Online Estimation and Compensation of Back-Electromotive Forces for Synchronous Reluctance Machine

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Outline

Introduction

Model of the SynREL machine

Online Determination of the back-EMF

Experimental results

Perspectives and Conclusion

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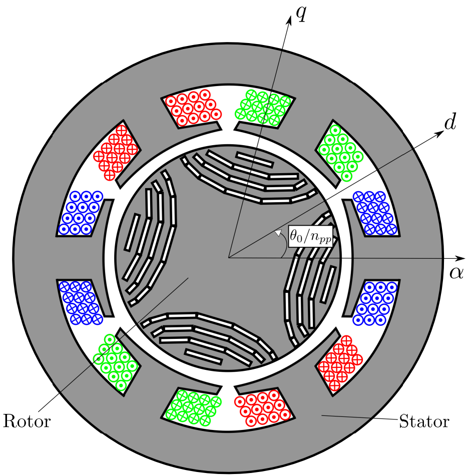
The SynREL technology

- Same stator as PMSM and IM,
- absence of permanent magnet,
- competitor to Induction Machines,
- presence of residual magnetism in the rotor [1][2] and in the stator [3].



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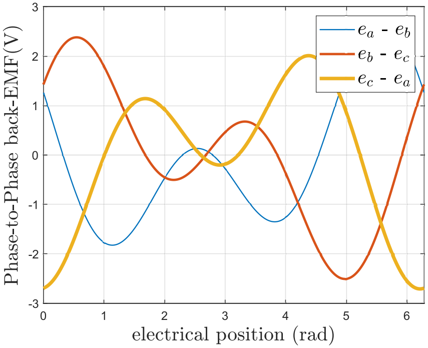
Model of the SynREL machine

The SynREL machine is model by the equation (1) in the three-phase reference frame :

$$\frac{dL(\theta_e)i_{abc}}{dt} = v_{abc} - R_s i_{abc} - e_{abc} \qquad (1)$$

ReMa Model : $e_a = -\Phi_{rot}\omega_e sin(\theta_e + \delta_0) - 3I_{stat}\omega_e M_2 sin(2\theta_e - \sigma_0)$; e_b, e_c phase-shifted by $\pm 2\pi/3$.



Back-EMF in SynREL machines

- Negligible in nominal operation,
- preponderant in low-current operation,
- crucial for start-up procedure,
- developing methods to estimate e_{abc}.

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Short-circuit currents measurement

When the SynREL machine's terminals are short circuited :

$$e_{abc} = -\frac{dL(\theta_e)}{dt} i^{sc}_{abc} - L(\theta_e)\frac{di^{sc}_{abc}}{dt} - R_s i^{sc}_{abc} \tag{2}$$

Assumption : the short-circuit currents contain the same frequencies as e_{abc} :

$$i^{sc} = A_0 cos(\theta_e + \Phi_0) + A_2 cos(2\theta_e + \Phi_2), \tag{3}$$

- A Goertzel algorithm [4][5] is used for the determination of A_0, A_2 ,Φ_0 and Φ_2.
- The derivatives of the short-circuit currents are analytically computed.
- e_{abc} are deduced from equation (2).

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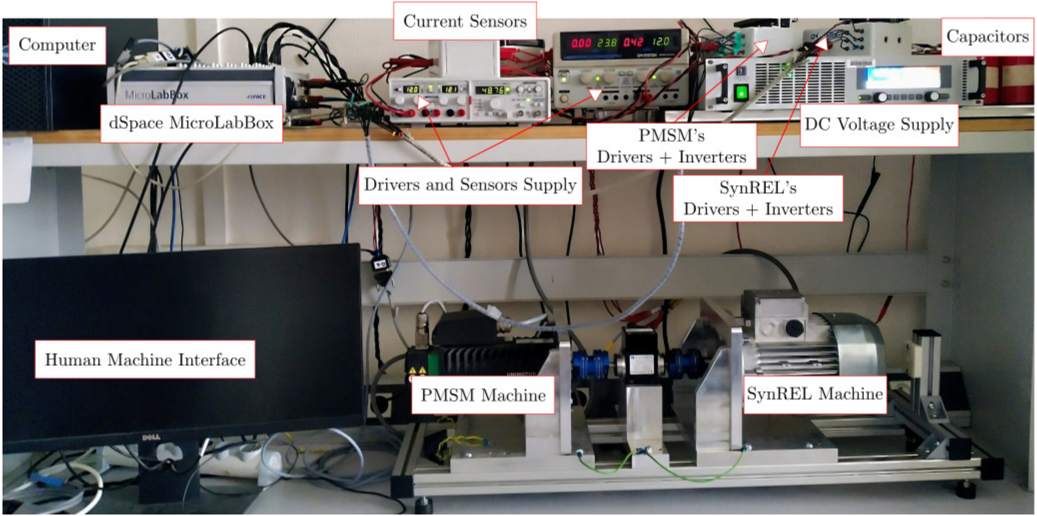
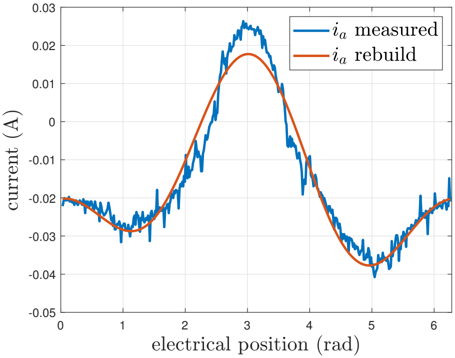
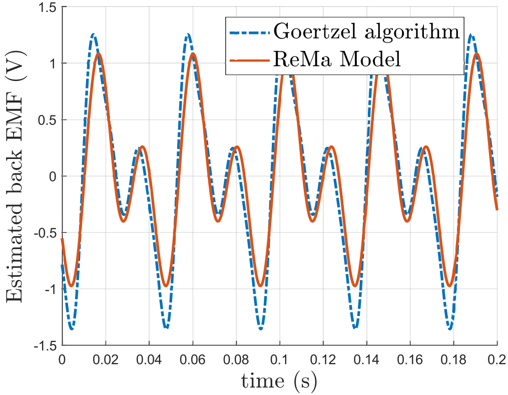
Experimental setup



