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DIEEI

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Combined Rotor Position Estimation and Temperature Monitoring in Synchronous Reluctance and PMSM Motor Drives

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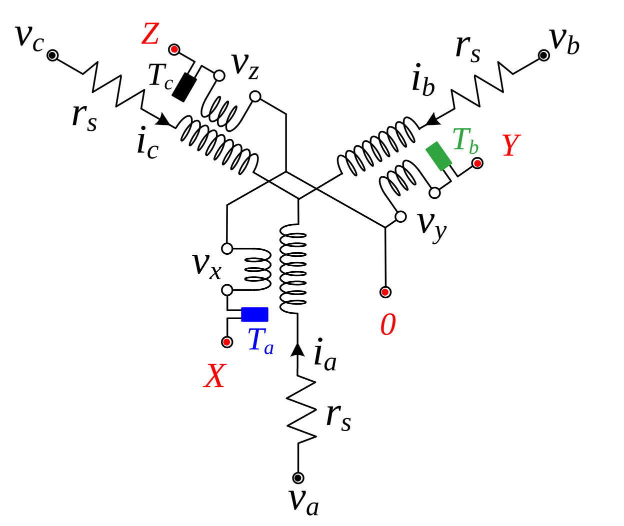
RESEARCH ACTIVITY

A novel approach is described in this paper exploiting the stator temperature monitoring system to sensorless estimate the rotor position. The rotor position is, in fact, estimated by processing the voltages induced in Thermistors cablings, which are modified in order to work as search coils. Using search coils, some typical drawbacks of sensorless position estimation techniques based on the manipulation of fundamental components of stator voltages and currents, such as those related to inverter non-linearities, stator resistance voltage drops, magnetic saturation and cross-coupling can be overcome or mitigated. According to the proposed approach, a rotor position tracking technique for Surface Mounted Permanent Magnet Synchronous Machine and Synchronous Reluctance Motor drives is developed fully independent from motor parameters. Such a sensorless rotor position estimation technique, can be directly used to build up a sensorless controller, or to improve the performance of conventional model based sensorless control systems. Simulations and experimental tests confirm the effectiveness of the proposed approach.

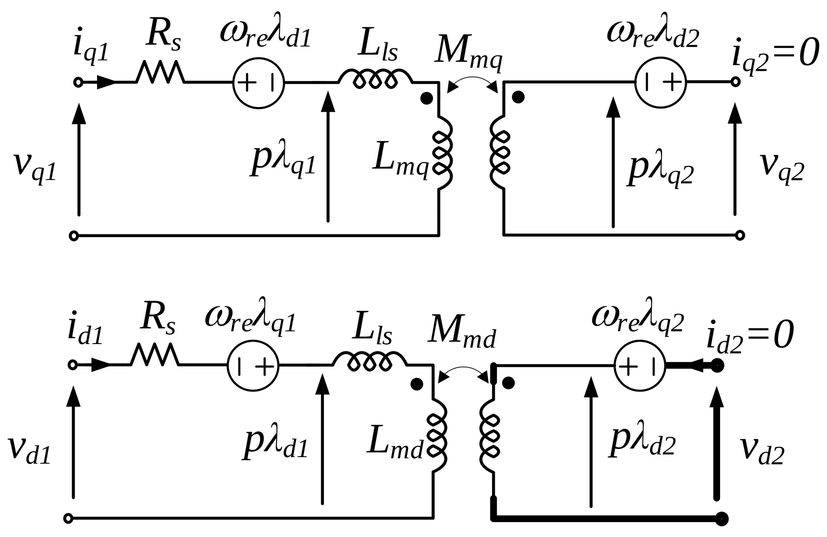
Model of Synchronous Reluctance Machine with Search Coils

