

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

Al Kassam 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 now 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 now 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

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

and we have the useful relation

$$\frac{dM_p}{dp} = KM_p = M_p K.$$

### B. Energy-based model

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

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

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

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

with  $\psi_{dq}$  flux linkage due to the current;  $\psi_m := (\lambda, 0)^T$  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  $u_{a,b,c} := M_\theta u_{dq}$  while the physically measurable

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# Sensorless Position Estimation Of Permanent Magnet

**Sadegh Vaez-Zadeh**



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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

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Krishnan, 2017-12-19 Despite two decades of massive strides in research and development on control strategies and their subsequent implementation most books on permanent magnet motor drives still focus primarily on motor design providing only elementary coverage of control and converters Addressing that gap with information that has largely been disseminated only in journals and at conferences Permanent Magnet Synchronous and Brushless DC Motor Drives is a long awaited comprehensive overview of power electronic converters for permanent magnet synchronous machines and control strategies for variable speed operation It introduces machines power devices inverters and control and addresses modeling implementation control strategies and flux weakening operations as well as parameter sensitivity and rotor position sensorless control Suitable for both industrial and academic audiences this book also covers the simulation low cost inverter topologies and commutation torque ripple of PM brushless DC motor drives Simulation of the motor drives system is illustrated with MATLAB codes in the text This book is divided into three parts fundamentals of PM synchronous and brushless dc machines power devices inverters PM synchronous motor drives and brushless dc motor drives With regard to the power electronics associated with these drive systems the author Explores use of the standard three phase bridge inverter for driving the machine power factor correction and inverter control Introduces space vector modulation step by step and contrasts with PWM Details dead time effects in the inverter and its compensation Discusses new power converter topologies being considered for low cost drive systems in PM brushless DC motor drives This reference is dedicated exclusively to PM ac machines with a timely emphasis on control and standard and low cost converter topologies Widely used for teaching at the doctoral level and for industrial audiences both in the U S and abroad it will be a welcome addition to any engineer's library

**Control of Permanent Magnet Synchronous Motors** Sadegh Vaez-Zadeh, 2018 Permanent magnet synchronous PMS motors stand at the forefront of electric motor development due to their energy saving capabilities and performance potential This book is a timely advancement along that path as the first comprehensive self contained and thoroughly up to date book devoted solely to the control of PMS motors

**Permanent Magnet Synchronous Motor Drives for Gearless Traction Elevators** Guoqiang Zhang, Gaolin Wang, Nannan Zhao, Dianguo Xu, 2022-02-25 This book focuses on the control strategies for gearless permanent magnet synchronous motor traction elevators Both basic principles and experimental evaluation have been addressed This is achieved by providing in depth study on a number of major topics such as speed detection at low speed operation starting torque strategy based on dichotomy and staircase methods fuzzy self tuning method MPC and ADRC etc The comprehensive and systematic treatment of control strategies for cost effective

gearless PMSM traction elevators and practical issues are the major features of the book which is particularly suited for readers who are interested to learn the control strategies for cost effective gearless PMSM traction elevators The book benefits researchers engineers and graduate students in the fields of ac motor drives and control strategies for cost effective gearless PMSM traction elevators etc

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Fuchun Sun,Huaping Liu,Dewen Hu,2019-04-27 This two volume set CCIS 1005 and CCIS 1006 constitutes the refereed proceedings of the 4th International Conference on Cognitive Systems and Signal Processing ICCSIP2018 held in Beijing China in November and December 2018 The 96 revised full papers presented were carefully reviewed and selected from 169 submissions The papers are organized in topical sections on vision and image algorithms robotics human computer interaction deep learning information processing and automatic driving     **Electrical Actuators** Bernard de Fornel,Jean-Paul Louis,2013-03-04 The different chapters of this book cover a large range of information regarding electrical actuators including synchronous and asynchronous machine modeling in order to measure and identify offline and online parameters using modern optimization methods identification in real time of parameters with Luenberger filter and the extended Kalman filter estimation of non measurable variables first by linear estimates and observers then by lower observers Robustness is a very problematic issue as well which is fully explored in a chapter dedicated to the subject Finally the estimate of non measurable mechanical variables is particularly dealt with estimate of load moment then observation of the positioning of a command without mechanical sensor The conditions to measure variables and real implementation of numerical algorithms are also examined with particular attention

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