

# 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

PERMANENT-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

**L Cohen**

A decorative graphic element consisting of a light blue horizontal bar with a rounded right end, and a red circular glow behind it.

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**Sensorless Position Estimation in Sinusoidal Permanent Magnet Synchronous Motor** Deepak Shivaram Shet, 1998 Real Time Implementation of Sensorless Position Estimation in a Permanent Magnet Synchronous Motor Using DSP TMS320C24X Rohit Khetarpal, 2003

**Position Sensorless Control Techniques for Permanent Magnet Synchronous Machine Drives** Gaolin Wang, Guoqiang Zhang, Dianguo Xu, 2019-11-15 The book focuses on position sensorless control for PMSM drives addressing both basic principles and experimental evaluation It provides an in depth study on a number of major topics such as model based sensorless control saliency based sensorless control position estimation error ripple elimination and acoustic noise reduction Offering a comprehensive and systematic overview of position sensorless control and practical issues it is particularly suitable for readers interested in the sensorless control techniques for PMSM drives The book is also a valuable resource for researchers engineers and graduate students in fields of ac motor drives and sensorless control

**The Electric Generators Handbook - 2 Volume Set** Ion Boldea, 2005-11-16 The modern world hungers for electricity Traditionally this hunger was sated with predominantly constant speed regulated synchronous generators However new demands require the stable quick and efficient delivery and control offered by variable speed generators Surveying all of the technologies used to satisfy the world s demand for o

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The Proceedings of the 9th Frontier Academic Forum of Electrical Engineering Weiming Ma, Mingzhe Rong, Fei Yang, Wenfeng Liu, Shuhong Wang, Gengfeng Li, 2021-04-21 This book includes the original peer reviewed research papers from the 9th Frontier Academic Forum of Electrical Engineering FAFEE 2020 held in Xi'an China in August 2020 It gathers the latest research innovations and applications in the fields of Electrical Engineering The topics it covers including electrical materials and equipment electrical energy storage and device power electronics and drives new energy electric power system equipment IntelliSense and intelligent equipment biological electromagnetism and its applications and insulation and discharge computation for power equipment Given its scope the book benefits all researchers engineers and graduate students who want to learn about cutting edge advances in Electrical Engineering

Optimization and Control of Electrical Machines Abdel Ghani Aissaoui, Ahmed Tahour, Ilhami Colak, 2018-07-18 Electrical machines are used in the process of energy conversion in the generation transmission and consumption of electric power In addition to this electrical machines are considered the main part of electrical drive systems Electrical machines are the subject of advanced research In the development of an electrical machine the design of its different structures is very important This design ensures the robustness energy efficiency optimal cost and high reliability of the system Using advanced techniques of control and new technology products has brought electrical machines into their optimal functioning mode Different techniques of control can be applied depending on the goals considered The aim of this book is to present recent work on the design control and applications of electrical machines

*AC Motor Control and Electrical Vehicle Applications* Kwang Hee Nam, 2018-09-03 AC Motor Control and Electrical Vehicle Applications provides a guide to the control of AC motors with a focus on its application to electric vehicles EV It describes the rotating magnetic flux based on which dynamic equations are derived The text not only deals with the induction motor but covers the permanent magnet synchronous motors PMSM Additionally the control issues are discussed by taking into account the limitations of voltage and current The latest edition includes more experimental data and expands upon the topics of inverter pulse width modulation methods loss minimizing control and vehicle dynamics Various EV motor design issues are also reviewed while comparing typical types of PMSMs Features Considers complete dynamic modeling of induction and PMSM in the rotating frame Provides various field oriented controls while covering advanced topics in PMSM high speed control loss minimizing control and sensorless control Covers inverter sensors vehicle dynamics driving cycles etc not just motor control itself Offers a comparison between BLDC surface PMSM and interior PMSM Discusses how the motor produces torque and is controlled

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**Reluctance Machines** Antonio Barrio Barrio,2018 The purpose of the project is to achieve a robust SENSORLESS control of a Permanent Magnet assisted Synchronous Reluctance Motor It is a part of an industrial project call CICYT carried out at MCIA research group in UPC This thesis concentrates on a special electrical control method called Field Oriented Control FOC Computer simulations of machine fed with a two levels voltage source inverter were performed Analisis of the robustnes of most usual sensorless methods have been performed and results corroborate that general sensorless observers methods are more insensitive to the gaussian noise *Proceedings of the ... Annual Conference of the IEEE Industrial Electronics Society* IEEE Industrial Electronics Society. Conference,2003 **Second International Conference on Power Electronics, Machines, and Drives (PEMD 2004)** ,2004 *Proceedings of ... International Conference on Power Electronics and Drive Systems* ,2005 *ICEMS'2001* Fengxiang Wang,Renyuan Tang,2001

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