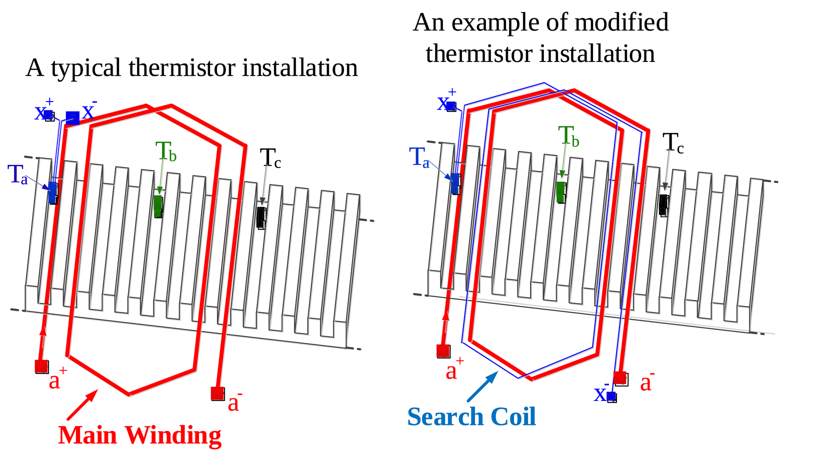
A set of search coils can be obtained by modifying the wiring of three Thermistors featuring a common lead configuration placed on the stator winding of a three phase SynchRel, as shown.



- ➢Thermistors feature very small size and mass and a medium impedance, hence the wires connecting the motor and device can be of inexpensive light gauge.
- ➢Thermistors are physically placed inside the machine to sense the temperature of likely hot spots, whose location depends on the motor design.

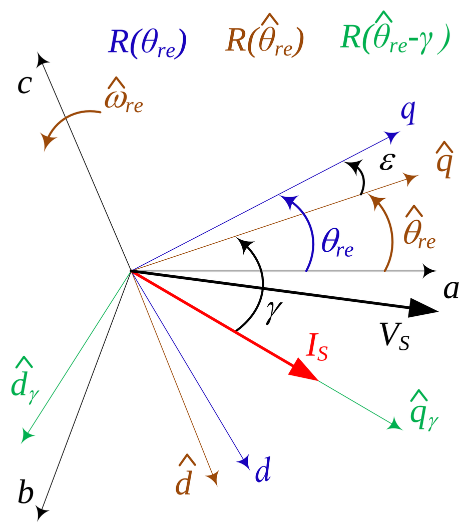
Under the hypotheses that the SC are operated at zero current (i_{xyz}=0), the mathematical model of the machine including the set of search coils is given in the *qd* synchronous reference frame by the following equations:





Rotor Flux Position Estimation

As shown in Fig. 7, the mathematical model of the SC set can be referred to three different rotating reference frames:



By considering ε, the rotor position estimation error, it can be written: $\theta_{re} = \hat{\theta}_{re} + \varepsilon$

By supposing that the estimation error ε is constant or slowly variable, we can approximate $\omega_{re} \approx \hat{\omega}_{re}$

Moreover, the currents flowing in the stator winding can be expressed as:

$i_{as}=I_s\cos(\hat{\theta}_{re}-\gamma)$

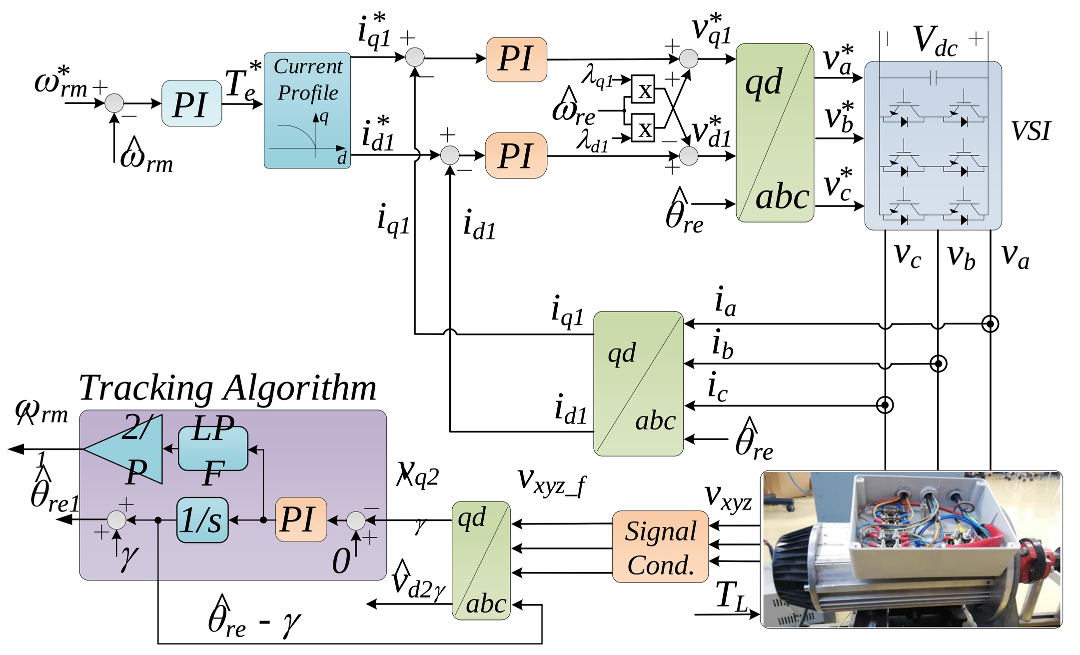
$i_{bs}=I_s\cos(\hat{\theta}_{re}-2\pi/3-\gamma)$