Back-EMF estimation





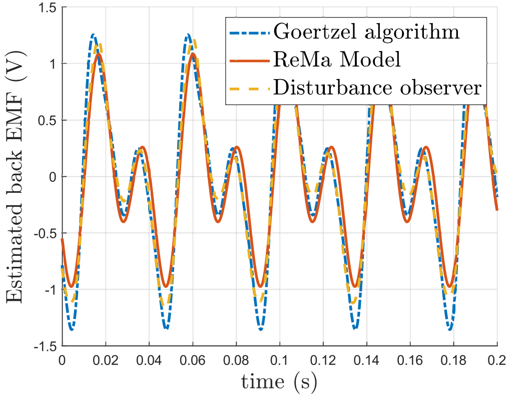
$A_0 = 19.6$ mA	$A_2 = 14.3$ mA
$\Phi_0 = -1.712$ rad	$\Phi_2 = 2.368$ rad

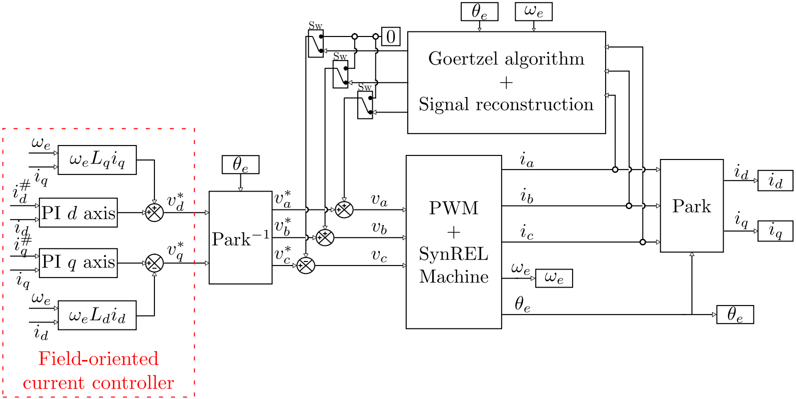
Back-EMF estimation - second method

- Back-EMF are composed of a constant and a sinus in the Park reference frame,
- constant speed implies a linear model,

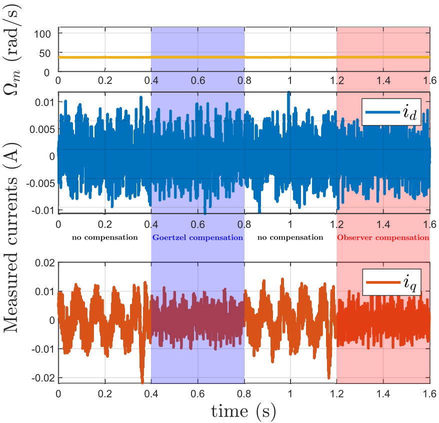
Linear observer in the Park frame

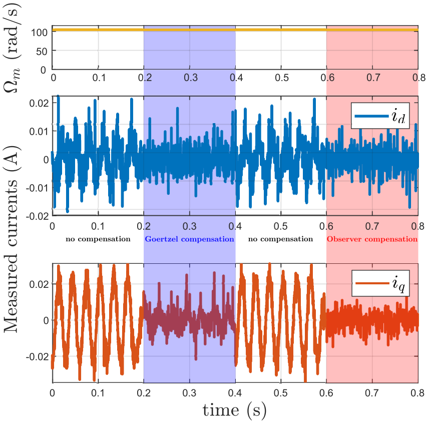
- No short-circuit required,
- less sensitive to uncertainties,
- requires non zero DC voltage.




