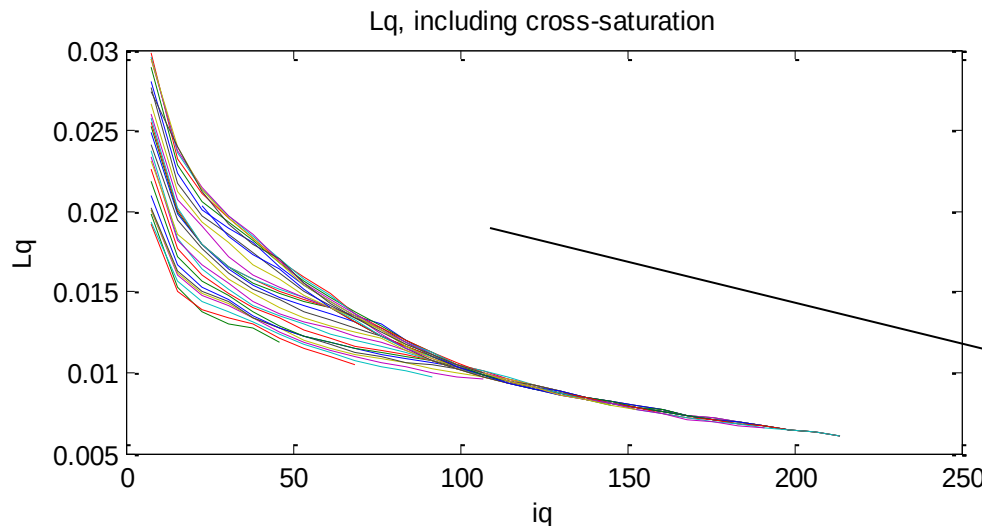
$$\Lambda_{Ld}(i_q) = \frac{-\Delta_L(i_q)}{i_{rated}} i_q$$

$$L_d(i_d, i_q) = L_d(i_d) + \Lambda_d^{\text{sec1\&1}}(i_q)$$

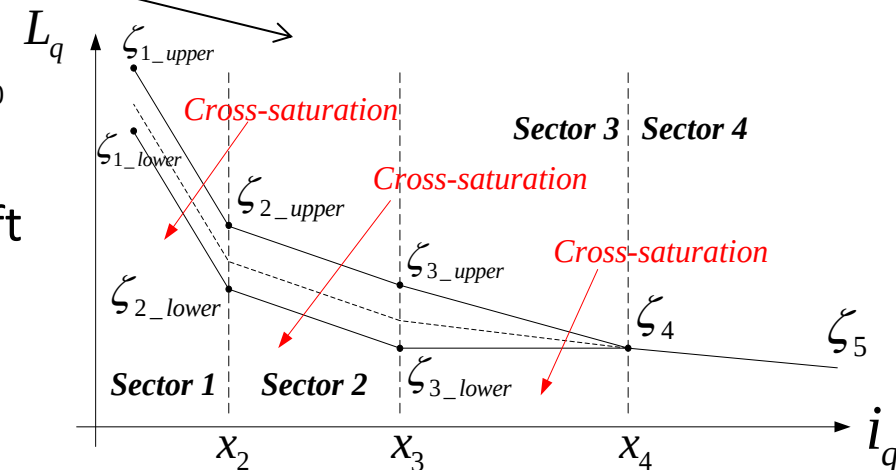


Proposed Linear approximation

- q-axis inductance approximation:



Using 4 linear sectors it is possible to represent the true $L_q(i_d, i_q)$.



Sector 1 and 2: Linear function with shift dependent on i_d .

Sector 3: Linear function, where slope changes as a function of i_d .

Sector 4: One linear function.