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

$$R(\hat{\theta}_{re}-\gamma)=\frac{2}{3}\begin{bmatrix}\cos(\hat{\theta}_{re}-\gamma) & \cos(\hat{\theta}_{re}-\gamma-2\pi/3) & \cos(\hat{\theta}_{re}-\gamma+2\pi/3)\\ \sin(\hat{\theta}_{re}-\gamma) & \sin(\hat{\theta}_{re}-\gamma-2\pi/3) & \sin(\hat{\theta}_{re}-\gamma+2\pi/3)\end{bmatrix}$$

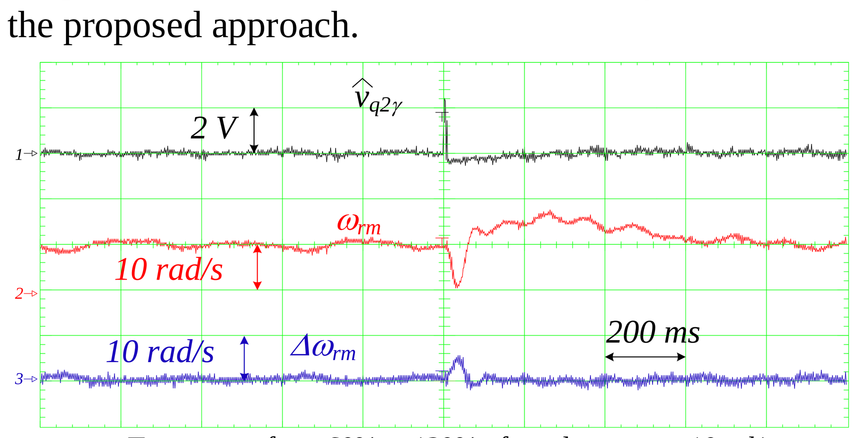
$$\hat{v}_{q2\gamma}=\frac{3}{2}I_s\,\hat{\omega}_{re}M_B\sin(2\varepsilon+2\gamma) \qquad \hat{v}_{d2\gamma}=-\frac{3}{2}I_s\,\hat{\omega}_{re}M_A+\frac{3}{2}I_s\,\hat{\omega}_{re}M_B\cos(2\varepsilon+2\gamma)$$

Rated torque	5 Nm
Rated speed	1500 rpm
Inertia	0.0045 kg m²
Pole pairs	4
Rated voltage	400 V
Rated current	8 A
R_s	1.4 Ω
L_q	0.011 H
L_d	0.057 H
M_q	0.0023 H
M_d	0.0115 H

