Researcher Links UK-Russia Workshop

Scientific and Technical Grounds of Future Low-Carbon Propulsion

Torque Estimation in Traction Electric Drives

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Outline

- PEMC Group @ UoN
- Traction electrification
- Machine types used in traction
- Torque calculation
- Magnetic model
- Torque estimation results
- Conclusion

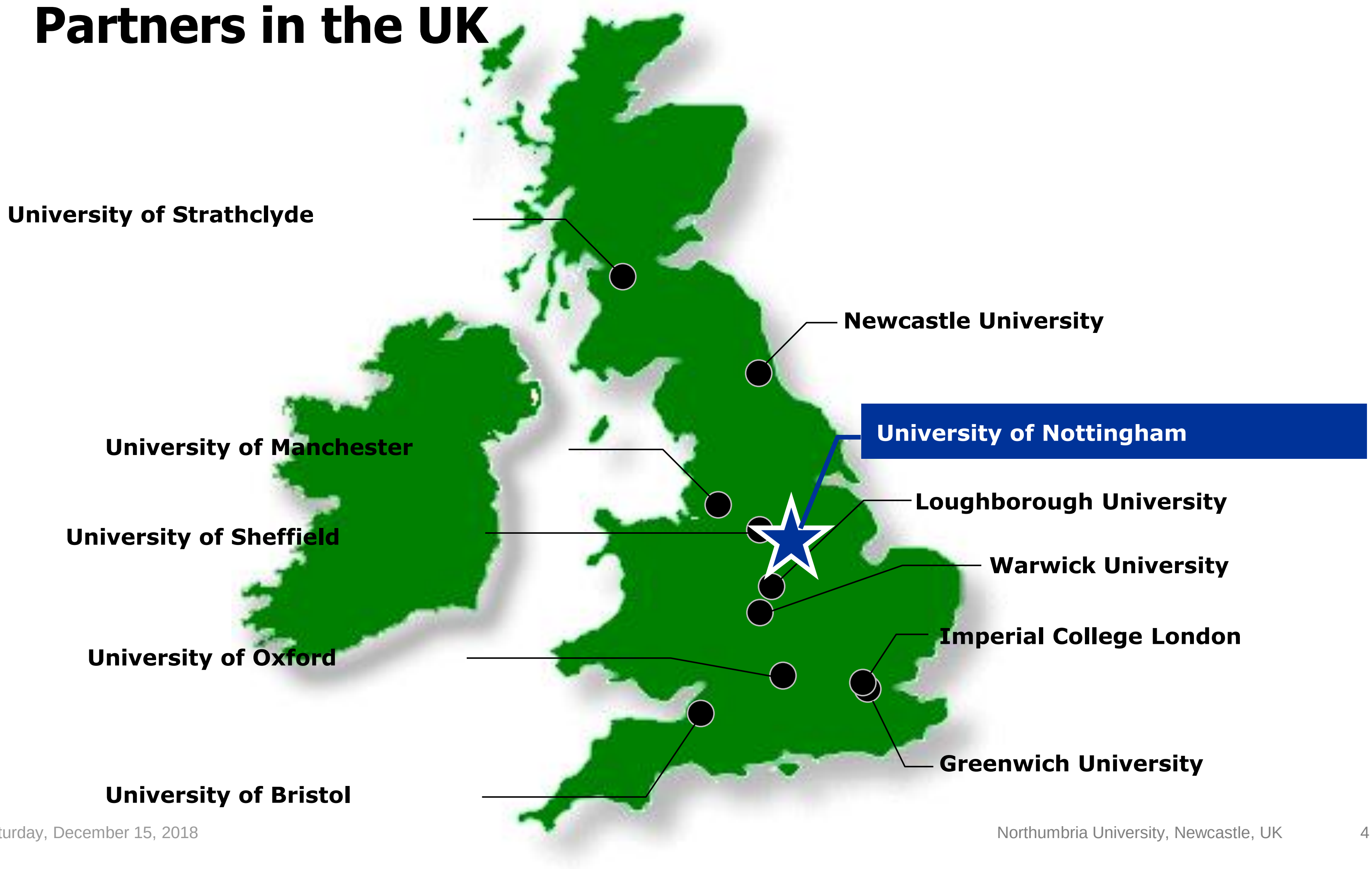
PEMC Group @ UoN

- Staff
  - 19 academics
  - ≈ 45 RFs
  - ≈ 60+ Ph.D. students
  - ≈ 10 visiting scholars

- Research portfolio
  - Active grants ≈ € 28M+
- Strategic partnerships/activities
  - EPSRC Power Electronics Centre Hub and Directorate
  - Advanced Propulsion Centre – Power Electronics “spoke”
  - Clean Sky (EU Aerospace) – Associate Partner
  - Clean Sky 2 (EU Aerospace) – Core Partner
  - Cummins Innovation Centre
  - GE Grid Centre of Excellence

PEMC Group @ UoN

Partners in the UK



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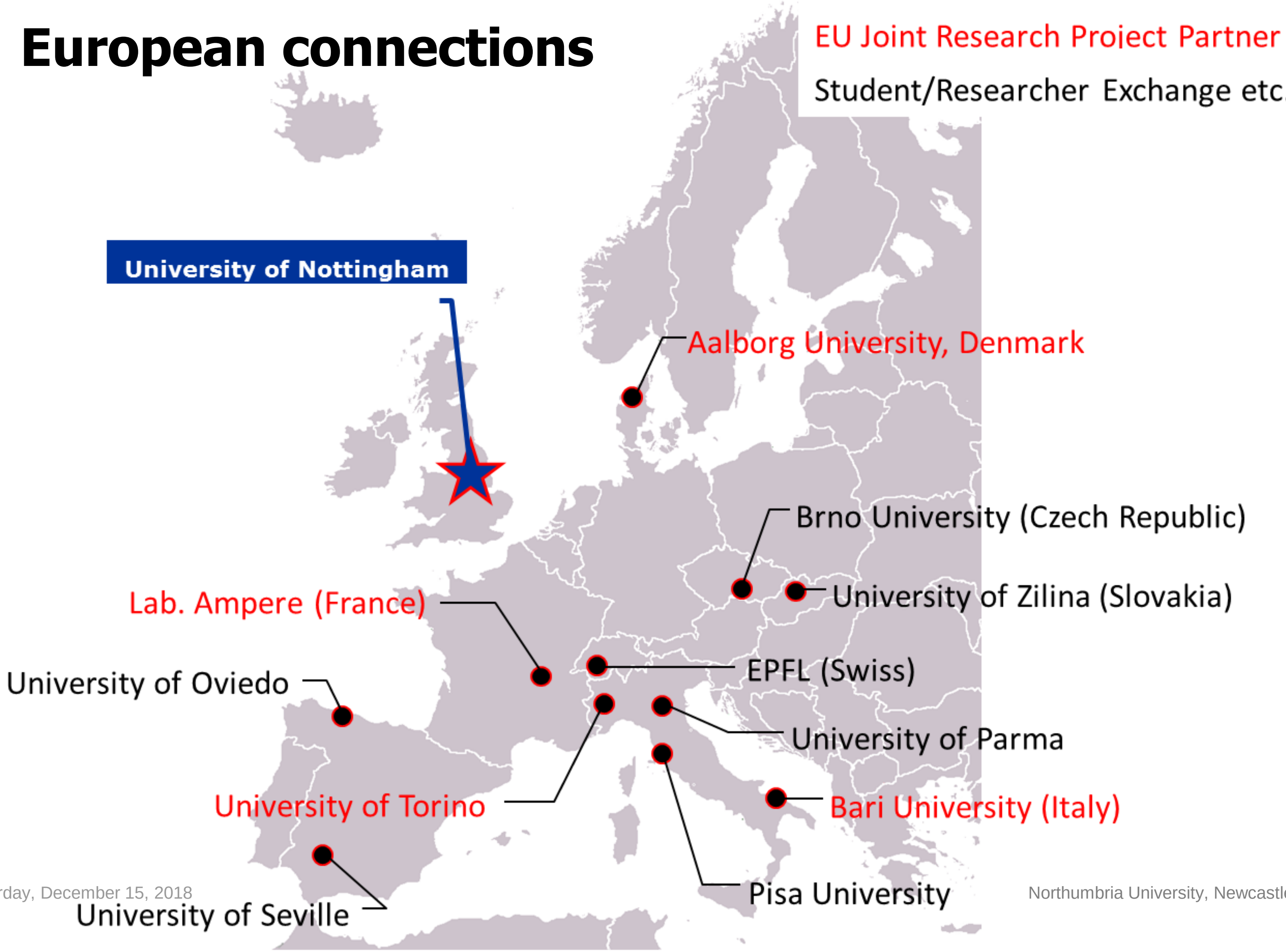
European connections