Proposed Linear approximation

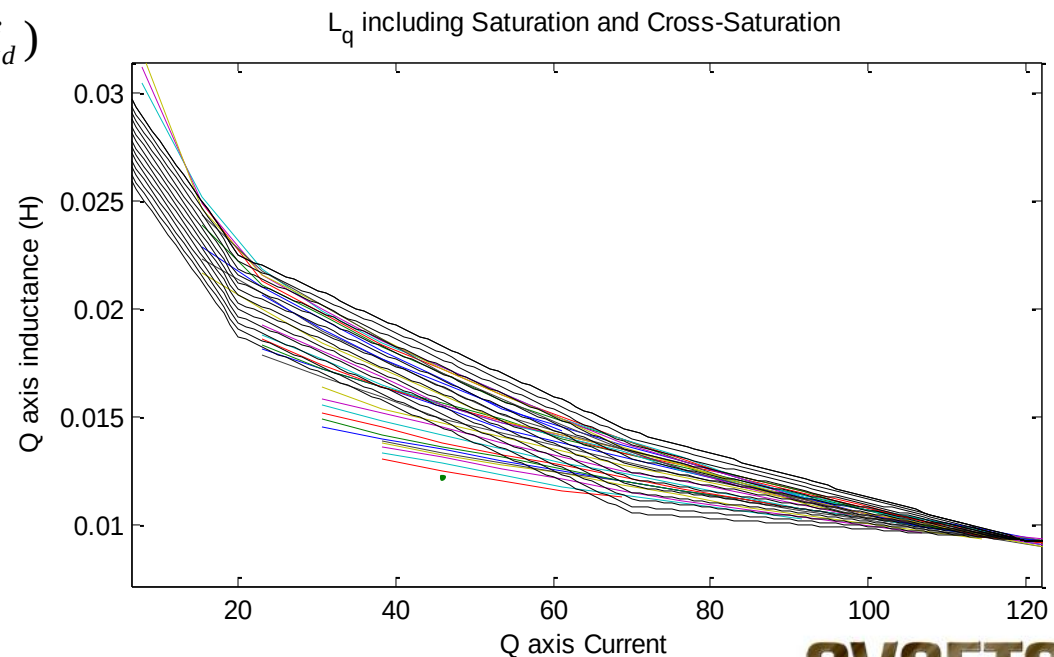
- Q-axis inductance approximation sector 3:

$$m(i_d) = \frac{\zeta_{3_lower} - \zeta_{3_upper}}{i_{d_rated} \cdot (x_4 - x_3)} \cdot i_d + \frac{\zeta_4 - \zeta_{3_upper}}{x_4 - x_3}$$

$$\Lambda_d^{sec.3}(i_d) = \frac{\zeta_{3_upper} - \zeta_{3_lower}}{i_{rated}} \cdot i_d + \zeta_{3_upper}$$

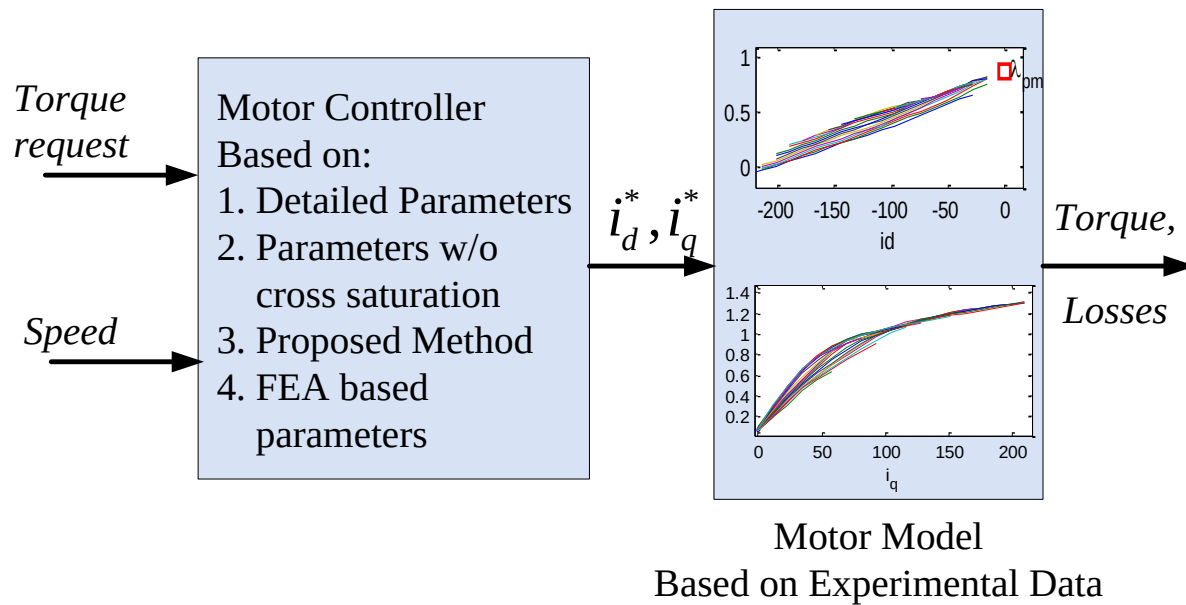
$$L_q(i_d, i_q) \Big|_{sec.3} = m(i_d) \cdot (i_q - x_3) + \Lambda_d^{sec.3}(i_d)$$

The proposed method to estimate the q-axis inductance, closely follows the experimentally determined inductance.