ω_e
i_q
$\omega_e L_q i_q$
$i_d^\#$
PI d axis
i_d
$i_q^\#$
PI q axis
i_q
ω_e
$\omega_e L_d i_d$
i_d
v_d^*
v_q^*
Field-oriented
current controller
θ_e
Park^{-1}
v_a^*
v_b^*
v_c^*
Sw
Sw
Sw
0
θ_e
ω_e
Goertzel algorithm
+
Signal reconstruction
v_a
v_b
v_c
PWM
+
SynREL
Machine
i_a
i_b
i_c
ω_e
ω_e
θ_e
θ_e
Park
i_d
i_d
i_q
i_q

Back-EMF compensation





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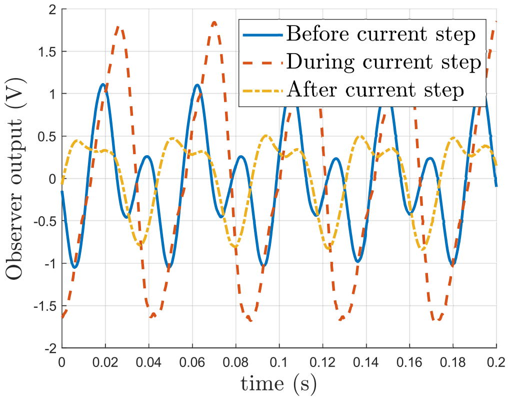
Perspectives

Perspectives

- Making the estimation and compensation more accurate at higher current,
- improving the voltage build-up procedure of stand-alone SynREL generators.



Conclusion

Conclusion of the presentation

- Two consistent methods for estimating back-EMF online,
- in accordance with the reference model,
- require only commonly known parameters of the machine.

Bibliography

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Thank you for your attention !

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Details on the disturbances observer

When the electrical speed ω_e is constant, the electrical model can be expression by a linear matrix equation : (noting $e_d = -p_{d0} - p_{d2}(\theta_e)$ and $e_q = -p_{q0} - p_{q2}(\theta_e)$)

$$\begin{cases} \dot{x} &= Ax + Bu, \\ y &= Cx, \end{cases} \qquad \begin{aligned} x &= \begin{pmatrix} i_d & i_q & p_{d2} & \dot{p_{d2}} & p_{q2} & \dot{p_{q2}} & p_{d0} & p_{q0} \end{pmatrix}^\intercal, \\ u &= \begin{pmatrix} v_d & v_q \end{pmatrix}^\intercal, \\ y &= \begin{pmatrix} i_d & i_q \end{pmatrix}^\intercal. \end{aligned}$$

with :

$$A = \begin{pmatrix} -\frac{R_s}{L_d} & \omega_e \frac{L_q}{L_d} & \frac{1}{L_d} & 0 & 0 & 0 & \frac{1}{L_d} & 0 \\ -\omega_e \frac{L_d}{L_q} & -\frac{R_s}{L_q} & 0 & 0 & \frac{1}{L_q} & 0 & 0 & \frac{1}{L_q} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\omega_e^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\omega_e^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \qquad B = \begin{pmatrix} \frac{1}{L_d} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L_q} & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^\intercal,$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

Details on the disturbances observer

- A Luenberger linear observer is designed, the observed states ($\widehat{x}$) follow the dynamical equation :

$$\dot{\widehat{x}} = A\widehat{x} + Bu + L_{obs}(y - C\widehat{x}).$$

- The gain observer matrix L_{obs} is chosen so that the matrix $(A - L_{obs}C)$ is Hurwitz.
- The back-EMF $e_d = -p_{d0} - p_{d2}$ and $e_q = -p_{q0} - p_{q2}$ are calculated.

Details on the Goertzel algorithm

N : number of samples
F_i : frequency to detect
F_e : sampling frequency
K := floor(0.5 + N F_i/F_e)
ω := $2\pi F_i$
cosine := cos(ω)
sine := sin(ω)
sprev := 0
sprev2 := 0

```
for each index n in range 0 to N-1 do
        s := x[n] + 2 · cosine · sprev - sprev2
        sprev2 := sprev
        sprev := s
end
```

Real := 2 (-sprev2 + sprev · cosine)/N
Imag := 2 · sprev · sine/N
Ampl := $\sqrt{\text{Real}^2 + \text{Imag}^2}$
Phase := atan2(Imag,Real)

Details on the Goertzel algorithm

$$\boxed{N \cdot \Delta f = F_e}$$

N : number of samples,
F_e : sampling frequency,
f : frequency resolution.

example :

N = 256 samples
Fe = 400 Hz
$\Rightarrow \Delta f$ = 1.5625 Hz

The algorithm works for electrical speed multiples of $2\pi\Delta f$