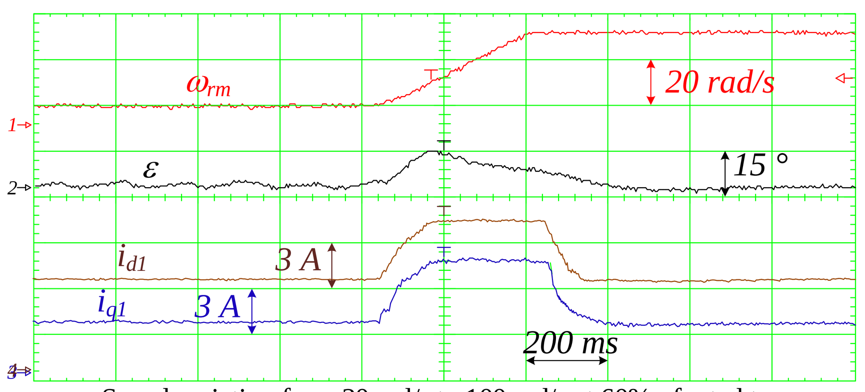


Experimental Validation

A specific test bench, tailored around a SynchRel motor drive, has been realized to accomplish a practical evaluation of the proposed approach.

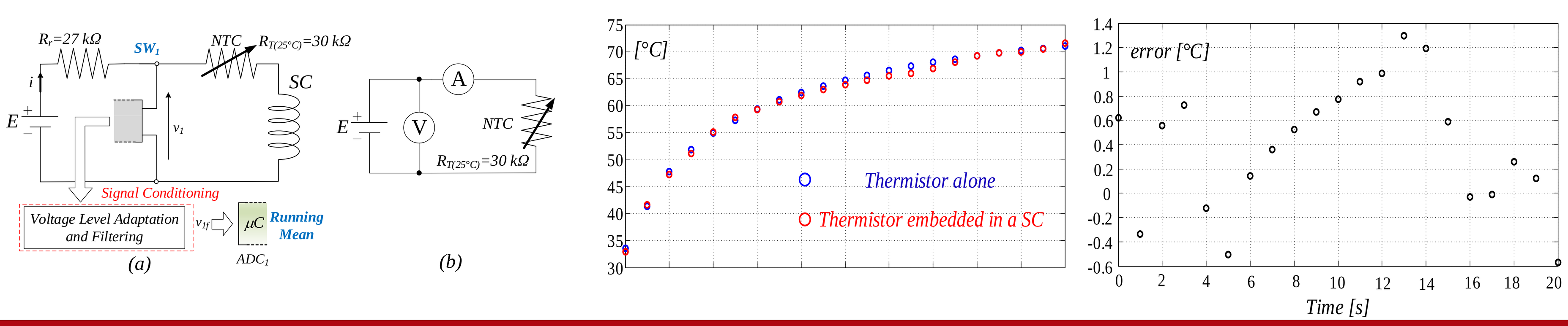


Torque step from 60% to 120% of rated torque, at *10rad/s*



Speed variation from 20 rad/s to 100 rad/s at 60% of rated torque

Temperature monitoring in the SyncRel motor via: a DC supply of the series connection of the thermistor and SC (a); typical temperature measurement by exploiting a DC supply voltage (b).



Model of Surface Mounted Permanent Magnet Synchronous Machine with Search Coils

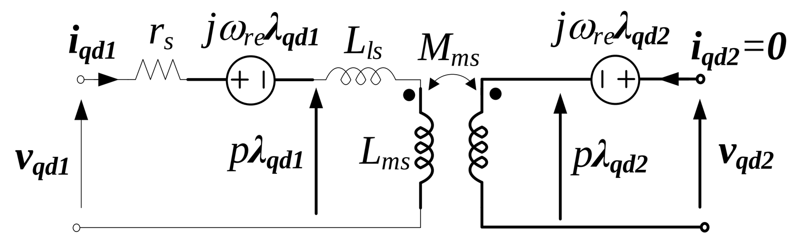
Voltage Equations:

$$v_{qd1}=R_s\,i_{qd1}+\frac{d\lambda_{qd1}}{dt}+j\,\omega_{re}\,\lambda_{qd1}$$
$$v_{qd2}=\frac{d\lambda_{qd2}}{dt}+j\,\omega_{re}\,\lambda_{qd2}$$

Flux Equations:

$$\lambda_{qd1}=L_s\,i_{qd1}-j\lambda_{pm}$$
$$\lambda_{qd2}=M_s\,i_{qd1}-j\,\lambda_{pmSC}$$