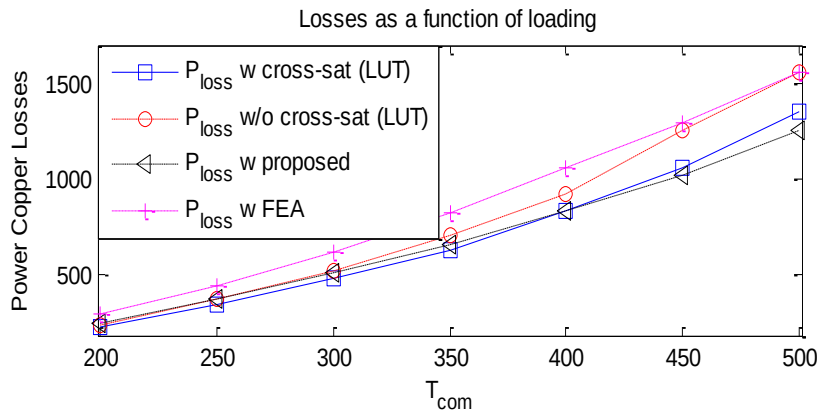
Controller Evaluation

- The performance degradation due to the exclusion of the saturation effects is evaluated using a motor controller.

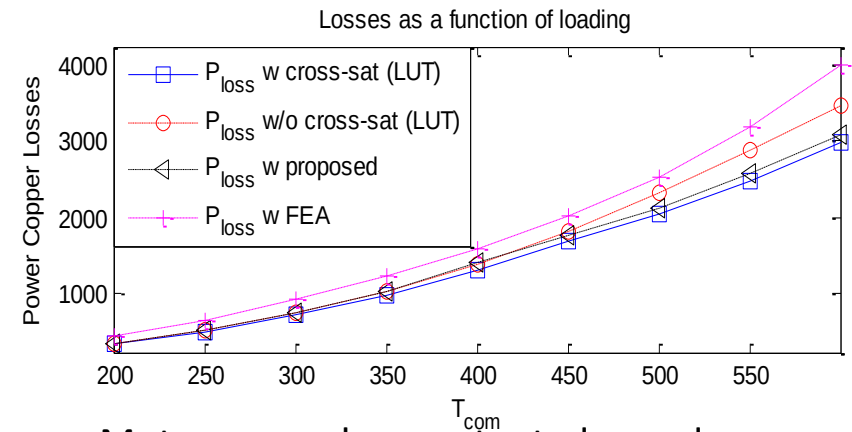


- Controllers based on different parametric information were developed and evaluated in the most accurate model.