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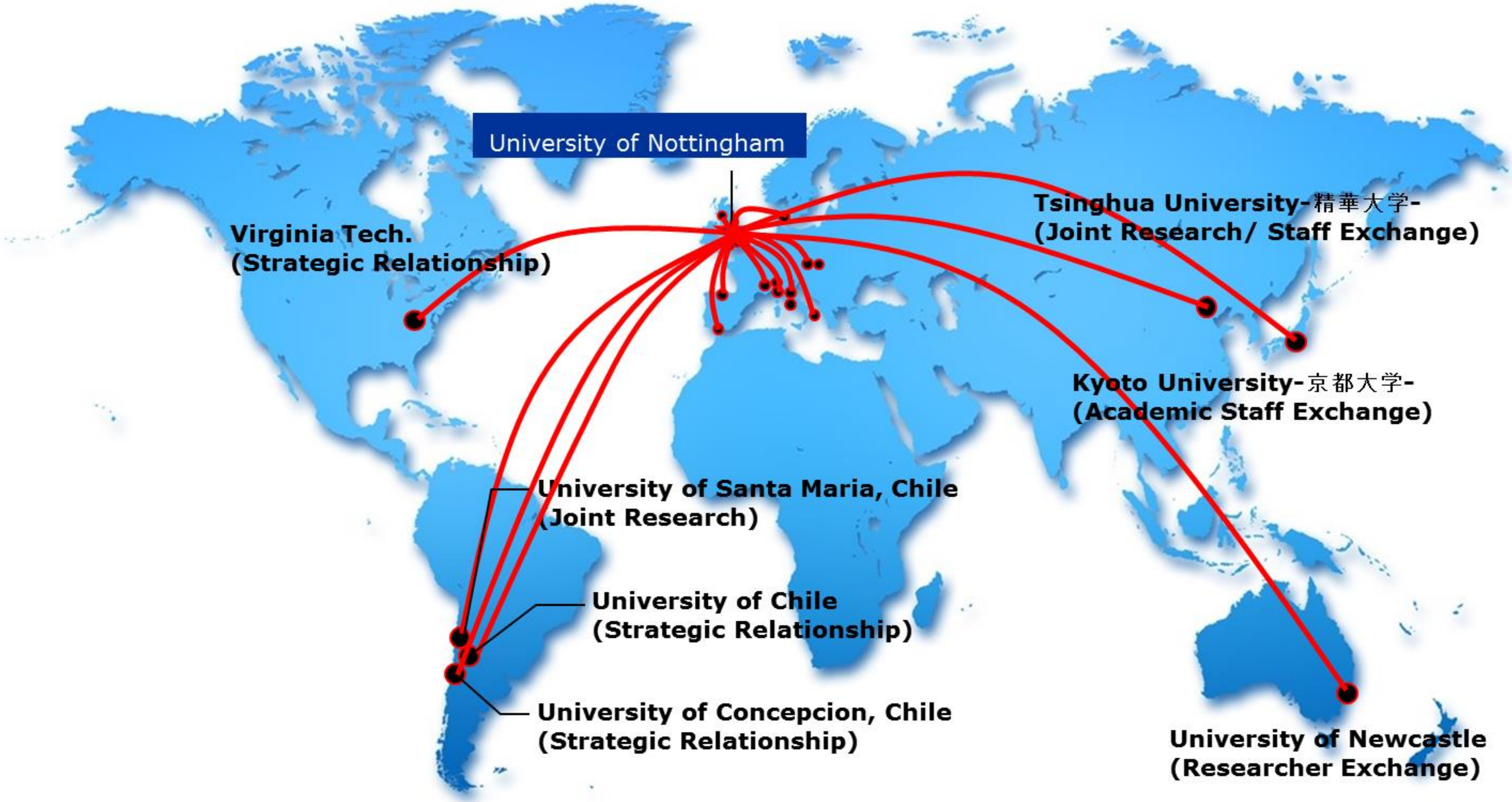
Across the world…



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Industrial partners

AIRBUS
AN EADS COMPANY
BOEING
GE Aviation
SAFRAN
Messier-Bugatti-Dowty
LIEBHERR
THALES
BAE SYSTEMS
EADS
EADS INNOVATION WORKS
EUROCOPTER
AN EADS COMPANY
DASSAULT
AVIATION
GOODRICH
MBDA
MISSILE SYSTEMS
BestMotion
B&F
Seamless Control
e·on
GE
Energy
e2v
Cummins
CASTLET
ENGINEERING THE SOLUTION
Infineon
NISSAN

Automotive

ROHM
SEMICONDUCTOR
DYNEX
SEMICONDUCTOR
TT electronics
SEMELAB

Traction electrification

- Growing public awareness about environmental concerns is one of the ‘driving’ forces behind electrification of transport sector.
- Fast depleting fossil fuel reserves call for early action on part of governments to diversify energy mix as well as to incentivize newer, more efficient, technologies.
- In the UK, the government is being advised to bring forward the proposed ban on new petrol and diesel passenger cars to 2030 (from the current target of 2040).

Traction electrification

- For achieving a higher degree of electrification, the challenges of competing with the internal combustion engines are to be taken head on.
- Power to weight and power to volume (power density) are the key figures on which the traction machines and storage are making enormous progress for meeting the stringent requirements.
- Power electronics, on the other hand, is an enabling field that is playing a very crucial role in getting the most out of the electrical machine and energy storage.

Traction electrification

Directions we are headed in:

– Electrical machines: Multiphase and multi-three-phase machines are being promoted as flexible, intrinsically redundant and fault-tolerant alternative of three-phase machines.

– Power electronics: Modular and modular multilevel converters with fast switching semiconductor devices such as SiC and GaN devices allow faster dynamics and higher speeds.

– Energy storage: On this front, super-capacitors and flywheel based solutions are being toed as hybrid energy storage systems.

Machine types used in traction

Being at the heart of transportation electrification, the types and design alternatives of electrical machines have grown exponentially over the past two decades.

