

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

Al Kasseem 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

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 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 $x_{i,j} := (x_i, x_j)^T$ the vector made from the real numbers x_i and x_j , where i,j can be dq , qd 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

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

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

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

with ψ_{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; ω and θ rotor (electrical) speed and position; R stator resistance; n number of pole pairs; J inertia moment and τ_L load torque. The physically impressed voltages are $u_{\alpha\beta} := M_p u_{dq}$ while the physically measurable

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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 Control of Electric Machine Drive Systems Seung-Ki Sul, 2011-04-20 A unique approach to sensorless control and regulator design of electric drives Based on the author's vast industry experience and collaborative works with other industries Control of Electric Machine Drive Systems is packed with tested implemented and verified ideas that engineers can apply to everyday problems in the field Originally published in Korean as a textbook this highly practical updated version features the latest information on the control of electric machines and apparatus as well as a new chapter on sensorless control of AC machines a topic not covered in any other publication The book begins by explaining the features of the electric drive system and trends of development in related technologies as well as the basic structure and operation principles of the electric machine It also addresses steady state characteristics and control of the machines and the transformation of physical variables of AC machines using reference frame theory in order to provide a proper foundation for the material The heart of the book reviews several control algorithms of electric machines and power converters explaining active damping and how to regulate current speed and position in a feedback manner Seung Ki Sul introduces tricks to enhance the control performance of the electric machines and the algorithm to detect the phase angle of an AC source and to control DC link voltages of power converters Topics also covered are Vector control Control algorithms for position speed sensorless drive of AC machines Methods for identifying the parameters of electric machines and power converters The matrix algebra to model a three phase AC machine in d q n axes Every chapter features exercise problems drawn from actual industry experience The book also includes more than 300 figures and offers access to an FTP site which provides MATLAB programs for selected problems The book's practicality and realworld relatability make it an

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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 based on consistent mathematical

treatments Design and Operation of Permanent Magnet Machine for Integrated Starter-generator Application in Series Hybrid Bus Sinisa Jurkovic,2009 *Fundamental Sensing Issues in Motor Control* Michael C. Harke,2006 *Power Converters and AC Electrical Drives with Linear Neural Networks* Maurizio Cirrincione,Marcello Pucci,Gianpaolo Vitale,2012-05-07 The first book of its kind *Power Converters and AC Electrical Drives with Linear Neural Networks* systematically explores the application of neural networks in the field of power electronics with particular emphasis on the sensorless control of AC drives It presents the classical theory based on space vectors in identification discusses control of electrical drives and power converters and examines improvements that can be attained when using linear neural networks The book integrates power electronics and electrical drives with artificial neural networks ANN Organized into four parts it first deals with voltage source inverters and their control It then covers AC electrical drive control focusing on induction and permanent magnet synchronous motor drives The third part examines theoretical aspects of linear neural networks particularly the neural EXIN family The fourth part highlights original applications in electrical drives and power quality ranging from neural based parameter estimation and sensorless control to distributed generation systems from renewable sources and active power filters Simulation and experimental results are provided to validate the theories Written by experts in the field this state of the art book requires basic knowledge of electrical machines and power electronics as well as some familiarity with control systems signal processing linear algebra and numerical analysis Offering multiple paths through the material the text is suitable for undergraduate and postgraduate students theoreticians practicing engineers and researchers involved in applications of ANNs **Power Electronics Handbook** Muhammad H. Rashid,2010-07-19 Power electronics which is a rapidly growing area in terms of research and applications uses modern electronics technology to convert electric power from one form to another such as ac dc dc dc dc ac and ac ac with a variable output magnitude and frequency Power electronics has many applications in our every day life such as air conditioners electric cars sub way trains motor drives renewable energy sources and power supplies for computers This book covers all aspects of switching devices converter circuit topologies control techniques analytical methods and some examples of their applications 25% new content Reorganized and revised into 8 sections comprising 43 chapters Coverage of numerous applications including uninterruptable power supplies and automotive electrical systems New content in power generation and distribution including solar power fuel cells wind turbines and flexible transmission *Design Rules for Induction Machine Self-sensing* Ian P. Brown,2009 **Vehicle, Mechatronics and Information Technologies** X.D. Yu,2013-08-30 Selected peer reviewed papers from the 2013 International Conference on Vehicle Mechanical Engineering and Information Technology VMEIT 2013 August 17 18 2013 Zhengzhou Henan China *Proceedings of the 1995 IEEE IECON: Signal processing and control, Robotics vision and sensors, Emerging technologies, and Factory automation* ,1995 **Proceedings of the ... Annual Conference of the IEEE Industrial Electronics Society** IEEE Industrial Electronics Society. Conference,2003 **Second**

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