Dottorato di Ricerca in Ingegneria dei Sistemi, Energetica, Informatica e delle Telecomunicazioni, XXXIV Ciclo Borsa di Dipartimento

Sensorless Control of PMSM Drives through Modified Thermistors Wirings

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Outline

- Combined Temperature Monitoring and Rotor Flux Position Estimation;
- Model of the SMPMSM embedding SCs in the qd synchronous reference frame
- Rotor Flux Position Estimation in SMPMSM
- Experimental validation
- Other Research Activities

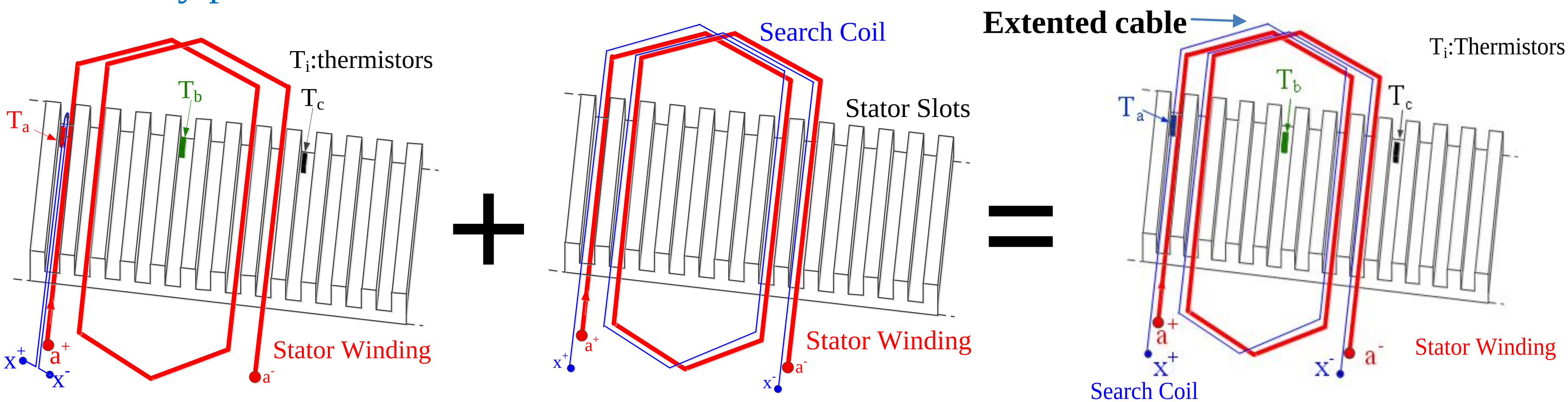
Combined Temperature Monitoring and Rotor Flux Position Estimation

DIEEI

The idea is to exploit the thermistors for measuring the temperature and their wirings to estimate the rotor flux position in sensorless synchronous motors.

How do it?

Search Coils can be obtained by slightly modifying the shape of thermistor (T_i) wirings, which are normally placed in the stator slots.



Thermistors (Temperature sensing)

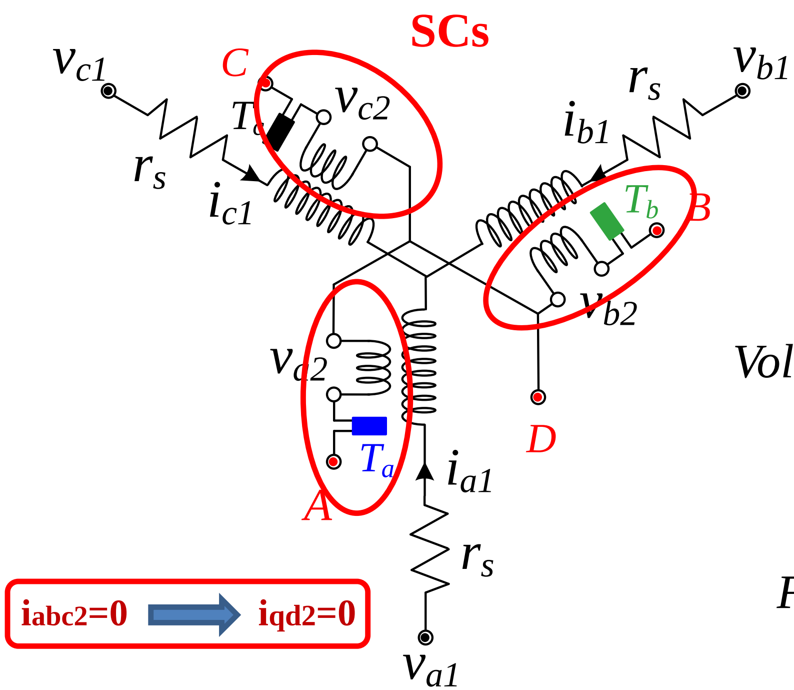
Search Coil (Rotor flux position estimation)

Search Coil with Thermistors (Rotor flux position estimation and temperature sensing)

- **The introduction of SC should require a very limited extra cost, mostly related to the introduction of some additional low-voltage signal conditioning circuits**

- **The temperature monitoring is completely unaffected by obtained search coils**

Model of the SMPMSM embedding SCs in a *qd* synchronous reference frame



Equivalent circuit of the electrical machine including search coils

Stationary $(\alpha\beta)$ to synchronous reference frame:

$$\mathbf{R}(\theta_{re}) = e^{j\theta_{re}} = \begin{bmatrix} \cos(\theta_{re}) & -\sin(\theta_{re}) \\ \sin(\theta_{re}) & \cos(\theta_{re}) \end{bmatrix}$$

Voltage Equations:

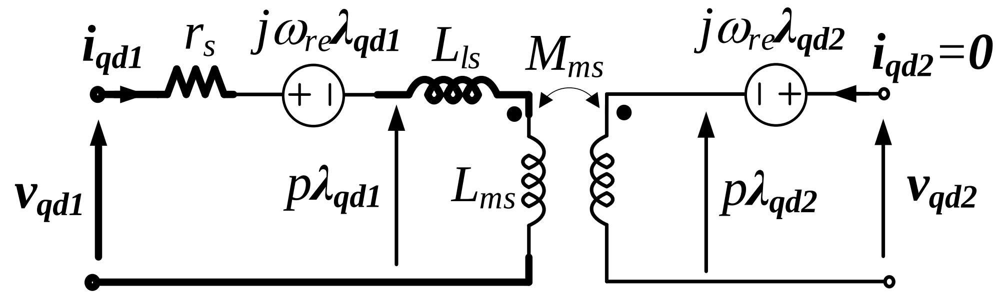
$$\begin{cases} \mathbf{v}_{qd1} = \mathbf{R}_s \, \mathbf{i}_{qd1} + \dfrac{d\boldsymbol{\lambda}_{qd1}}{dt} + j\,\omega_{re}\,\boldsymbol{\lambda}_{qd1} \\ \mathbf{v}_{qd2} = \dfrac{d\boldsymbol{\lambda}_{qd2}}{dt} + j\,\omega_{re}\,\boldsymbol{\lambda}_{qd2} \end{cases}$$

Flux Equations:

$$\begin{cases} \boldsymbol{\lambda}_{qd1} = \mathbf{L}_s \, \mathbf{i}_{qd1} - j\lambda_{pm} \\ \boldsymbol{\lambda}_{qd2} = \mathbf{M}_s \, \mathbf{i}_{qd1} - j\,\lambda_{pmSC} \end{cases}$$

The electromagnetic torque is given by:

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_{pm} i_{q1}$$



Equivalent circuit of the SMPMSM in the qd0 synchronous reference frame.

