A Karush-Kuhn-Tucker (KKT) approach to field-weakening for SPMSM

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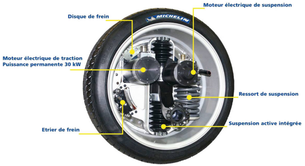
Problem Statement

Surface mounted Permanent Magnets Synchronous Motors (SPMSM)

Widely used in industry

Automotive

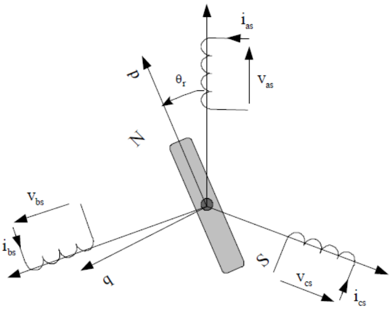


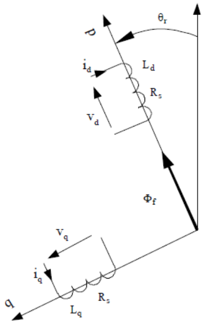
Robotics

Power generation

Objective : Produce torque, while minimizing current, despite saturations.

Problem statement





Problem Statement

Surface-mounted permanent magnet synchronous motor (SPMSM) modelling

$$\begin{cases} L\dfrac{di_d}{dt} = v_d - Ri_d + pL\omega i_q, \\ L\dfrac{di_q}{dt} = v_q - Ri_q - pL\omega i_d - p\phi_f\omega, \\ J\dfrac{d\omega}{dt} = \dfrac{3}{2}p\phi_f i_q - f\omega - \tau_l; \end{cases} \tag{1}$$

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Mainly subject to two constraints :

$$\|i_{dq}\|^2 = i_d^2 + i_q^2 \leq I_{max}^2, \quad (2)$$

$$\|v_{dq}\|^2 = v_d^2 + v_q^2 \leq V_{max}^2, \quad (3)$$

Problem Statement

SPMSM constraints

Mainly subject to two constraints :

$$\|i_{dq}\|^2 = i_d^2 + i_q^2 \leq I_{max}^2, \tag{4}$$

$$\|v_{dq}\|^2 = v_d^2 + v_q^2 \leq V_{max}^2, \tag{5}$$

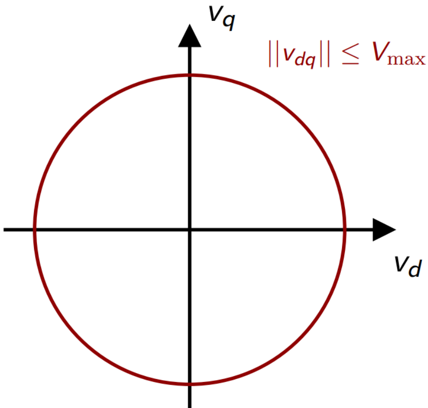
where I_{max} and V_{max} are the maximum acceptable current and voltage.

- I_{max} depends on the cooling capacity,
- V_{max} depends on the rated voltage of the inverter and the type of modulation