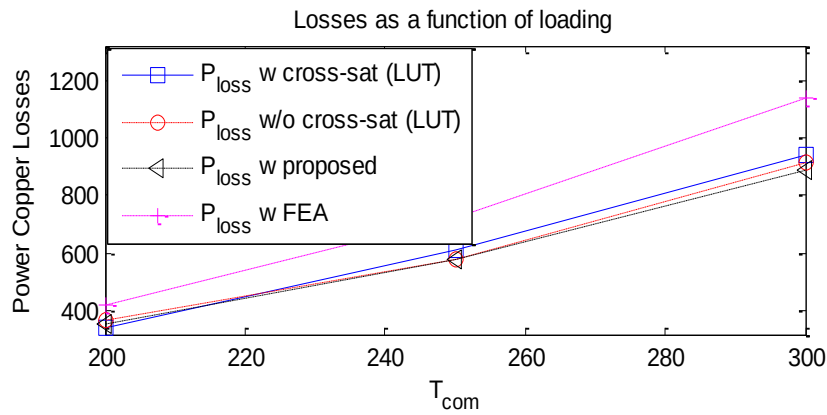
Results, Power Losses



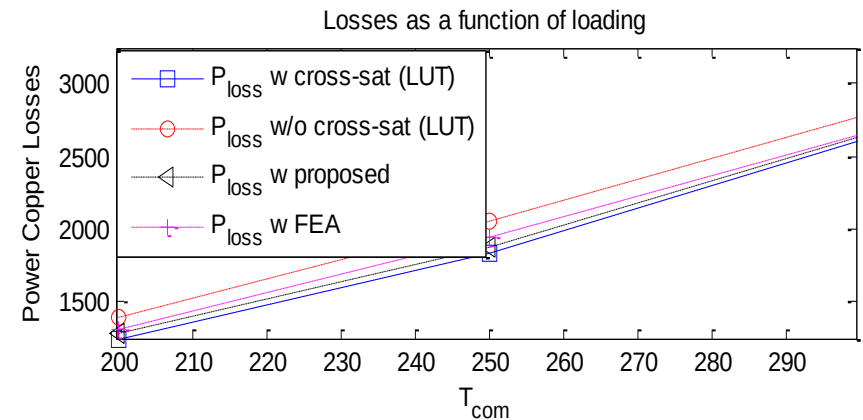
Generator power losses at rated speed



Motor power losses at rated speed



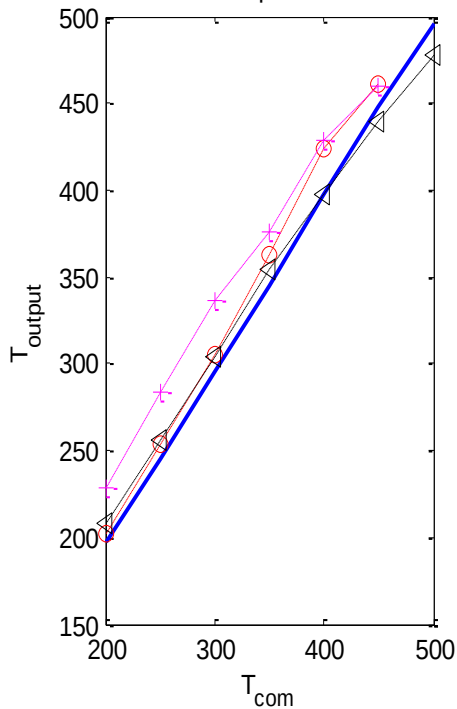
Generator power losses at 3000 RPM



Motor power losses at 3000 RPM

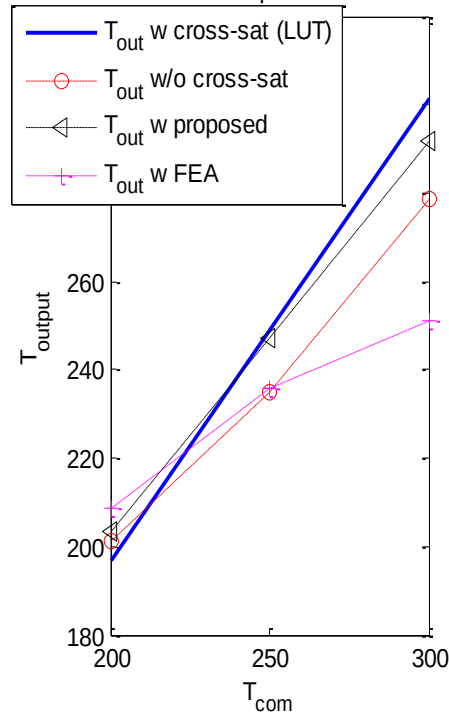
Results, Torque Performance

Generator Torque Performance



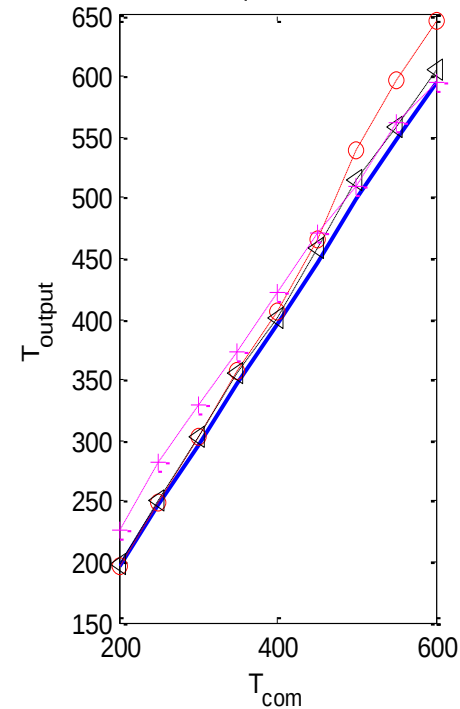
At rated speed,
Generator Torque performance,