SCs do not affect the electromagnetic torque

Rotor Flux Position Estimation in SMPMSM

The mathematical model of the SC set can be referred to an estimated qd0 reference frame by including the estimation error ε_θ:

$$\varepsilon_\theta = \theta_{re} - \hat{\theta}_{re}$$

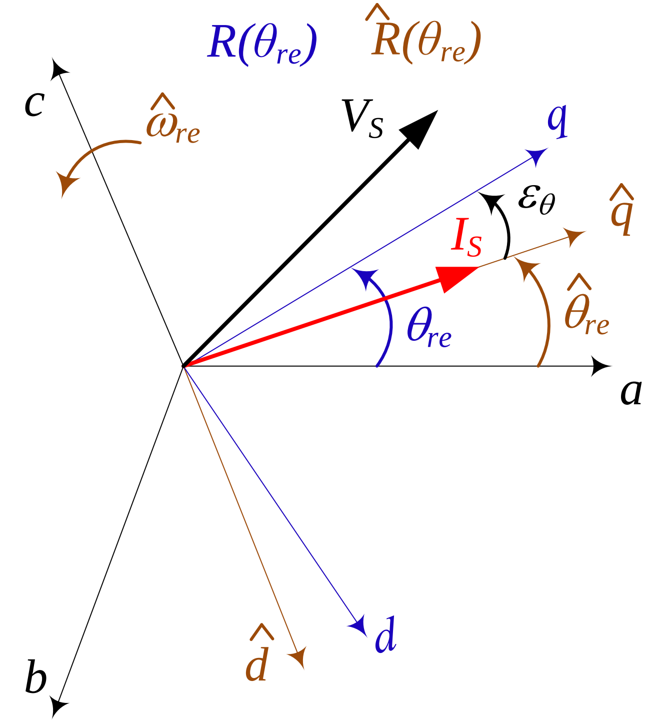
θ_{re}: real
$\hat{\theta}_{re}$: estimated by using SCs.

Stationary $(\alpha\beta)$ to the estimated synchronous reference frame:

$$\mathbf{R}(\hat{\theta}_{re}) = e^{j\hat{\theta}_{re}} = \begin{bmatrix} \cos(\hat{\theta}_{re}) & -\sin(\hat{\theta}_{re}) \\ \sin(\hat{\theta}_{re}) & \cos(\hat{\theta}_{re}) \end{bmatrix}$$

- It is assumed that the currents flowing in the main stator windings can be expressed as:

$$i_{as} = I_s \cos(\hat{\theta}_{re})$$
$$i_{bs} = I_s \cos(\hat{\theta}_{re} - 2\pi/3)$$
$$i_{cs} = I_s \cos(\hat{\theta}_{re} + 2\pi/3)$$



- By supposing that the estimation error ε_θ is constant, we get:

$$\omega_{re} \approx \hat{\omega}_{re}$$

$$\hat{v}_{q2} = \hat{\omega}_{re}\lambda_{pm_{SC}}\cos(\varepsilon_\theta)$$

$$\hat{v}_{d2} = -\hat{\omega}_{re}MI_S - \hat{\omega}_{re}\lambda_{pm_{SC}}\sin(\varepsilon_\theta)$$

Rotor Flux Position Estimation in SMPMSM

1. Estimation of rotor flux position by using the estimated d axis voltage:

$$\hat{v}_{d2} = -\hat{\omega}_{re} M I_S - \hat{\omega}_{re} \lambda_{pmsc} \sin(\varepsilon_\theta) \Rightarrow \hat{v}_{d2} + \hat{\omega}_{re} M I_S = -\hat{\omega}_{re} \lambda_{pmsc} \sin(\varepsilon_\theta)$$

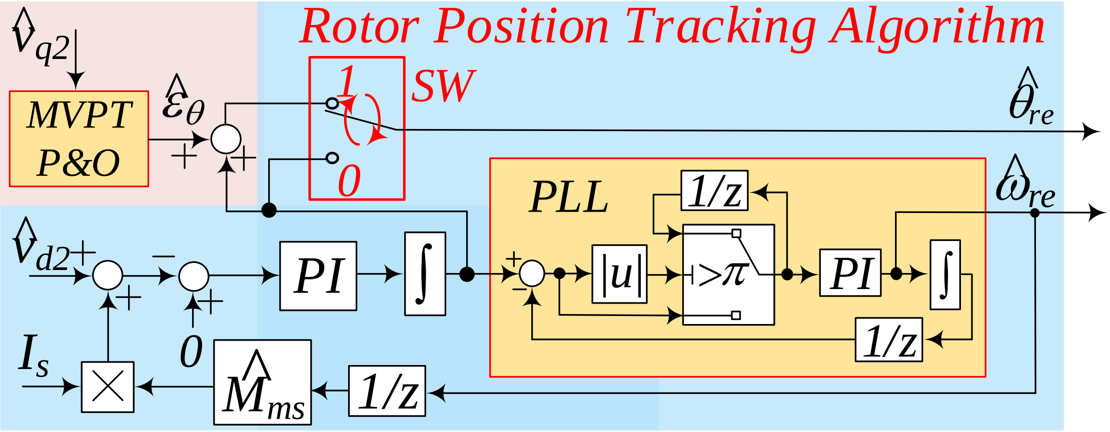
The sum between the induced voltage $\hat{v}_{d2}$ and $\hat{\omega}_{re} M I_S$ has to be forced to zero in order to drive the estimation error ε_θ to zero.