Electromagnetic Torque Equation: $T_e=\frac{3}{2}\frac{P}{2}\lambda_{pm}i_{q1}$



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:

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

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

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

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

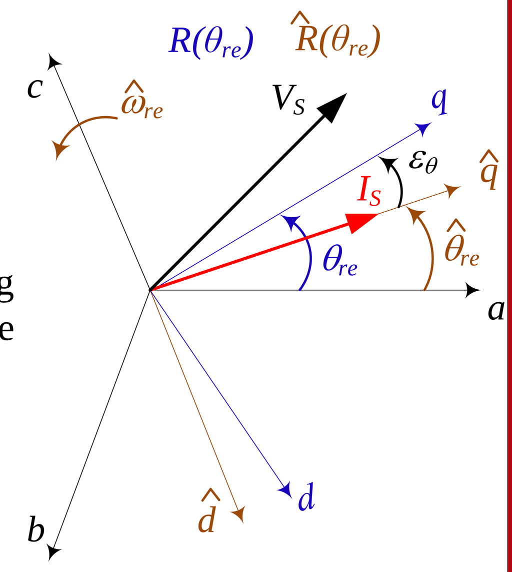
$$R(\hat{\theta}_{re})=e^{j\hat{\theta}_{re}}=\begin{bmatrix}\cos(\hat{\theta}_{re}) & -\sin(\hat{\theta}_{re})\\ \sin(\hat{\theta}_{re}) & \cos(\hat{\theta}_{re})\end{bmatrix}$$

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

$i_{as}=I_s\cos(\hat{\theta}_{re})$

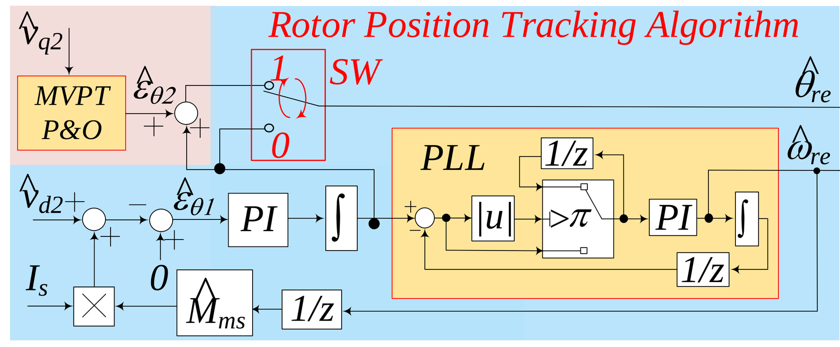
$i_{bs}=I_s\cos(\hat{\theta}_{re}-2\pi/3)$

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



Search Coils Voltages in Estimated synchronous reference frame, in Steady State Conditions:

$$\hat{v}_{q2}=\hat{\omega}_{re}\lambda_{pm_{SC}}\cos(\varepsilon_\theta)$$
$$\hat{v}_{d2}=-\hat{\omega}_{re}MI_S-\hat{\omega}_{re}\lambda_{pm_{SC}}\sin(\varepsilon_\theta)$$



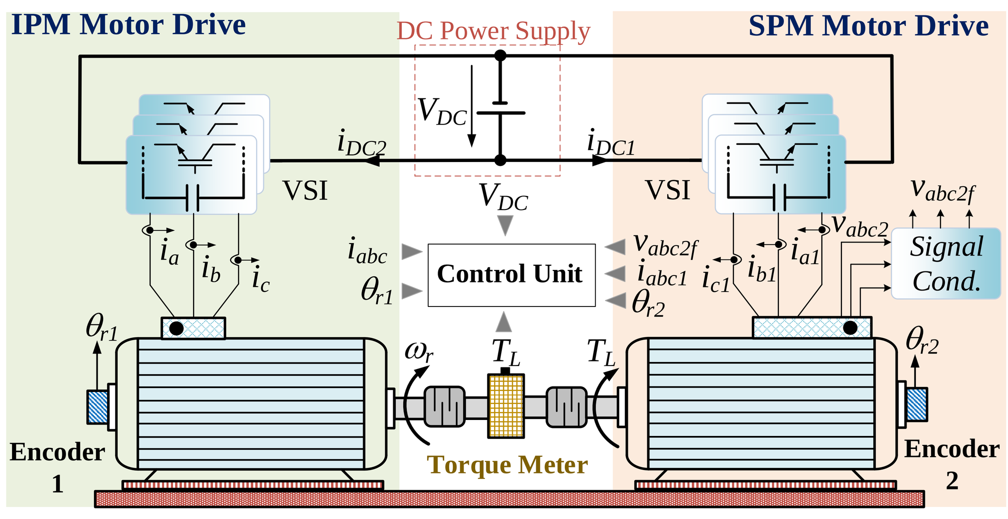
It is possible to correct the rotor position estimation error caused by ***M*** variation according to the load condition. This can be accomplished by tracking the maximum of the voltage $\boldsymbol{v_{q2}}$ which coincides with a zero estimation error $\boldsymbol{\varepsilon_\theta=0}$, independently from motor parameters variations.

- 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

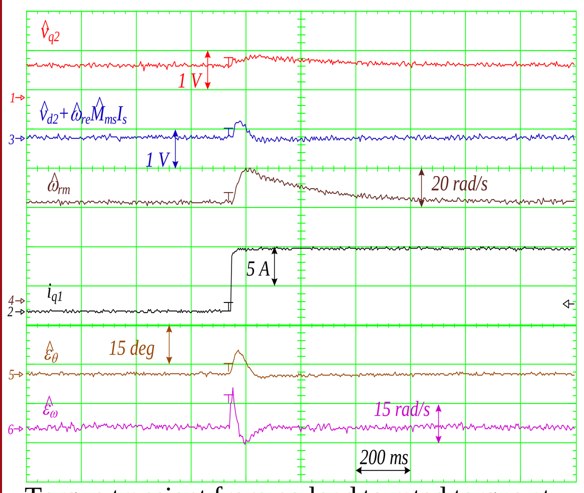
Specifically, the MVPT can be exploited to build suitable compensation maps (2D – look up tables) with a small set of data, to provide a fast correction of the rotor position estimation. The MVPT may also continuously performed to update the compensation maps.

Experimental Validation

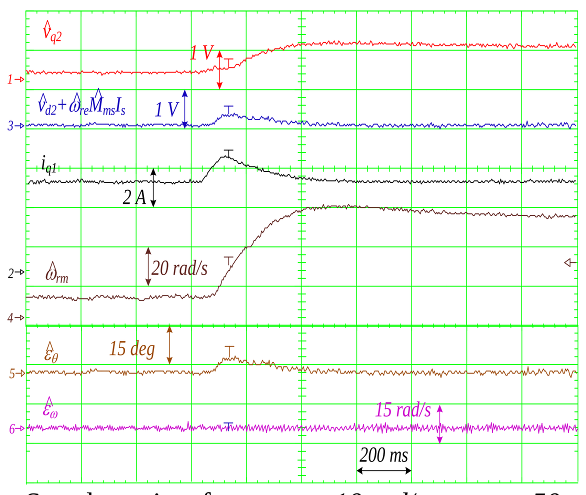
- ***2,6 kW IMPMSM Three phase PWM inverter for IPM, with a 600V DC bus voltage and fs=20kHz***
- ***2kW SMPMSM Three phase PWM inverter for SPM, with a 600V DC bus voltage and fs=10kHz***



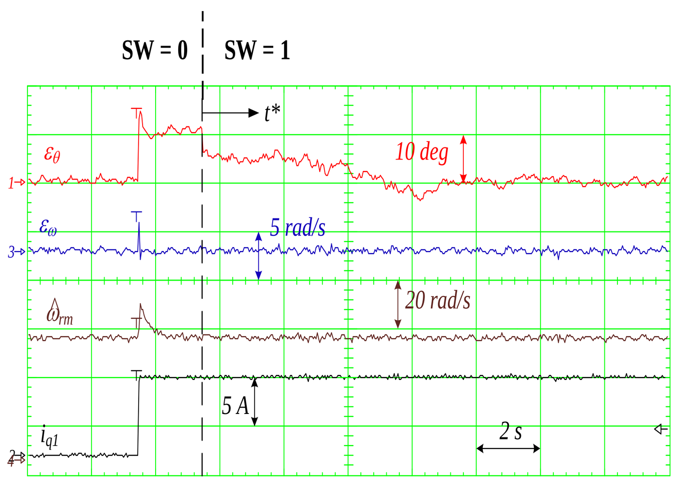
Rated torque	5 Nm
Rated speed	6000 rpm
Inertia	0.0025 kg m²
Pole pairs	3
Rated voltage	565 V
Rated current	5 A
R_s	0.84 Ω
L_s	4.7 mH
M_{ms}	0.2 mH
Thermistor resistance value at 25 °C R_{25}	210 kΩ