Generator Torque Performance



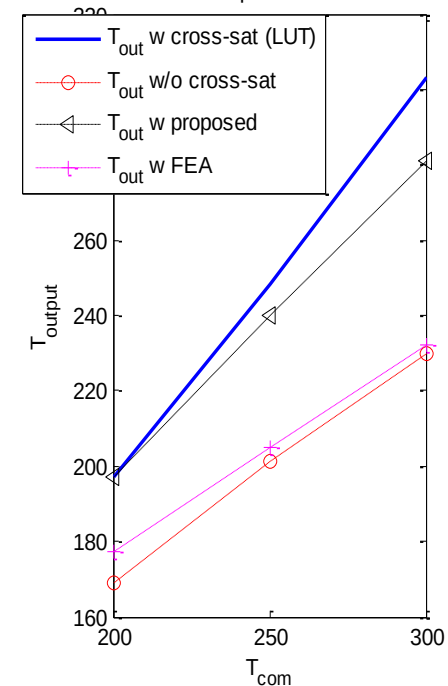
At 3000 RPM

Motor Torque Performance



At rated speed,
Motor Torque performance,

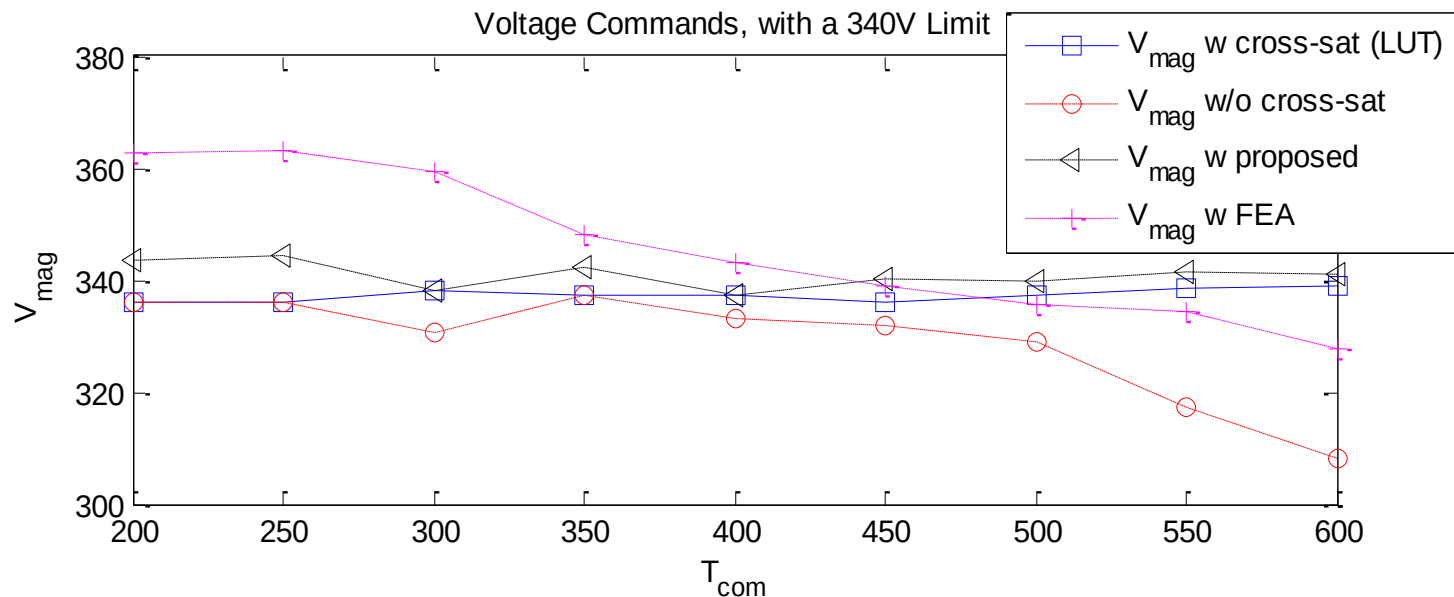
Motor Torque Performance



At 3000 RPM

Voltage Performance

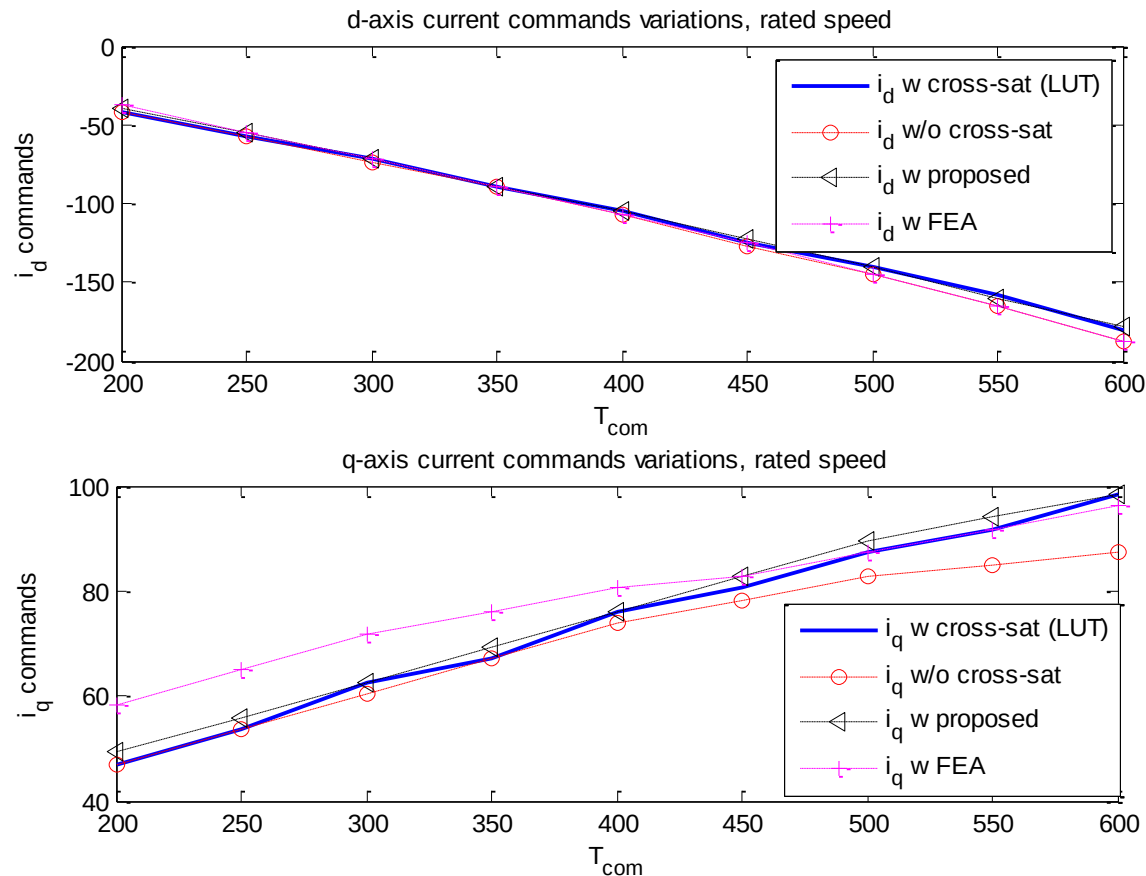
- Voltage commands are vital for proper operation of the motor drive.
- Inverters have a voltage limit and field weakening performance depends on the voltage command.



Motor Voltage Commands at rated Speed

Current Performance

- Motor controller, dq-axis currents commands, as a function of torque command at rated speed.



Conclusions

- Including the saturation effects of a PMSM improves the torque performance of a motor drive system.
- Higher torque performance aids in reducing the motor losses. Hence, better efficiency is achieved.
- Increments in the torque performance increases the efficiency of the overall system.
- The piecewise linear approximation accurately describes the non-ideal behavior of a PMSM.
- This approach demonstrated a reduction in copper loss of up to 900W (efficiency gain of 1.36%) for a 125kW machine.
- This method is realizable in the majority of motor control DSPs due to its computational efficiency with no additional cost.