2. It is possible to correct the rotor position estimation error caused by M variation according to the load condition.

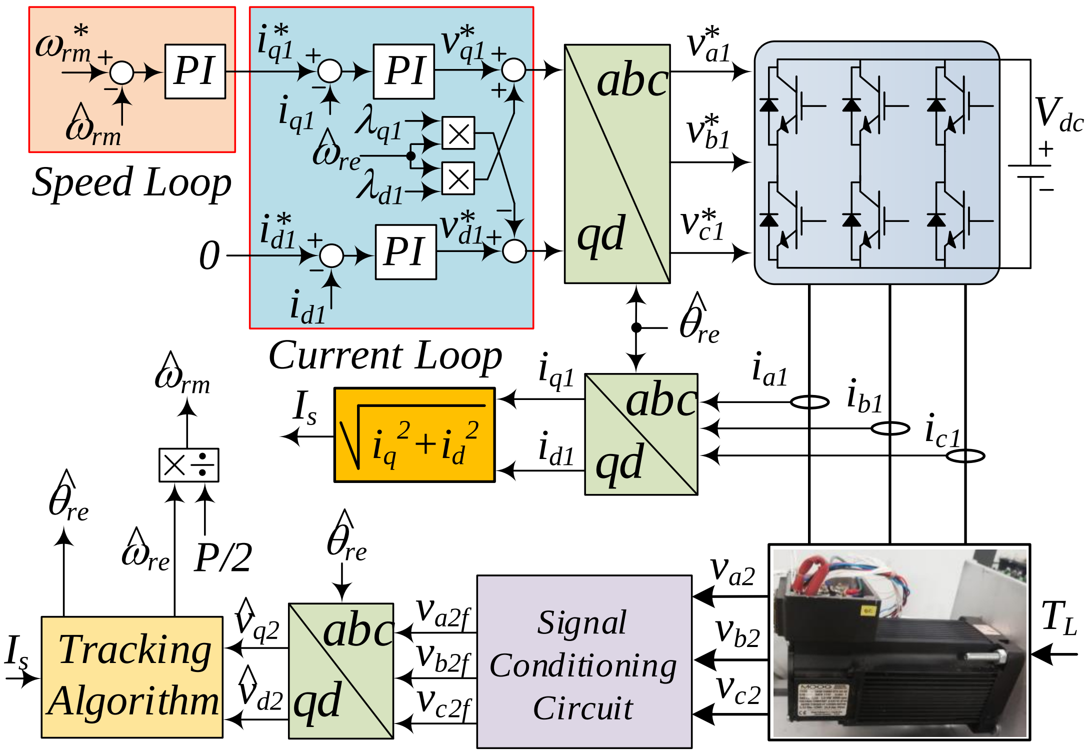
This can be accomplished by tracking the maximum of the voltage $\hat{v}_{q2}$ which coincides with a zero estimation error $\hat{\varepsilon}_\theta = 0$, independently from motor parameters variations.

$$\Rightarrow \hat{v}_{q2} = \hat{\omega}_{re} \lambda_{pmsc} \cos(\varepsilon_\theta)$$

- A maximum voltage point tracking (MVPT) based on the perturb and observe (P&O) algorithm has been integrated into the zero crossing tracking algorithm
- The MVPT – P&O is of simple implementation, but it features a slow dynamic



Sensorless Field Oriented Control



Block diagram of the sensorless motor drive

Table I Motor Data

Rated torque	**5 Nm**
Rated speed	6000 rpm
Inertia	0.0025 kg m^2
Pole pairs	3
Rated voltage	565 V
Rated current	5 A
R_s	0.84 Ω
L_s	4.7 mH

Table II Technical specification of the Search Coils and Thermistors

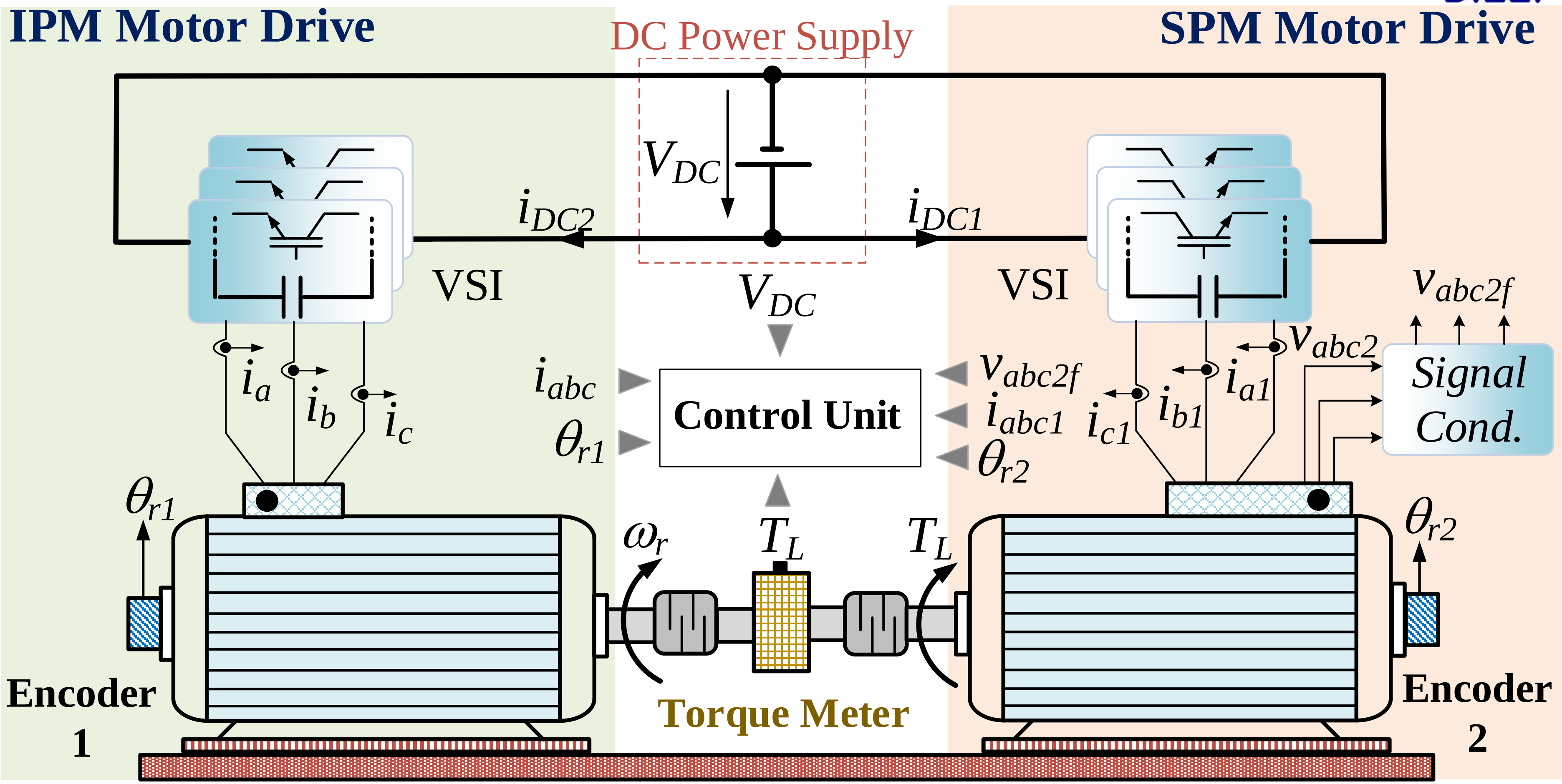
M_{ms}	**0.2 mH**
Thermistor resistance value at 25 °C R_{25}	210 kΩ

Tracking Algorithm

- ***Tracking the zero crossing point of $\hat{v}_{d2} + \hat{\omega}_{re} M I_S$***
- ***Tracking the maximum of $\hat{v}_{q2}$***

Estimated rotor flux position independent from motor parameters

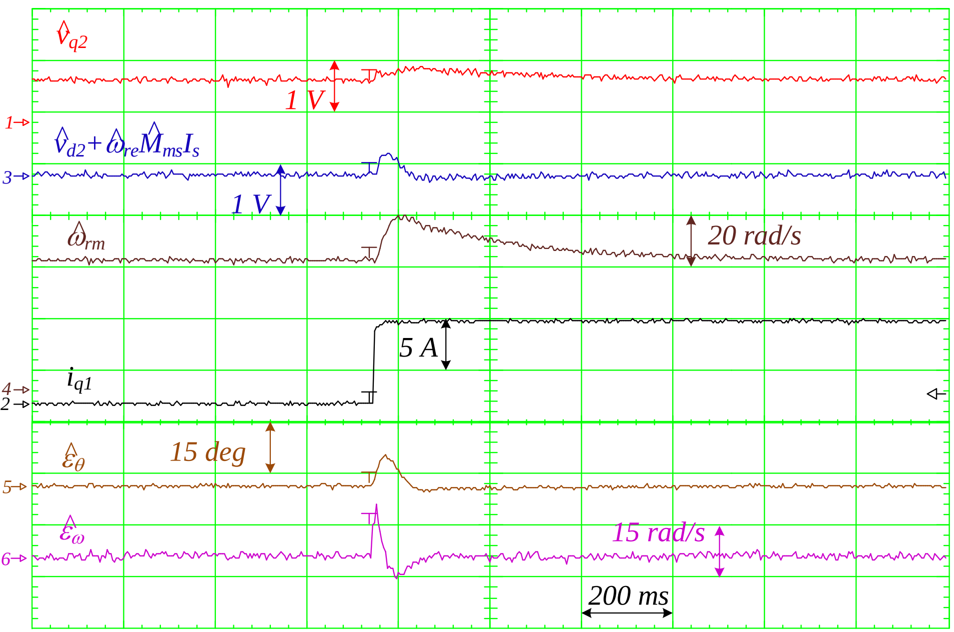
Experimental Setup



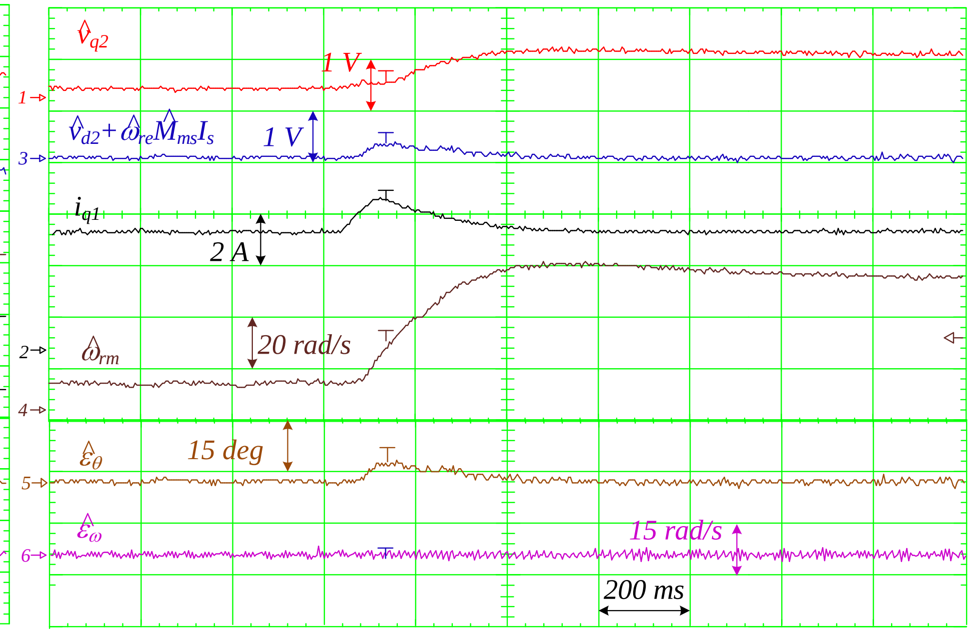
- ❖ *2,6 kW IMPMSM*
- ❖ *2kW SMPMSM*
- ❖ *Three phase PWM inverter for IPM, with a 600V DC bus voltage and fs=20kHz*
- ❖ *Three phase PWM inverter for SPM, with a 600V DC bus voltage and fs=10kHz*

Sensorless Dynamic Operation

Sensorless Control Algorithm based on $\hat{v}_{d2} + \hat{\omega}_{re} M I_S$



Torque transient from no load to rated torque at ω_{rm} = 50 rad/s, with the switch SW set to 0, that is to say with the MVPT deactivated



Speed transient from ω_{rm} = 10 rad/s to ω_{rm} = 50 rad/s at rated torque, with the switch SW set to 0, MVPT deactivated

Only negligible estimation errors were recorded

Low speed
High current

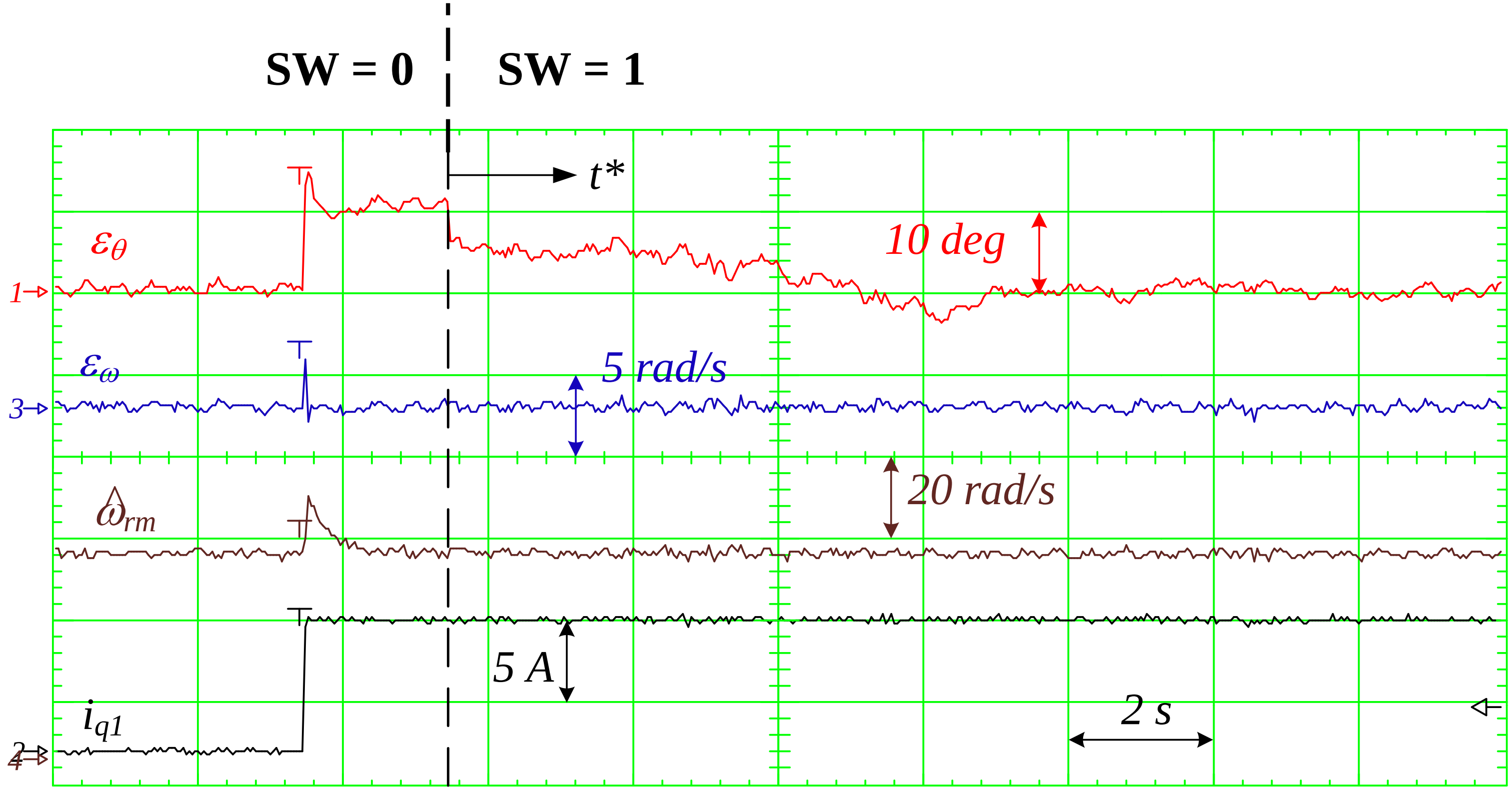
→

SC method Satisfying dynamic behavior

Maximum Voltage Point Tracking (MVPT)

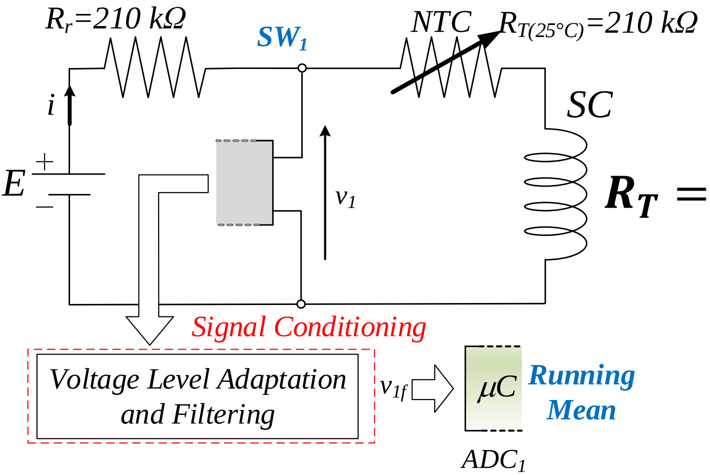
The proposed method with $\hat{v}_{q2}$. Maximum Tracking Point to compensate the parameters mismatching in the rotor position tracking algorithm

A quite large variation of the mutual inductance $\boldsymbol{\widehat{M}}$ with the load has been purposely generated to assess the operation of the additional MVPT tracking loop.



Activation of the MVPT algorithm on the estimated rotor position at the instant t^*

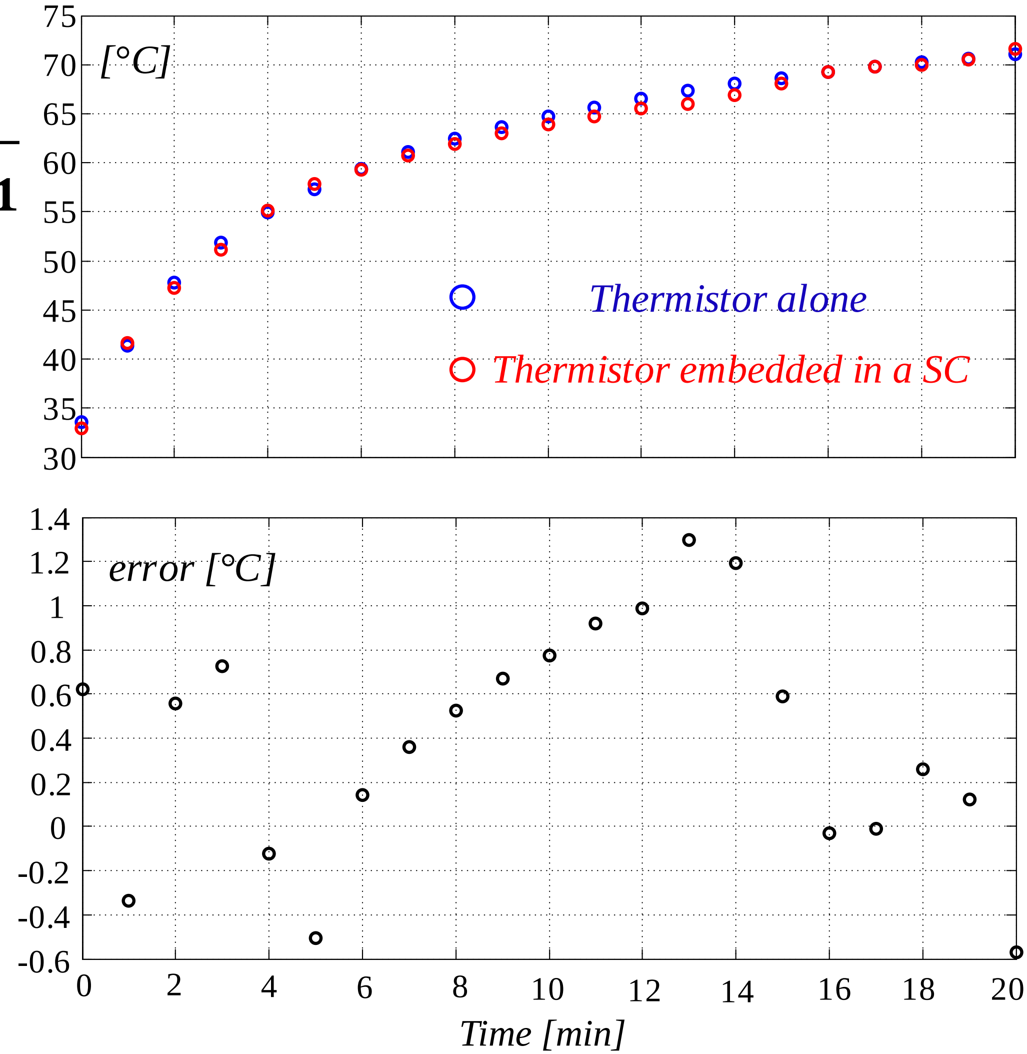
Temperature Monitoring with SCs

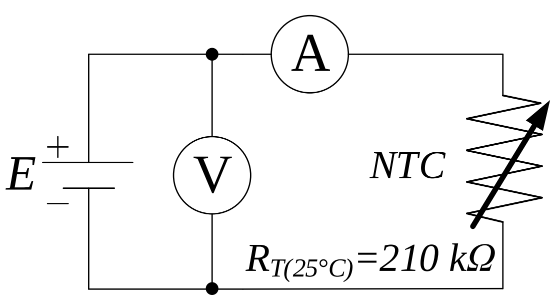


$$R_T = \frac{R_r}{\frac{E}{g v_{1f}} - 1}$$

Signal conditioning circuit for proposed temperature measurement with a DC supply of the series connection of the thermistor and SC

