A NEW SPEED SENSORLESS CONTROL FOR PERMANENT MAGNET SYNCHRONOUS MOTOR

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A NEW METHOD OF SPEED SENSORLESS CONTROL FOR PERMANENT MAGNET SYNCHRONOUS MOTOR

by

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LIST OF ABBREVIATIONS

AC	Alternating current
ADC	Analog to digital conversion
ANFIS	Adaptive neuro-fuzzy inference system
ANN	Artificial neural network
BLDC	Brushless Direct Current
CTs	Current transducers
DC	Direct current
DSP	Digital signal processors
EEMF	Extended electromotive force
EKF	Extended Kalman filters
EMF	Electromotive force
EMI	Electromagnetic interference
FCM	Fuzzy C-Means
FIS	Fuzzy inference system
FLC	Fuzzy logic control
FOC	Field-oriented control
HF	High frequency
IM	Induction motor
IPMSM	Interior permanent magnet synchronous motor

LPF	Low pass filter
MF	Membership function
MOSFETs	Metal–oxide–semiconductor field-effect transistor
MRAS	Model Reference Adaptive System
NB	Negative big
NM	Negative medium
PB	Positive big
PI	Proportional Integral
PM	Positive medium
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation
RBFN	Radial basis function neural network
SMO	Sliding-mode observers
SNRs	Signal-to-noise ratios
SPMSM	Surface-mounted permanent magnet synchronous motor
SVPWM	Space vector pulse width modulation
TS-FIS	Takagi Sugeno Fuzzy Inference System
VSI	Voltage source inverter
Z	Zero

LIST OF SYMBOLS

i_d	Direct current
i_a	Phase A current
i_b	Phase B current
i_c	Phase C current
i_{ds}	d-axis of the stator current
i_{qs}	q-axis of the stator current
L_q	Self-inductance of the q-axis winding
L_d	Self-inductance of the d-axis winding
L_{qd}	Mutual inductance between the q- and d-axes windings
θ_{re}	Rotor position information
T^*	Torque command
ω_{re}	Measured rotor speed
ω_{re}^*	Desired rotor speed
R_d	d-axis of stator winding resistance
R_q	q-axis of stator winding resistance
v_{dc}	DC Voltage
v_{qs}	Voltage in the q-axis of the stator windings

v_{ds}	Voltage in the d-axis of the stator windings
v_d^*	Reference direct voltage
v_q^*	Reference quadrature voltage
v_α^* and v_β^*	Two-axis voltage orthogonal stationary reference frame
V_{AB}, V_{BC} and V_{CA}	Line-to-line voltages
V_A, V_B and V_C	line-to-neutral voltages
ψ_{qs}	q-axis of stator flux linkage
ψ_{ds}	d-axis of stator flux linkage
ψ_{af}	Rotor magnet flux
θ_r	Instantaneous rotor position
θ_o	Initial rotor position estimated
τ_e	Developed motor torque
τ_L	Load torque
P	Number of poles
S_{A1},S_{A2}	Semiconductor switches for pole A
S_{B1},S_{B2}	Semiconductor switches for pole B
S_{C1},S_{C2}	Semiconductor switches for pole C
ω_m	Rotor mechanical speed
ω_r	Rotor electrical speed

$\vec{I}_s$	Stator current space vector
$\alpha\beta$	Two orthogonal stationary frame
X	State variables of the reference model
$\hat{X}$	State variables of the adaptive model
$\hat{\omega}_r$	Estimated rotor electrical speed
k_1	Scaling factor speed tuning signal
k_2	Scaling factor speed change
k_3	Scaling factor actual value of the estimated speed