SPMSM constraints

- Voltage saturation

$$||v_{dq}|| = \sqrt{v_d^2 + v_q^2} \leq V_{\max},$$



Problem Statement

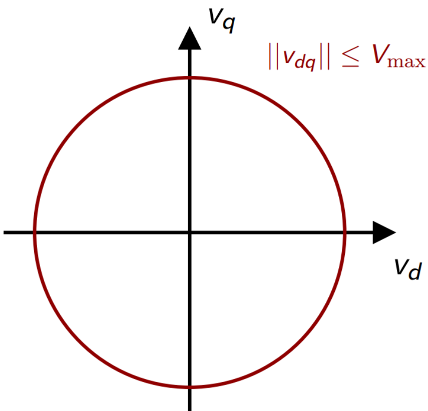
SPMSM constraints

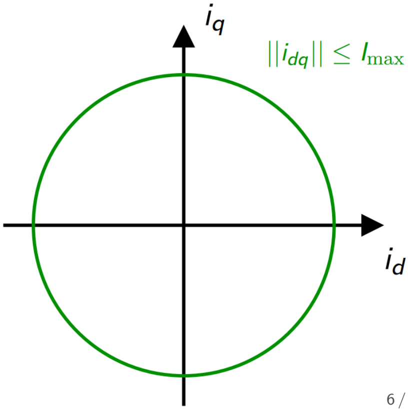
- Voltage saturation

$$||v_{dq}|| = \sqrt{v_d^2 + v_q^2} \leq V_{\max},$$

- Current saturation

$$||i_{dq}|| = \sqrt{i_d^2 + i_q^2} \leq I_{\max}.$$





Problem Statement

SPMSM constraints

$$\begin{cases} L\dfrac{di_d}{dt} = v_d - Ri_d + pL\omega i_q, \\ L\dfrac{di_q}{dt} = v_q - Ri_q - pL\omega i_d - p\phi_f\omega, \\ J\dfrac{d\omega}{dt} = \dfrac{3}{2}p\phi_f i_q - f\omega - \tau_l; \end{cases} \tag{6}$$

Mainly subject to two constraints :

$$\|i_{dq}\|^2 = i_d^2 + i_q^2 \leq I_{max}^2, \tag{7}$$

$$\|v_{dq}\|^2 = v_d^2 + v_q^2 \leq V_{max}^2, \tag{8}$$

Problem Statement

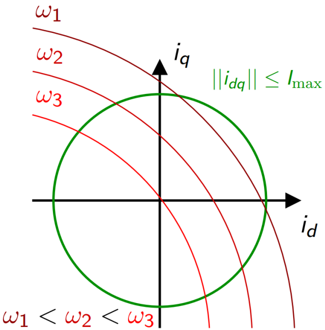
SPMSM constraints

At steady state :

$$\begin{cases} i_d^2 + i_q^2 \leq I_{max} \\ (i_d + a(\omega))^2 + (i_q + b(\omega))^2 \leq c(\omega) \end{cases}$$

such that

$$\begin{cases} K(\omega) = \dfrac{p\omega\phi_f}{R^2 + (p\omega L)^2}, \\ a(\omega) = K(\omega)p\omega L, \\ b(\omega) = K(\omega)R, \\ c(\omega) = \dfrac{V_{max}^2}{R^2 + (pL\omega)^2}. \end{cases}$$



Problem Statement

- Desired behavior

minimum steady state currents i_{dq} to reach a given speed ω at a specific load torque τ

- Mathematical formulation :

$$\underset{i_d,\, i_q}{\text{minimize}} \quad i_d^2 + i_q^2,$$

subject to

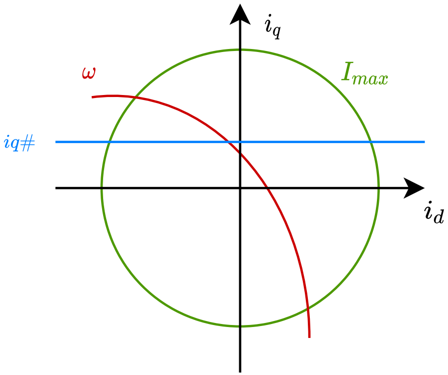
$$L\frac{di_{dq}}{dt} = v_{dq} - Ri_{dq} - p\omega L\mathcal{J}\, i_{dq} - e_{dq} = 0,$$

$$\|i_{dq}\|^2 = i_d^2 + i_q^2 \leq I_{max}^2,$$

$$\|v_{dq}\|^2 = v_d^2 + v_q^2 \leq V_{max}^2,$$

$$i_q = \frac{2}{3}\frac{\tau}{p\phi_f}.$$

SPMSM constraints



Outline

Problem Statement

KKT optimality conditions

Experimental Validation

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KKT optimality conditions

Possible cases of constraints

Active constraints	***Case***
None	1
Voltage	2
Current	3
Voltage and Current	4

A general way of writing and solving the Flux Weakening problem

Outline

Problem Statement

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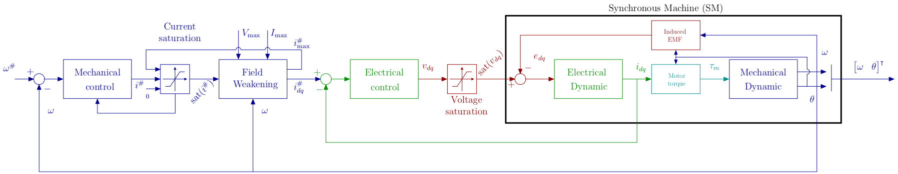
Experimental Validation

Experimental validation

Control strategy



Thank you for your attention

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