ω_{rm} = 50rad/s, T_L = 100%T_n





$$R_T = \frac{V}{I}$$

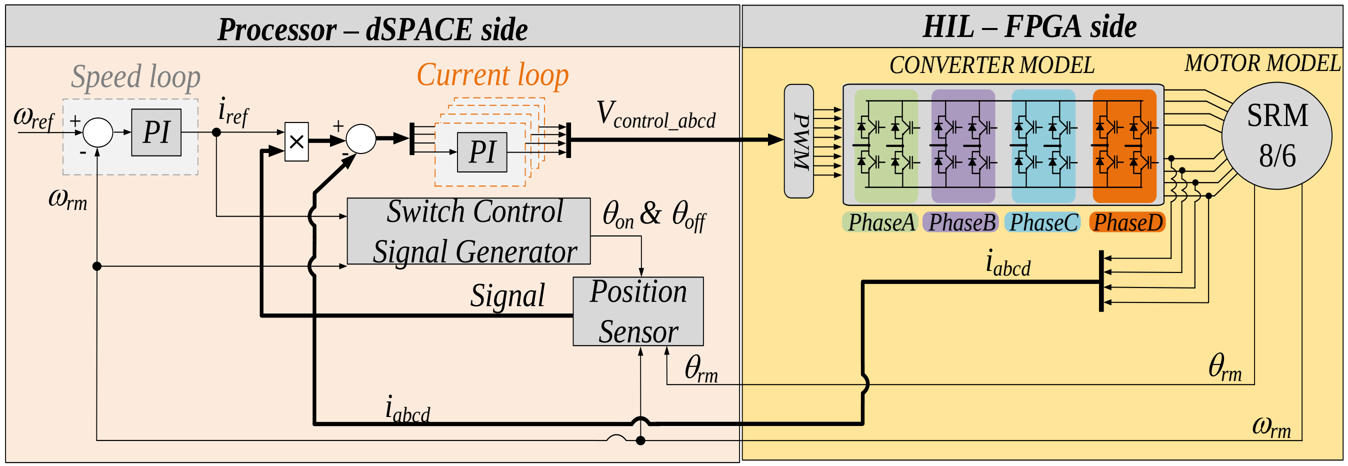
Signal conditioning circuit for typical temperature measurement by exploiting a DC supply voltage

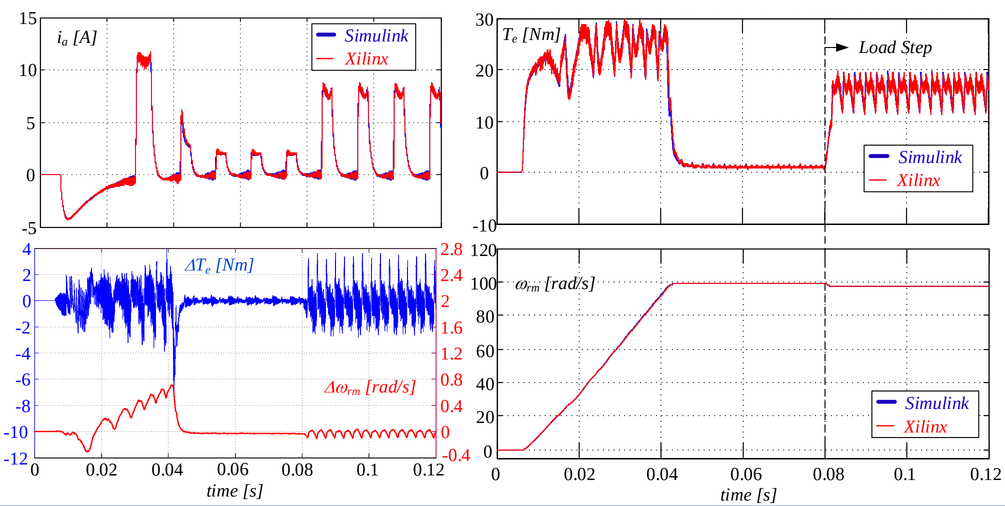
Other Research Activities During The Academic Year

❖ **AUTOMOTIVE**: FPGA-Based Design and Implementation of a Real Time Simulator of Switched Reluctance Motor (SRM) Drives

Hardware in the Loop workbench

- DS1006 (sample time=50µs) processor board with 4 core arm technology
- DS2211 I/O and CAN bus board
- DS5203 based on Xilinx FPGA technology (FPGA clock period=10ns), ensures high speed signal processin