KAWALAN KELAJUAN TANPA PENGESAN BARU BAGI MOTOR SEGERAK MAGNET KEKAL

ABSTRAK

Mesin segerak magnet kekal (PMSM) telah digunakan dalam pelbagai aplikasi perindustrian yang memerlukan tindak balas dinamik yang cepat dan kawalan yang tepat ke atas julat kelajuan yang luas. Walau bagaimanapun, adalah penting untuk mendapatkan sudut kedudukan pemutar dengan tepat dalam usaha untuk mengawal pemacu PMSM dengan cekap. Oleh itu, kawalan kelajuan tanpa pengesan menjadi pendekatan alternatif kerana kemampuannya untuk bertindak balas dinamik pada frekuensi yang sangat rendah untuk mengesan kedudukan pemutar dan kelajuan motor. Dengan itu, ianya dapat menggantikan penggunaan kaedah tradisional, seperti memasang alat pengekup optik, pengesan resolver atau pengesan Hall. Terdapat banyak cabaran untuk menghasilkan kedudukan kawalan vektor PMSM tanpa pengesan yang beroperasi dalam pelbagai had kelajuan, yang meliputi kelajuan rendah dan operasi kelajuan tinggi. Untuk menangani masalah yang disebut di atas, pengesan tanpa kelajuan yang baru telah dicadangkan. Kawalan tanpa pengesan kelajuan baru ini adalah berdasarkan sistem penyesuaian rujukan model (MRAS) di mana teknik penyesuaian baru direka bentuk untuk menggantikan teknik biasa iaitu pengawal proporsional-integral. Teknik baru ini adalah berdasarkan kepada sistem kabur kaedah pemahaman Takagi Sugeno (TS-FIS). Kaedah baru ini dapat mengatasi masalah penalaan parameter dalam kaedah tradisional apabila terdapat perubahan dalam keadaan motor seperti variasi laju. Prestasi skim yang dicadangkan disahkan menggunakan perisian Matlab/Simulink dan hasilnya dibandingkan dengan skim biasa. Simulasi dengan menggunakan perisian MATLAB/Simulink dijalankan untuk mengkaji kebolehlaksanaan algoritma yang dicadangkan. Algoritma yang dicadangkan diuji dalam masa sebenar dengan menggunakan DSpace. Analisis dilakukan dengan membandingkan pelaksanaan simulasi dan kerja eksperimen dalam keadaan sifat motor yang berlainan. Ia menunjukkan bahawa kaedah yang dicadangkan dapat mengesan sudut kedudukan pemutar dengan jitu bersama ralat minimum iaitu hamper kepada 0 rad. Selain itu, keputusan ujian untuk kedua-dua simulasi dan kerja-kerja eksperimen, menunjukkan MRAS berdasarkan TS-FIS berkemampuan dengan cekap dan jitu untuk mengesan sudut kedudukan pemutar dalam pelbagai keadaan operasi motor. Perbandingan dengan dua kaedah lain yang digunakan dalam teknik penyesuaian dari penyelidik terdahulu menunjukkan bahawa MRAS berdasarkan TS-FIS mampu mengesan kedudukan pemutar dengan cekap, dengan memberikan bacaan 0 rad untuk ralat kedudukan pemutar dalam keadaan mantap dan keadaan sementara. Serta ralat kelajuan yang memberikan ±3 rpm untuk kedua-dua keadaan.

A NEW SPEED SENSORLESS CONTROL FOR PERMANENT MAGNET SYNCHRONOUS MOTOR

ABSTRACT

Permanent magnet synchronous machine (PMSM) drives have been applied in a variety of industrial applications which require fast dynamic response and accurate control over wide speed range. However, it is important to get the accurate rotor position in order to control the PMSM drives efficiently. Therefore, speed sensorless control becomes an alternative approach due to its ability of dynamic response at very low frequencies to detect the rotor position and motor speed, which eliminates the use of traditional methods, such as optical encoders mounted shaft, resolver or hall sensor. There are many challenges to design speed sensorless vector control of PMSM operating in wide speed range, which cover low speed and high speed operation. To deal with the above-mentioned problem, a new speed sensorless control is proposed. This new speed sensorless control is based on model reference adaptive system (MRAS) with a new adaptation scheme. It was designed to replace the conventional technique which is proportional-integral controller. This new technique is based on Takagi Sugeno Fuzzy Inference System (TS-FIS). This new method can overcome the problem of tuning parameters in the traditional method when there is a change in the motor condition such as variation of speed. The performance of the proposed scheme is validated in Matlab/Simulink and obtained results are compared with conventional scheme. A simulation using MATLAB/Simulink software is conducted to investigate the feasibility of the proposed algorithm. DSpace is deployed for algorithm implementation. The analysis is carried out by comparing the simulation and hardware implementation in different cases of motor conditions. It shows that the proposed method can track the motor speed and rotor position angle accurately with minimum error which is almost 0 rad. Besides that, tests results for both simulation and experimental work, demonstrates the MRAS based on TS-FIS is capable of effectively and accurately locating the motor speed and rotor position angle in various conditions of speed with the given load to the motor for PMSM. Comparison with two other methods used in the adaptation from the previous researchers shows that MRAS based on TS-FIS is capable of detecting the rotor position efficiently, by giving 0 rad reading for rotor position error in steady state and transient conditions. As well as the speed error which gives ±3 radian for both states.