Examples:

IPMSM – Toyota Prius, Chevy Volt, Nissan Leaf, BMW i3, Honda Accord

IM – Tesla (Roadster, S and X), Mercedes Benz EQC

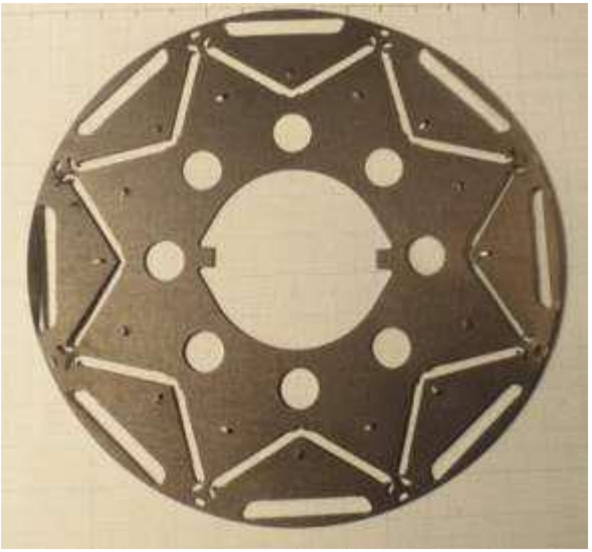
PMSM – Honda Civic (Hybrid)

Machine types used in traction

IPMSM rotor examples

Toyata Prius[1]

Chevy Volt[2]



Nissan Leaf[2]

1. K. M. Rahman et. al., TIA, 51(3) May/June 2015

2. Available online

Machine types used in traction

There is a new sheriff in town – synchronous reluctance machine

- A synchronous reluctance machine does not require costly permanent magnets and is thus a cost effective solution.
- The developed torque consists entirely of reluctance component.
- Unlike induction motor, there are no losses on the rotor side which helps improve efficiency.
- Its low power factor (compared to PM machines) is, however, a problem that is being addressed (low-cost ferrites for PMASR).
- The rotor’s mechanical withstand capability at high speeds is another open question.

Torque calculation

The torque developed by the electrical machine in an electrified vehicle needs to be estimated because…

- There usually are no torque sensors available that measure the machine torque.
- In hybrid electric vehicles, the hybrid controller optimizes the vehicle operation based on input parameters and decision-making algorithms. The electromagnetic torque produced by the electrical machine is one of the required inputs.
- The efficiency of the motor+inverter system can be estimated only if the output torque is correctly estimated (speed being measured).

Torque calculation

The torque developed by any electrical machine can be calculated using the general relation (valid in all reference frames):

$$T_e = \frac{3}{2} p \left(\bar{i}_s \wedge \bar{\lambda}_s \right)$$

Where, p is the number of pole-pairs, $\bar{i}_s$ is the stator current vector, $\bar{\lambda}_s$ is the stator flux vector and ^ indicates vector product.

In a standard electric drive, the stator current is a measured quantity while the stator (or rotor) flux is not.

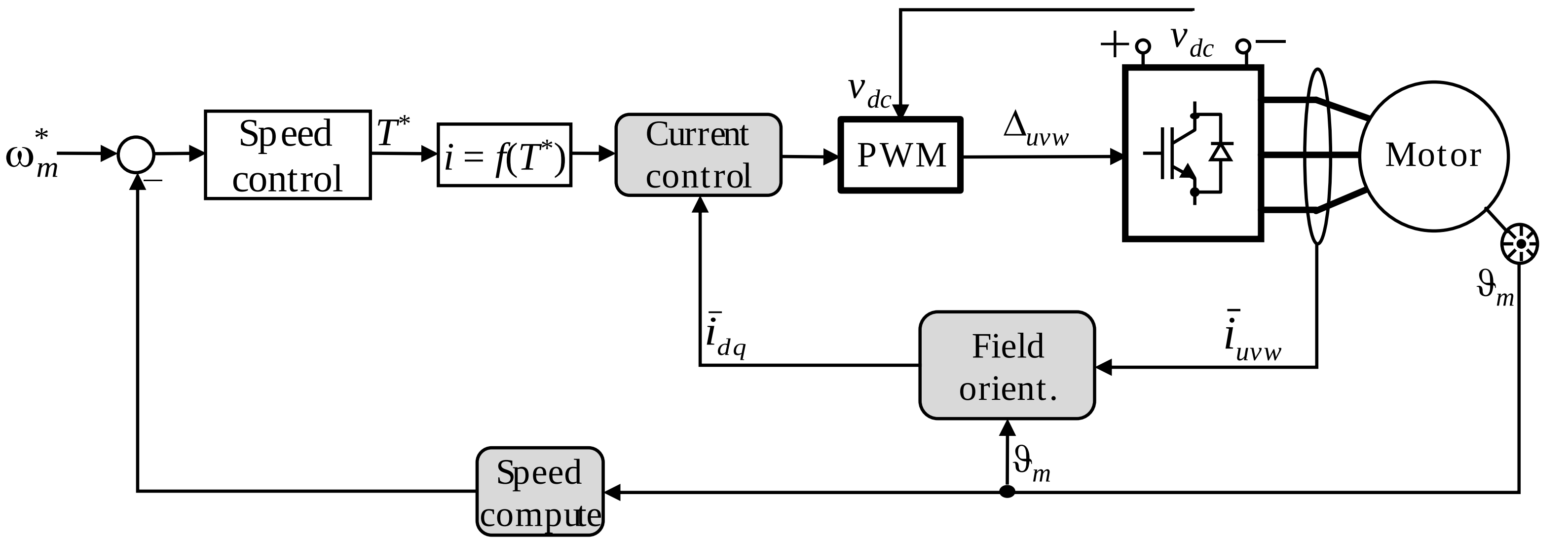
The torque can only be estimated if accurate information (magnitude and angle) about the stator flux is available.

Torque calculation

A standard electric drive

Measured quantities:

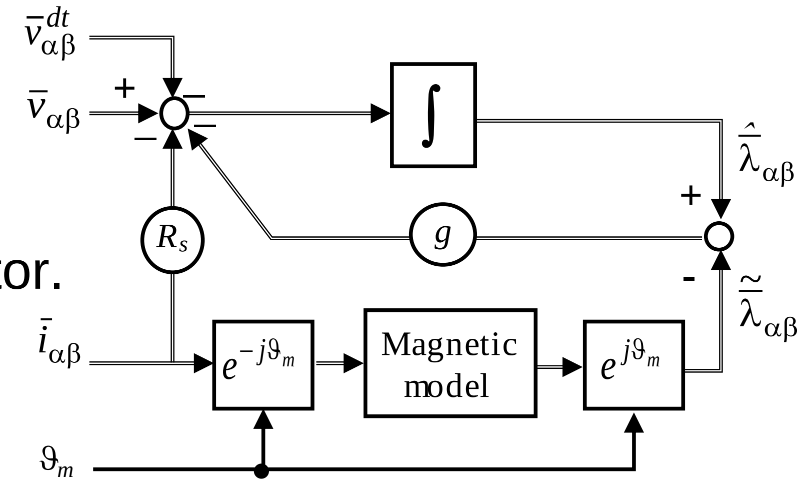
(i) Three-phase currents, (ii) dc-link voltage, (iii) rotor position (?)



Torque calculation

From the available measurements, the stator (and rotor) flux needs to be obtained. A flux observer is generally used.

The flux observer shown is general – applicable to all machine types.



$\bar{v}_{\alpha\beta}^{dt}$ is the compensated inverter dead-time voltage vector

$\bar{v}_{\alpha\beta}$ is the applied stator voltage vector.

$\bar{\lambda}_{\alpha\beta}$ represents the observed flux.

ϑ_m is the rotor mechanical angle.

g is the observer gain (cross-over frequency between magnetic model and stator voltage integration).

Magnetic model: It is the current-to-flux-linkage relationship of the machine. At low-speeds, the flux estimation accuracy depends on the accuracy of magnetic model.

Magnetic model

As said, the magnetic model plays an important role in flux and (hence) torque estimation accuracy. What is a magnetic model?

- It describes the non-linear relationship between stator current and stator (or rotor) flux.
- The non-linearity is introduced by core saturation.
- For SPM, IPM and SyncRel machines, the effects of cross-axis currents (termed cross-saturation) are also significant and need to be identified precisely for accurate flux estimation.
- The cross-saturation effect is mainly due to the rotor structure, highly anisotropic machines demonstrate significant cross-saturation effects.

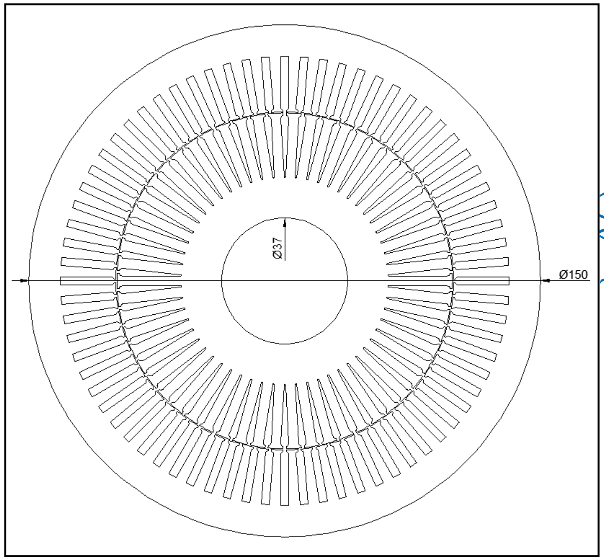
Generally,

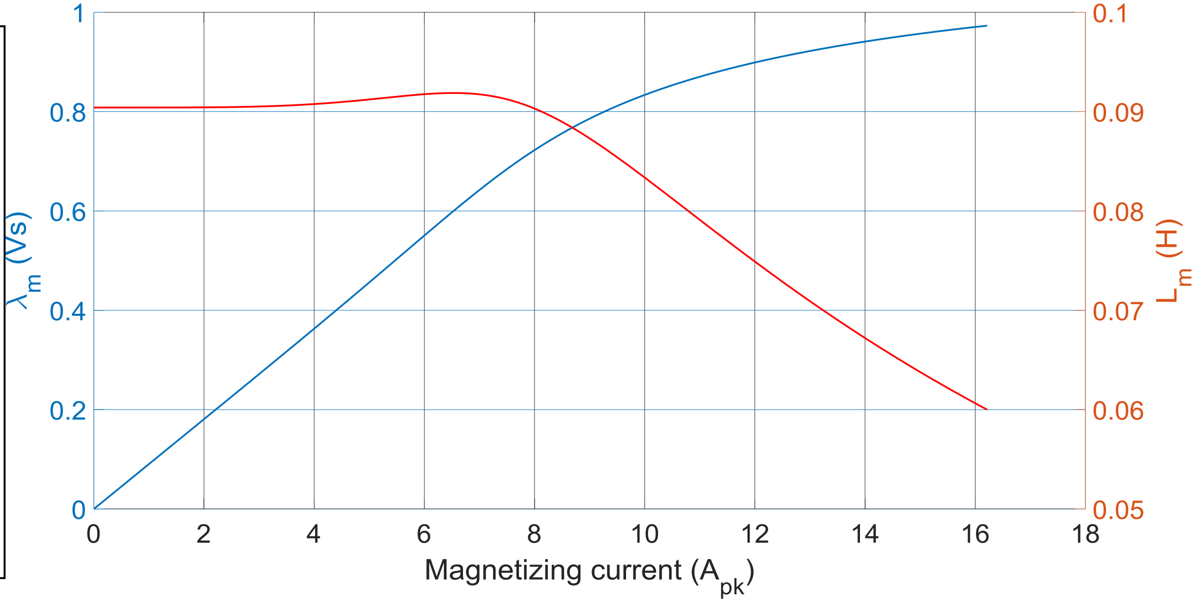
$$\lambda_d = f\left(i_d, i_q\right) \qquad \lambda_q = f\left(i_d, i_q\right)$$

Magnetic model

Examples of magnetic models

Magnetic model of an induction machine: the rotor is isotropic (magnetically speaking) and only self-axis saturation effect is dominant.

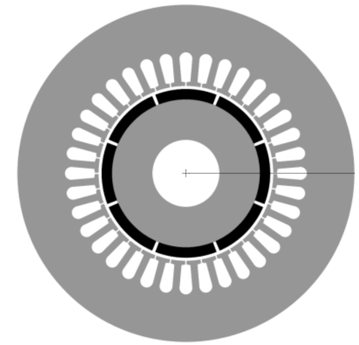


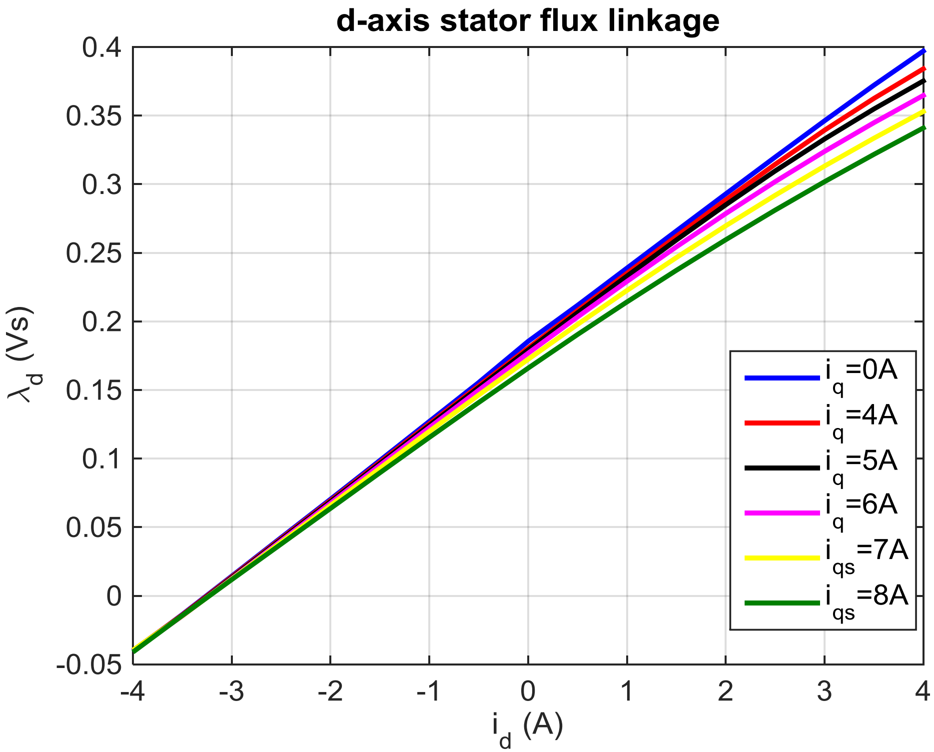


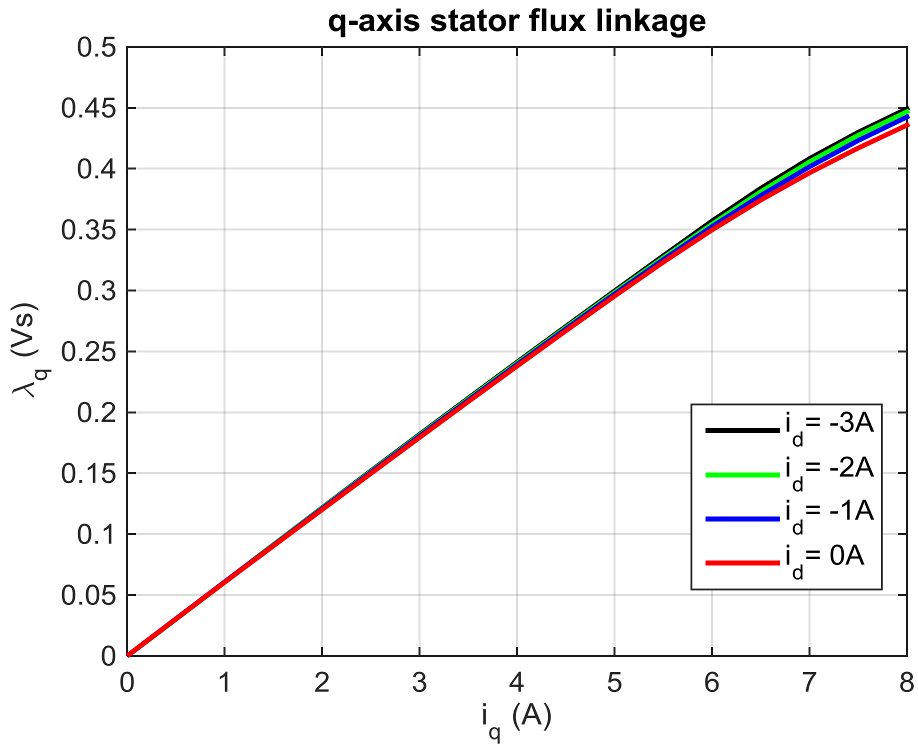
Magnetic model

Examples of magnetic models

Magnetic model of an SPM 1: isotropic rotor with negligible saturation caused by PMs. Cross-saturation is minimal.



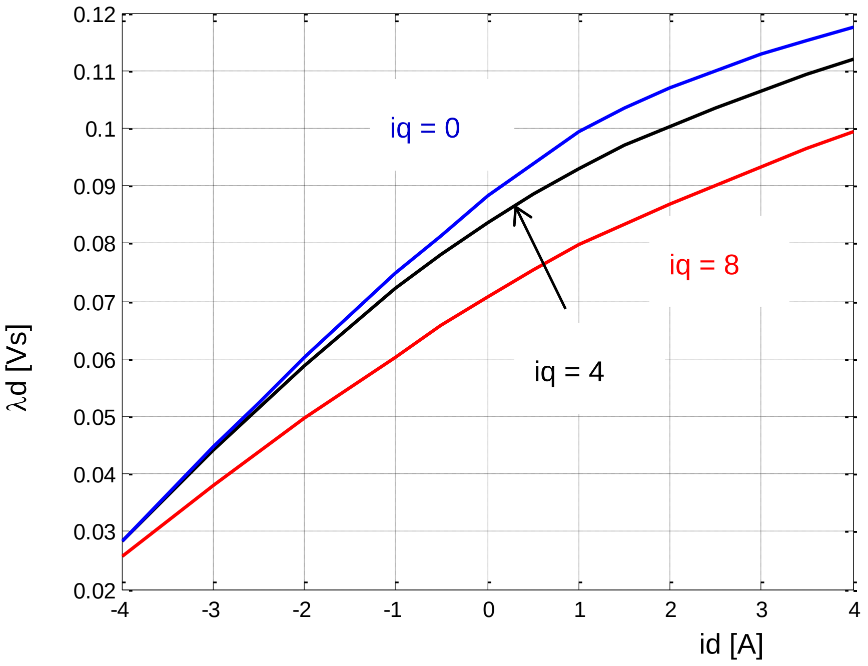


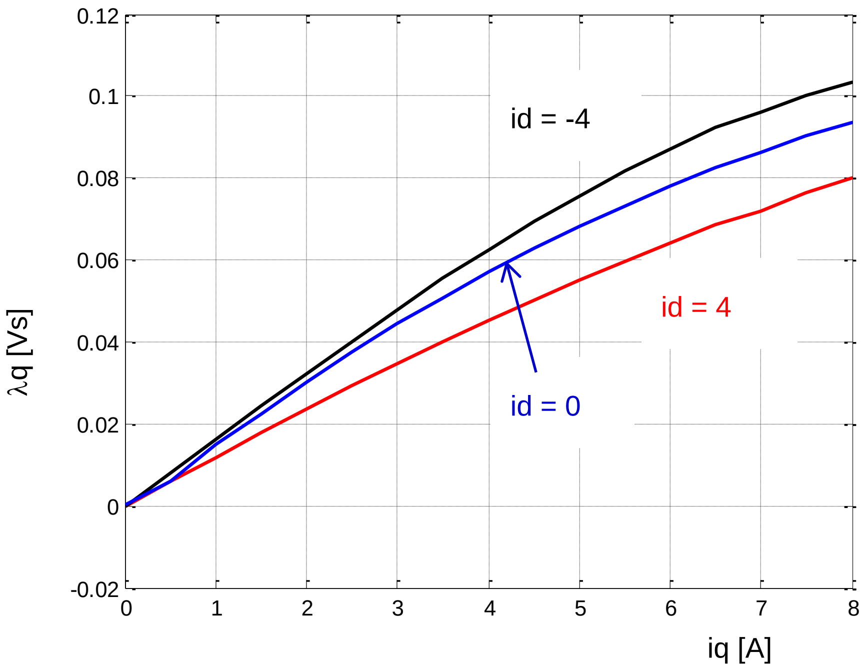


Magnetic model

Examples of magnetic models

Magnetic model of an SPM 2: isotropic rotor with heavy saturation caused by PMs – significant cross-saturation.

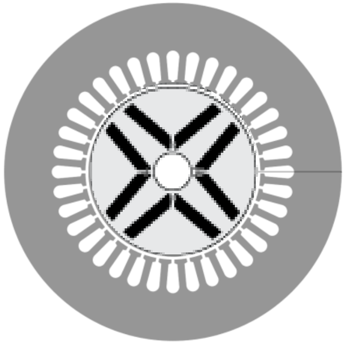


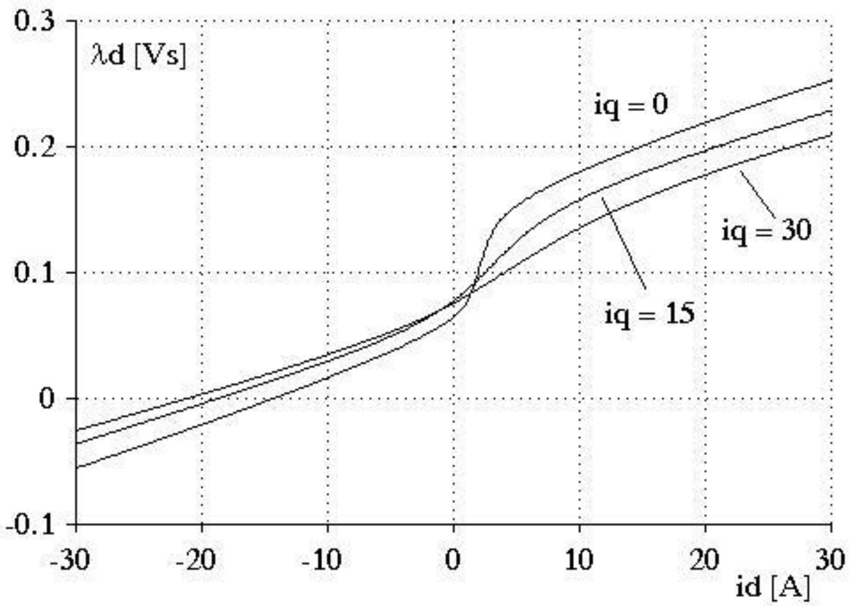


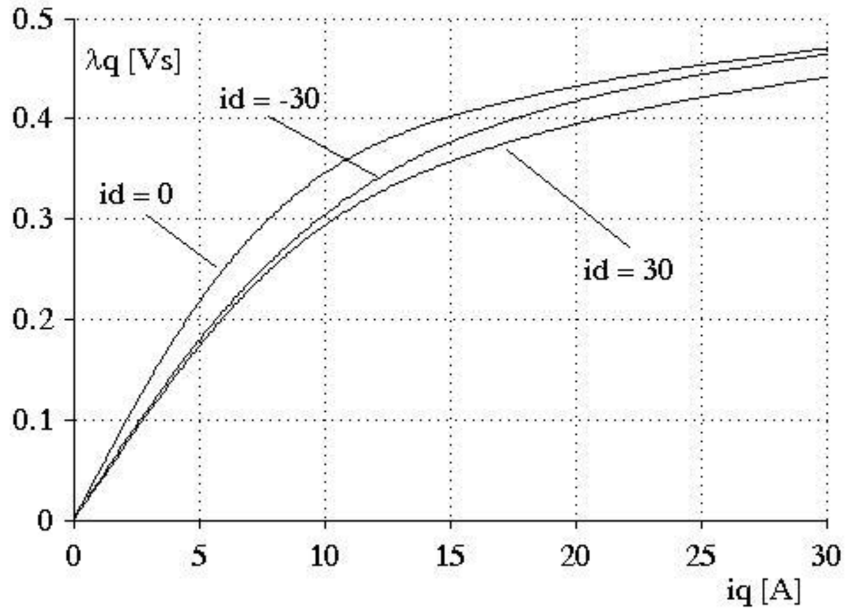
Magnetic model

Examples of magnetic models

Magnetic model of an IPM: anisotropic rotor with considerable cross-saturation effects even at light loads.



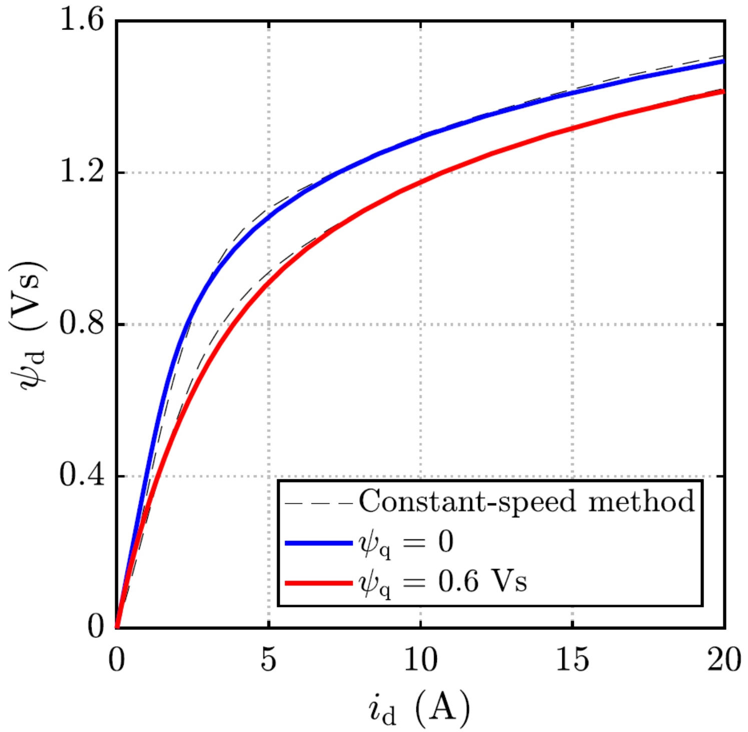


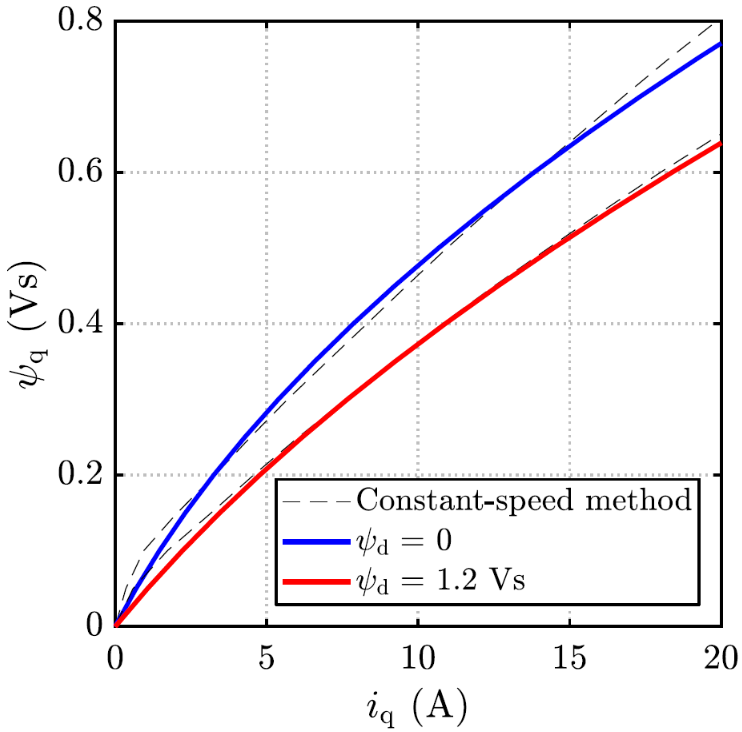


Magnetic model

Examples of magnetic models

Magnetic model of a SyncRel: highly anisotropic rotor with no PM flux contribution, high cross-saturation.



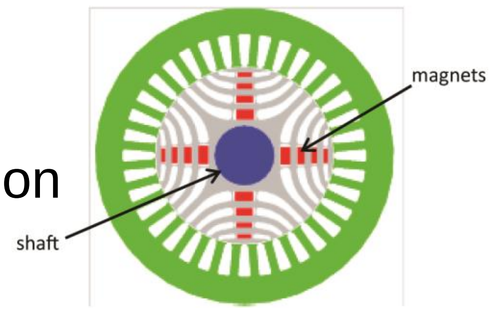


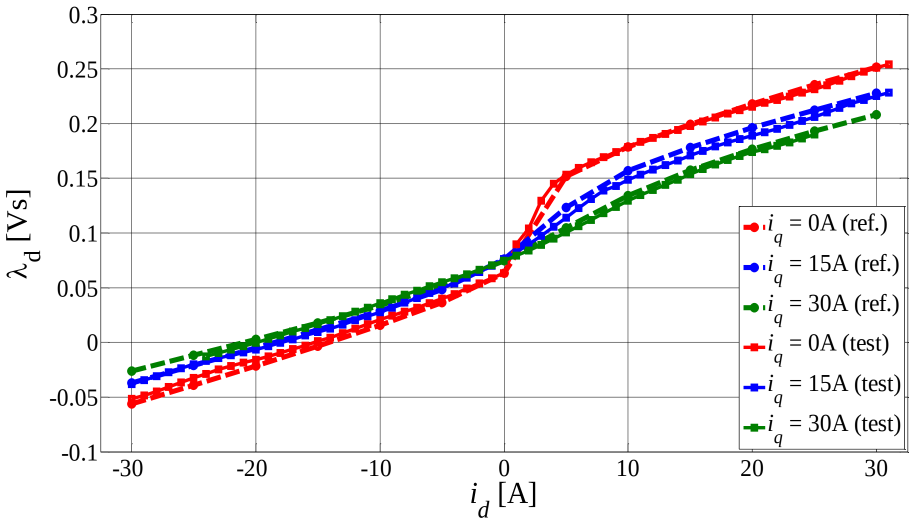
Magnetic model

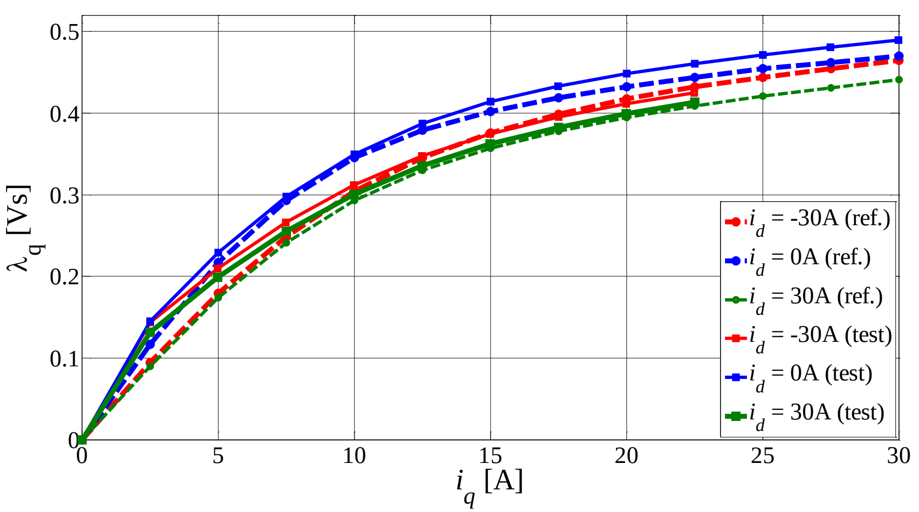
Examples of magnetic models

Magnetic model of a PMASR: highly anisotropic rotor with minimum PM flux contribution, high cross-saturation

This motor was designed as a traction motor for a light electric scooter.

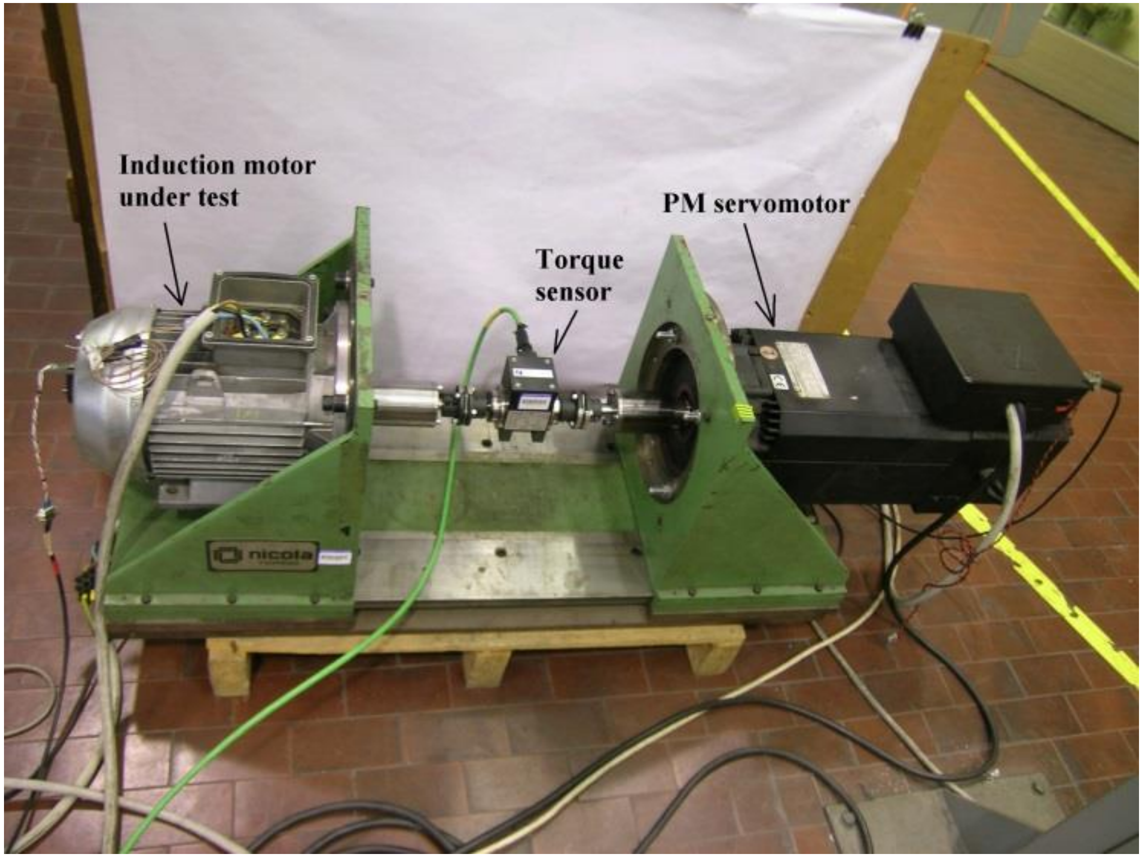






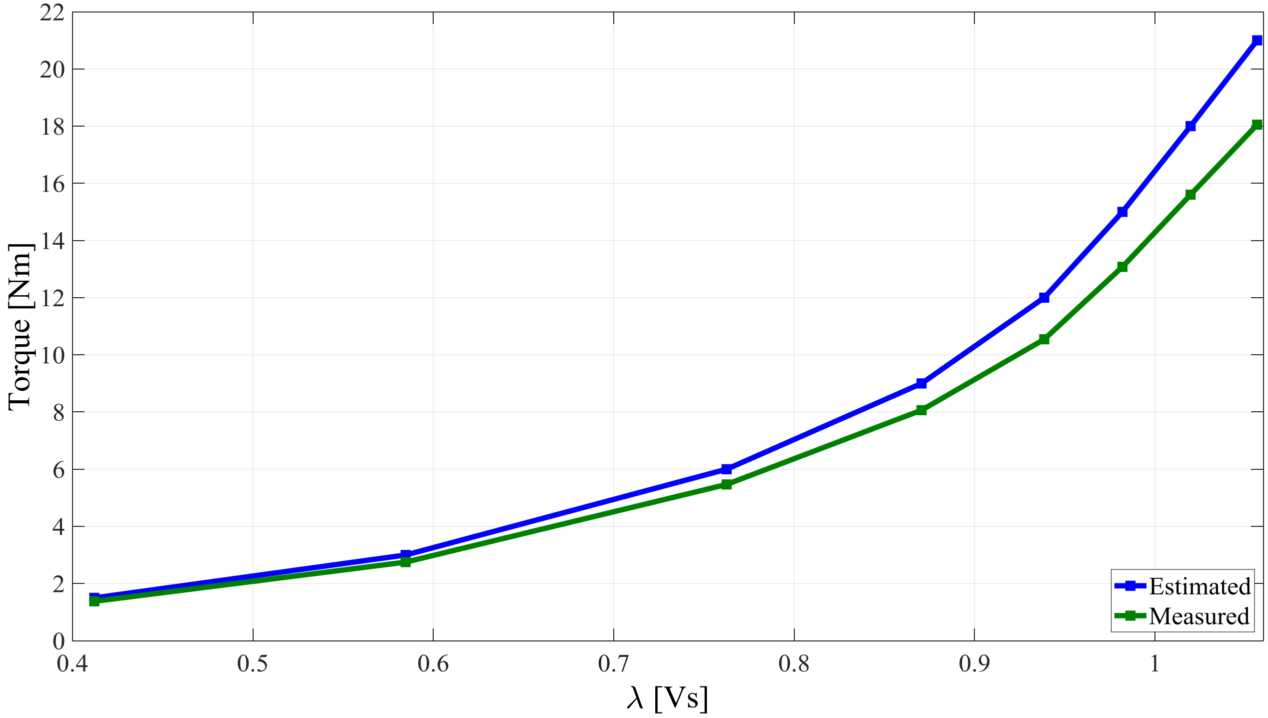
Torque estimation results

Experimental setup for torque estimation accuracy verification:



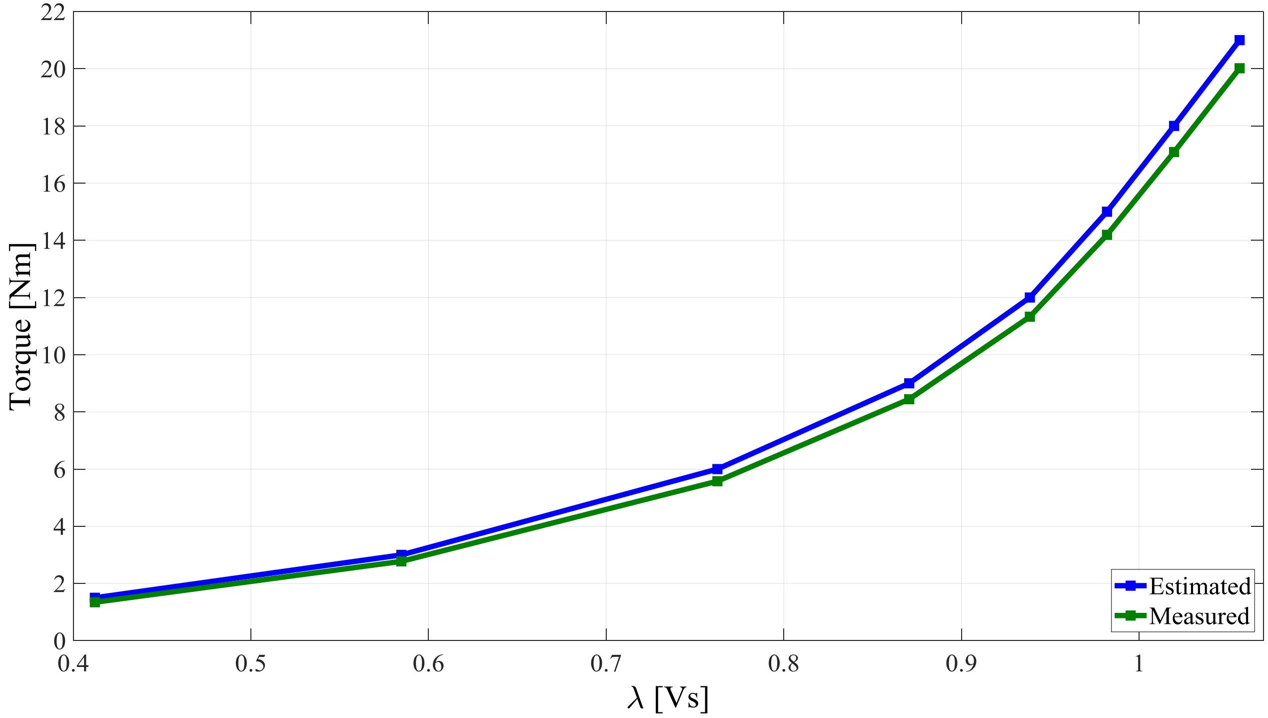
Torque estimation results

Induction motor measured and estimated torque when magnetic saturation is ignored. Significant torque error at high loading



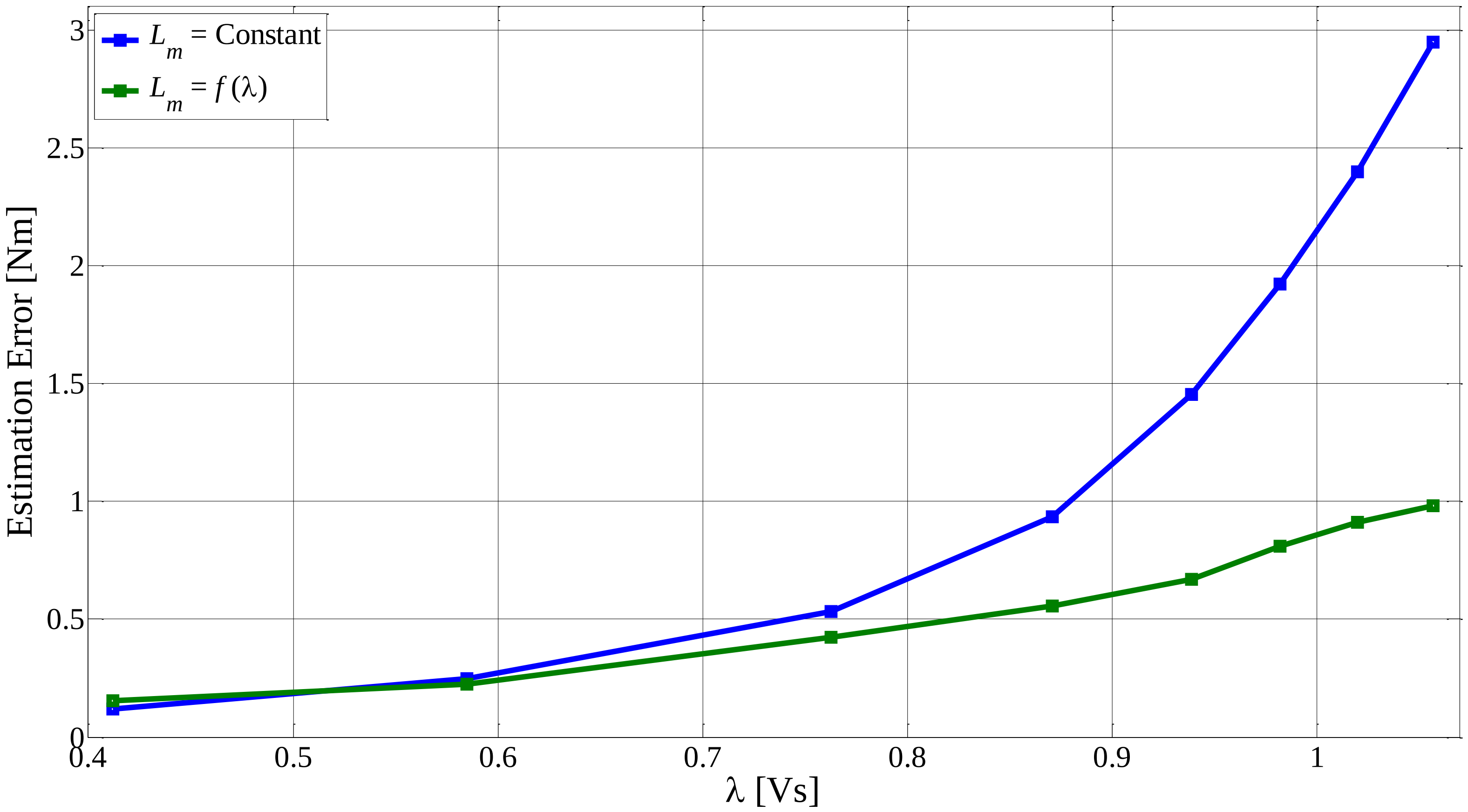
Torque estimation results

Induction motor measured and estimated torque when magnetic saturation is considered.



Torque estimation results

Comparison:



Conclusions

In electrified traction applications, the estimated torque of the electrical machine is needed for the supervisory vehicle control to make informed decisions to improve overall efficiency.

A number of different electrical machine types are used in electrified vehicles that have markedly different magnetic characteristics.

One input required for torque estimation is the stator flux vector which is not a measured quantity in a standard electrical drive.

The torque estimation depends on flux estimation which in turn depends on how well the used machine's magnetic model is known.

Thank you for your kind attention