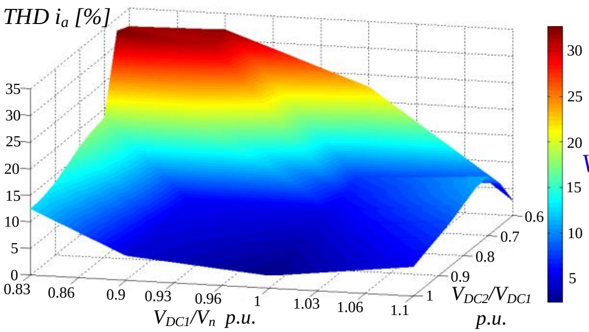


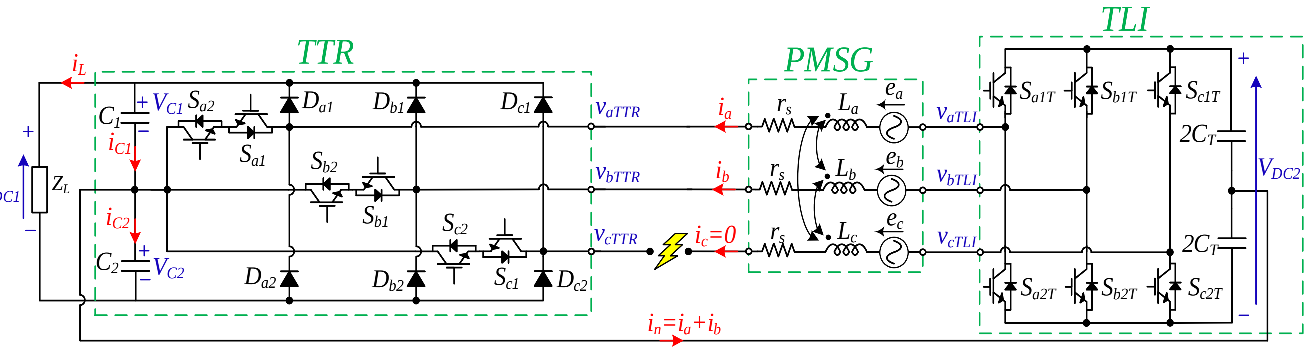


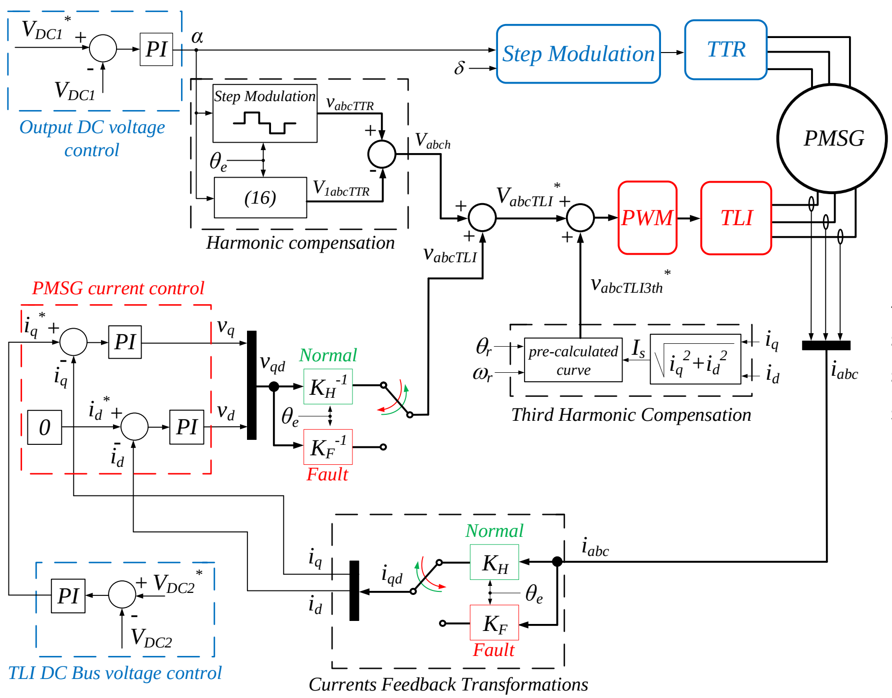
1. *Mathematical Models of SRM 4/6, 6/8 and 8/10*
2. *PWM Modulator and Power Converter Models*
3. *Flux Linkage and Current Profiles Measurement for Inductance and Torque look-up tables (LUTs)*
4. *SRM drive implementation on a Standard Model-Based design environment (SMB)*
5. *Model Validation*
6. *Hardware in the Loop (HIL) Performance Monitoring*

Other Research Activities During The Academic Year

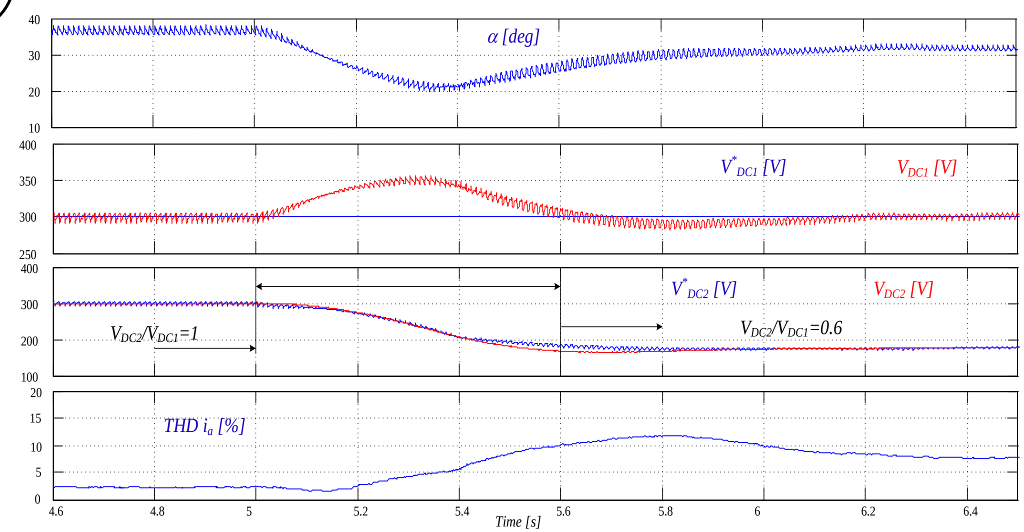
❖ **<u>Power Converter Topologies</u>: A Fault Tolerant AC/DC Converter for Electrical Gen-Set Applications**







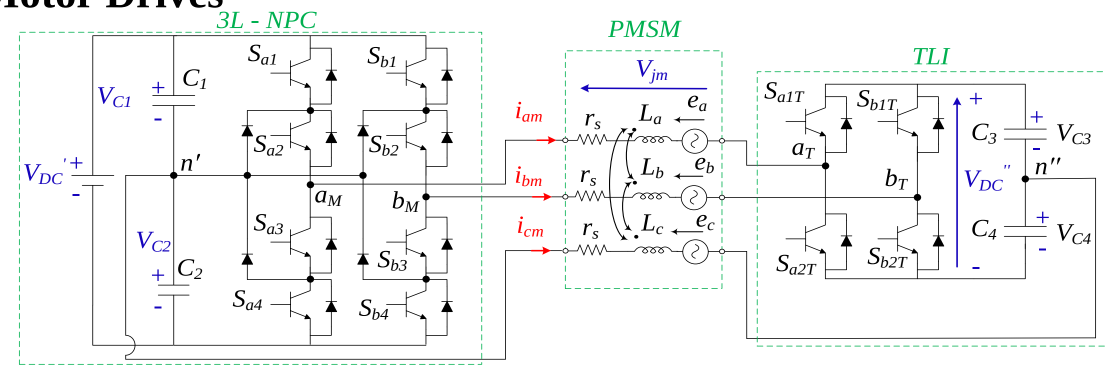
1. *PMSG Model during open-phase fault*
2. *Electrical Gen-Set Control Strategy*
3. *Simulation Results*