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CHAPTER ONE
INTRODUCTION

1.1 Background

Nowadays, alternating current (AC) electrical drives to control induction machines (IM), permanent magnet synchronous machines (PMSM) and switch reluctance machines (SRM), are widely used in industrial applications. Among that AC electrical drives, PMSM drive systems have been used abundantly in many applications, such as in home appliances (Suja et al., 2016) and (Chi et al., 2009), electric vehicles (J. Zhang et al., 2017) and (Chau et al., 2008), and wind energy conversion systems (Maisonnave et al., 2017) and (Chinchilla et al., 2006). This is due to the fact that PMSMs have high efficiency, high power density, and wide constant power region. Besides that, with the continuous reduction in cost of permanent magnet materials and development of control techniques, PMSM drives have become more attractive and competitive. Moreover, due to worldwide concerns over environmental problems and possible energy crisis, much effort from both academia and industry has gone into the development of renewable energy conversion systems and hybrid-electric vehicles, creating a large market for PMSM drive technologies. In the past 100 years, due to the convenience of torque and speed control, direct current (DC) electric machine drive system had been adopted in a variety of industrial applications. However, since 1980’s, with the development of power electronics, digital signal processors (DSPs), and computer-aided design technologies, AC motor drives have replaced DC motor drives and have become dominant in variable-frequency drive applications (Seung, 2011), (Novotny & Lipo, 1996), (Leonhard, 2001).

1.2 Permanent Magnet Synchronous Motor

There are two types of Permanent magnet brushless motor, which are sinusoidal back electromotive force (EMF) and trapezoidal back-(EMF). These become a major factor to differentiate between brushless DC and brushless AC. Brushless AC motor with sinusoidal back-EMF or also known as Permanent magnet synchronous motor (PMSM) are most popular because it produces much less torque ripple than the trapezoidal back-EMF equivalent. PMSM produces a fixed field because of the permanent magnet (PM) attached to the rotor core causing the change of rotor current cannot be easily controlled as in the classical synchronous motor. Therefore, vector control and direct torque control which simplifies the torque control in theory of vector control have been commonly used for PMSM. This thesis focuses in the research into driving a PMSM in speed sensorless mode of operation. PMSMs become popular in industrial and traction technology due to their advantageous such as good performance in speed regulation, low loss, high power factor, notable overload rating, high efficiency, excellence of less volume, lighter weight, higher reliability and easy to maintain (Bose, 2002), (Matsui, 1996), (Chi & Xu, 2006) and (K.-L. Kang et al., 2004).

Fundamentally, the most widely used PMSMs (Krishnan, 2009) have an external stator with conductors and an internal rotor with PMs. Based on the rotor structures, the PMSMs with an approximately sinusoidal back electromotive force (EMF) can be broadly highlighted into two major categories:

i. Non salient-pole PMSMs [surface-mounted PMSMs (SPMSM)]

ii. Salient-pole PMSMs [interior PMSMs (IPMSM)]

The difference between the two types of PMSMs have been reviewed by (Vagati et al., 2010) and (EL-Refaie & Jahns, 2005).

This thesis focuses on the surface-mounted rotor structure owing to the following reasons. Since the PMs are mounted on the surface of the rotor core, the SPMSM has a uniform effective air gap. This property makes the synchronous inductances in direct (*d*-) and quadrature (*q*-) axes to be equal. As a result, the SPMSM only produces an electromagnetic torque. