

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

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 $x_{ij} := (x_i, x_j)^T$ 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 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 $u_{a,b,c} := M_\theta u_{dq}$ while the physically measurable

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Permanent Magnet Synchronous and Brushless DC Motor Drives Ramu

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

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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

Advanced technologies for planning and operation of prosumer energy systems Bin Zhou,Siqi Bu,Liansong Xiong,Hugo Morais, Junjie Hu,Jingyang Fang,Jian Zhao,Peng Hou,2023-04-28

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

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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 invaluable resource for professionals and engineers involved in the research and development of electric machine drive business industrial drive designers and senior undergraduate and graduate students To obtain instructor materials please send an email to pressbooks_ieee@org To visit this book's FTP site to download MATLAB codes please click on this link ftp://ftp.wiley.com/public/sci_tech_med/electric_machine MATLAB codes are also downloadable from Wiley Booksupport Site at <http://booksupport.wiley.com>

Operation, Construction, and Functionality of Direct Current Machines Amin, Muhammad, Rehmani, Mubashir Husain, 2015-04-30 Direct current machines are a quickly evolving domain whose applications affect many aspects of modern life from computers and printers to toys electric vehicles and traction applications As their many uses continue to grow it has become apparent that understanding these machines is the key to understanding our future Operation Construction and Functionality of Direct Current Machines brings together many concepts from the most basic working principles and construction of DC machines to more advanced topics such as electro magnetism armature reaction parallel operations and many more Highlighting theoretical concepts and numerical problems this book is an essential reference source for students educators and anyone interested in the field of electric machines

Power Electronics and Motor Drives Bogdan M. Wilamowski, J. David Irwin, 2018-10-03 The Industrial Electronics Handbook Second Edition combines traditional and newer more specialized knowledge that will help industrial electronics engineers develop practical solutions for the design and implementation of high power applications Embracing the broad technological scope of the field this collection explores fundamental areas including analog and digital circuits electronics electromagnetic machines signal processing and industrial control and communications systems It also facilitates the use of intelligent systems such as neural networks fuzzy systems and evolutionary methods in terms of a hierarchical structure that makes factory control and supervision more efficient by addressing the needs of all production components Enhancing its value this fully updated collection presents research and global trends as published in the IEEE Transactions on Industrial Electronics Journal one of the largest and most respected publications in the field Power Electronics and Motor Drives facilitates a necessary shift from low power electronics to the high power varieties used to control electromechanical systems and other industrial applications This volume of the handbook Focuses on special high power semiconductor devices Describes various electrical machines and motors their principles of operation and their limitations Covers power conversion and the high efficiency devices that perform the necessary switchover between AC and DC Explores very specialized electronic circuits for the efficient control of electric motors Details other applications of power electronics aside from electric motors including lighting renewable energy conversion and automotive electronics Addresses power electronics used in very high power electrical systems to

transmit energy Other volumes in the set Fundamentals of Industrial Electronics Control and Mechatronics Industrial Communication Systems Intelligent Systems

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Recent Developments of Electrical Drives Slawomir Wiak, Maria Dems, Krzysztof Komeza, 2007-06-08 Recent Developments of Electrical Drives is composed of the papers which cover a wide spectrum of theory and practice thus they are deeply rooted in engineering problems being simultaneously of high theoretical level This way the contents touches the heart of the matter in electrical drives theory control systems and applications The book stating the recent developments of electrical drives can be useful for engineers and researchers investigating and designing electrical and electronic devices as well as for students and young researchers dealing with electrical and electronic engineering computer sciences advanced computer modelling sophisticated control systems with artificial intelligence tools applied optimal design by use of classical and genetic algorithms employed applied mathematics and all the topics where electromagnetic thermal mechanical phenomena occur Recent Developments of Electrical Drives covers a wide range of interests of industry engineers and scientists involved in modelling control measurements new motor structures design and could be also useful for engineers working in the field of electrical drives implementation

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Optimization and Control of Electrical Machines Abdel Ghani Aissaoui,Ahmed Tahour,Ihhami 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

Cognitive Systems and Signal Processing

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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