

# Sensorless position estimation of Permanent-Magnet Synchronous Motors using a saturation model

Al Kassem Jebai, François Malrait, Philippe Martin and Pierre Rouchon

**Abstract**—Sensorless control of Permanent-Magnet Synchronous Motors (PMSM) at low velocity remains a challenging task. A new well-established method consists in injecting a high-frequency signal and use the rotor saliency, both geometric and magnetic-saturation induced. This paper proposes a clear and original analysis based on second-order averaging of how to recover the position information from signal injection; this analysis blends well with a general model of magnetic saturation. It also proposes a simple parametric model of the saturated PMSM, based on an energy function which simply encompasses saturation and cross-saturation effects. Experimental results on a surface-mounted PMSM and an interior magnet PMSM illustrate the relevance of the approach.

**Index Terms**—Permanent-magnet synchronous motor, sensorless position estimation, signal injection, magnetic saturation, energy-based modeling, averaging.

## I. INTRODUCTION

**P**ERMANENT-Magnet Synchronous Motors (PMSM) are widely used in industry. In the so-called “sensorless” mode of operation, the rotor position and velocity are not measured and the control law must make do with only current measurements. While sensorless control at medium to high velocities is well understood, with many reported control schemes and industrial products, sensorless control at low velocity remains a challenging task. The reason is that observability degenerates at zero velocity, causing a serious problem in the necessary rotor position estimation.

A new well-established method to overcome this problem is to add some persistent excitation by injecting a high-frequency signal [1] and use the rotor saliency, whether geometric for Interior Permanent-Magnet machines or induced by main flux saturation for Surface Permanent-Magnet machines [2]–[10]. Signal injection is moreover considered as a standard building block in hybrid control schemes for complete drives operating from zero to full speed [11]–[15].

However to get a good position estimation under high-load condition it is important to take cross-saturation into account [16]–[26]. It is thus necessary to rely on a model of the saturated PMSM adapted to control purposes, i.e. rich enough to capture in particular cross-saturation but also simple enough to be used in real-time and to be easily identified in the field; see [27]–[32] for references more or less in this spirit.

The contribution of this paper, which builds on the preliminary work [33], is twofold: on the one hand it proposes a clear

and original analysis based on second-order averaging of how to recover the position information from signal injection; this analysis can accommodate to any form of injected signals, e.g. square signals as in [34], and blends well with a general model of magnetic saturation including cross-saturation. On the other hand a simple parametric model of the saturated PMSM, well-adapted to control purposes, is introduced; it is based on an energy function which simply encompasses saturation and cross-saturation effects.

The paper runs as follows: section II presents the saturation model. In section III position estimation by signal injection is studied thanks to second-order averaging. Section IV is devoted to the estimation of the parameters entering the saturation model using once again signal injection and averaging. Finally section IV-C experimentally demonstrates on two kinds of motors (with interior magnets and surface-mounted magnets) the relevance of the approach and the necessity of considering saturation to correctly estimate the position.

## II. AN ENERGY-BASED MODEL OF THE SATURATED PMSM

### A. Notations

In the sequel we denote by  $x_{ij} := (x_i, x_j)^T$  the vector made from the real numbers  $x_i$  and  $x_j$ , where  $ij$  can be  $dq$ ,  $\alpha\beta$  or  $\gamma\delta$ . We also define the matrices

$$M_\mu := \begin{pmatrix} \cos \mu & -\sin \mu \\ \sin \mu & \cos \mu \end{pmatrix} \quad \text{and} \quad K := \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix},$$

and we have the useful relation

$$\frac{dM_\mu}{d\mu} = KM_\mu = M_\mu K.$$

### B. Energy-based model

The model of a two-axis PMSM expressed in the synchronous  $d-q$  frame reads

$$\frac{d\phi_{dq}}{dt} = u_{dq} - R i_{dq} - \omega K(\phi_{dq} + \phi_m) \quad (1)$$

$$\frac{J}{n^2} \frac{d\omega}{dt} = \frac{3}{2} i_{dq}^T K(\phi_{dq} + \phi_m) - \frac{\tau_L}{n} \quad (2)$$

$$\frac{d\theta}{dt} = \omega, \quad (3)$$

with  $\phi_{dq}$  flux linkage due to the current;  $\phi_m := (\lambda, 0)^T$  constant flux linkage due to the permanent magnet;  $u_{dq}$  impressed voltage and  $i_{dq}$  stator current;  $\omega$  and  $\theta$  rotor (electrical) speed and position;  $R$  stator resistance;  $n$  number of pole pairs;  $J$  inertia moment and  $\tau_L$  load torque. The physically impressed voltages are  $u_{\alpha\beta} := M_\mu u_{dq}$  while the physically measurable

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# Sensorless Position Estimation Of Permanent Magnet

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