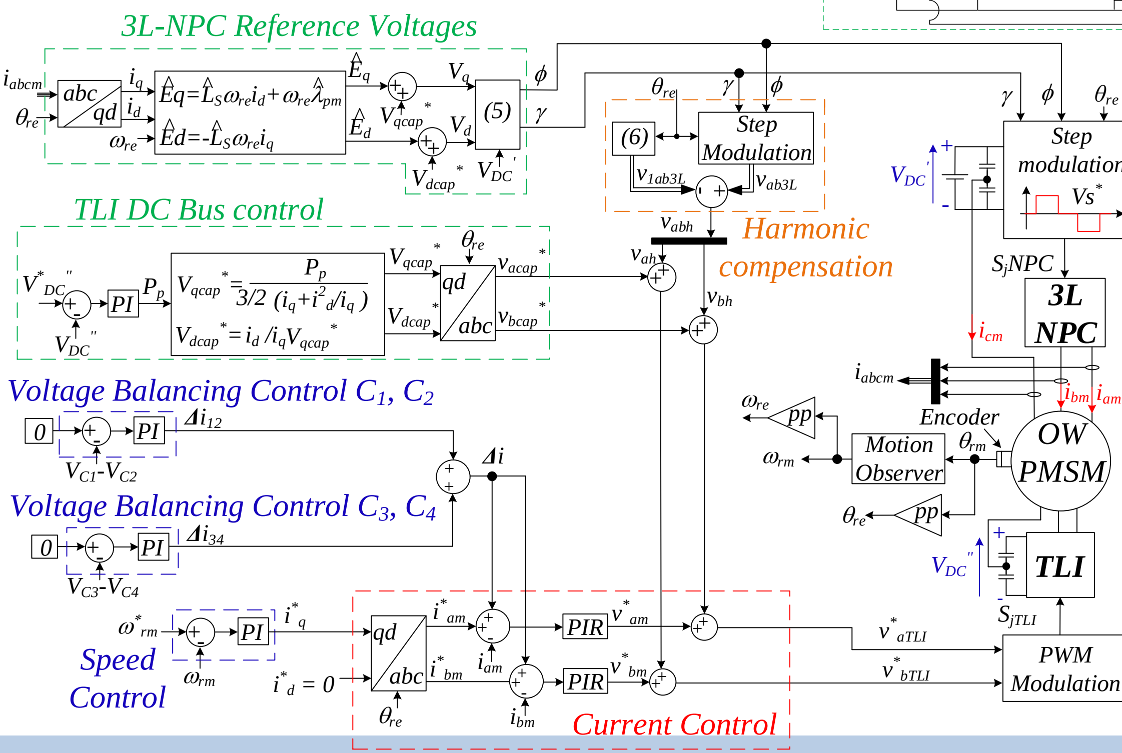


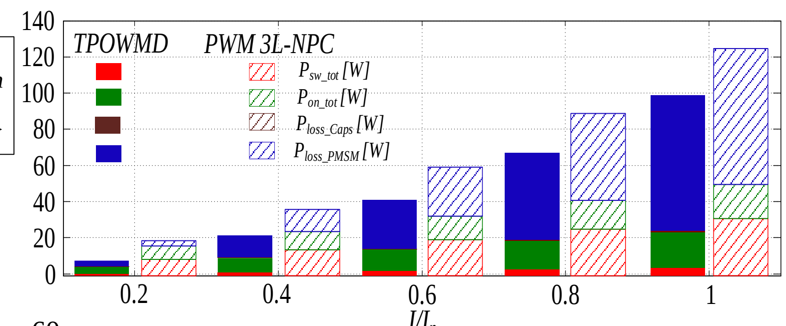
Other Research Activities During The Academic Year

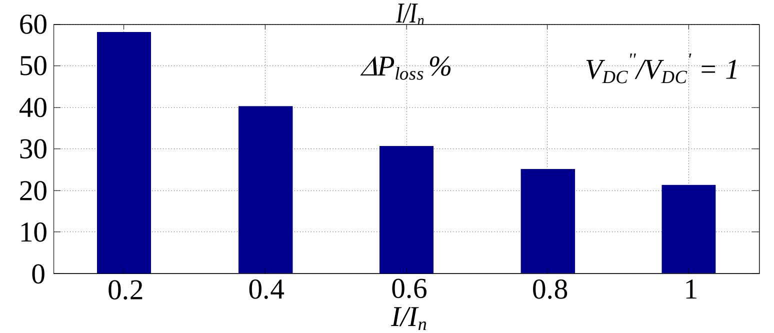
❖ **<u>Power Converter Topologies</u>: A Novel Three-Phase Multilevel Inverter Topology with Reduced Deviced Count for Open-end Winding Motor Drives**

1. *Three-phase, Two Poles, Open-end Winding Motor Drive (TPOWMD) model*
2. *Control Strategy for a TPOWMD*
3. *Simulation and Performance Analysis*
4. *Power Losses (3L-PWM vs TPOWMD)*









Research Activities During The Academic Year

❖ Papers / Journal:

1. L. D. Tornello, G. Scelba, S. Scarcella, M. Cacciato, A. Testa, S. Foti, S. De Caro, M. Pulvirenti "Combined Rotor Position Estimation and Temperature Monitoring in Sensorless Synchronous Reluctance Motor Drive", IEEE Transaction on Industrial Applications, vol. 55, Year 2019.

❖ Papers / Conferences:

1. G. Aiello, L. D. Tornello, G. Scelba, S. Scarcella, M. Cacciato, A. Palmieri, E. Vanelli, C. Pernaci, R. Di Dio, "FPGA-Based Design and Implementation of a Real Time Simulator of Switched Reluctance Motor Drives", International Conference and Exposition on Electrical And Power Engineering (EPE 2019), Genova, Italy.
2. S. Foti, A. Testa, S. De Caro, T. Scimone, G. Scelba, L. D. Tornello, "A Fault Tolerant AC/DC Converter for Electrical Gen – Set Applications", International Conference and Exposition on Electrical And Power Engineering (EPE 2019), Genova, Italy.
3. S. Foti, A. Testa, S. De Caro, T. Scimone, G. Scelba, L. D. Tornello, "An Integrated Battery Charger for EV applications based on an Open-End Winding Multilevel Converter configuration", International Conference and Exposition on Electrical And Power Engineering (EPE 2019), Genova, Italy.
4. L. D. Tornello, G. Scelba, G. Scarcella, M. Cacciato, S. Foti, A. Testa, "Sensorless Control of PMSM Drives through Modified Thermistors Wirings", 2019 IEEE 10th International Symposium on Sensorless Control for Electrical Drives (SLED), Torino, Italy.
5. S. Foti, A. Testa, S. De Caro, T. Scimone, G. Scelba, L. D. Tornello, "Sensorless Estiamtion of Machine Parameters in Synchronous Reluctance Motor Drives", 2019 IEEE 10th International Symposium on Sensorless Control for Electrical Drives (SLED), Torino, Italy.
6. S. Foti, A. Testa, S. De Caro, T. Scimone, L. D. Tornello, G. Scarcella, G. Scelba, "A Novel Three – Phase Multilevel Inverter Topology with Reduced Device Count for Open – end Winding Motor Drives", 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA.
7. S. Foti, A. Testa, S. De Caro, T. Scimone, L. D. Tornello, G. Scarcella, G. Scelba, "A novel Hybrid N – Level T – Type Inverter Topology", 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA.

❖ Tutorial / Ph.D School:

1. ECPE Tutorial: "Power Semiconductor Devices & Technologies", 4-5 October 2018, STMicroelectronics, Catania, Italy.
2. European PhD School, "Power Electronics, Electrical Machines, Energy Control and Power Systems", 20-24 May 2019, Gaeta, Italy.
3. Riunione Annuale Congiunta CMAEL-Gusee 2019, 16-17 Settembre 2019, Cagliari, Italia.