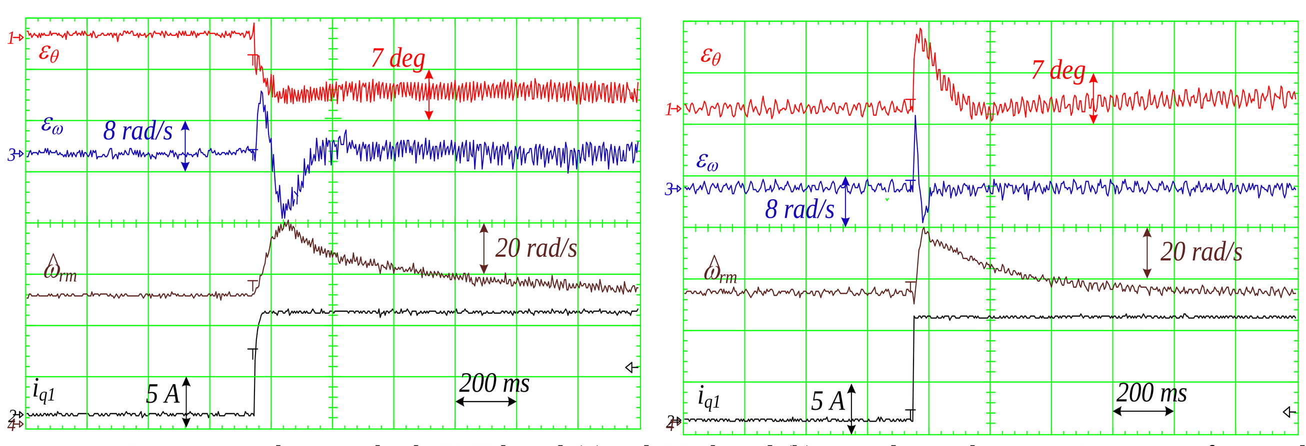
Torque transient from no load to rated torque at ω_{rm} = 50 rad/s.

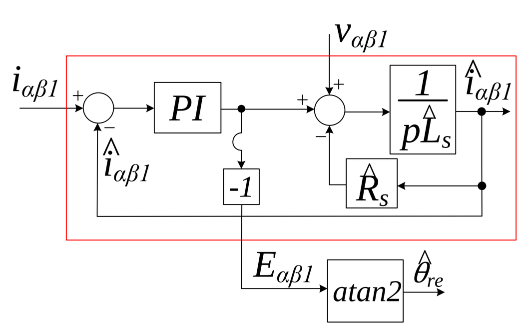


Speed transient from ω_{rm} = 10 rad/s to ω_{rm} = 50 rad/s at rated torque.



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





Comparisons between back-EMF based *(a)* and SCs-based *(b)* sensorless techniques: Step torque from no load to 120% rated torque, at ω_{rm} = 50rad/s.

PUBLICATIONS

- L. D. Tornello, G. Scelba, G. 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.
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- 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.
- 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.
- G. Nobile, M. Cacciato, G. Scarcella, G. Scelba, E. Vasta, L. D. Tornello, A. G. F. Di Stefano, G. Leotta, P. M. Pugliatti, F. Bizzarri, "A novel model – based approach for the energy management of distributed storage systems in utility – scale PV fileds", International Conference and Exposition on Electrical And Power Engineering (EPE 2019), Genova, Italy.
- 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.
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- 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.
- 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.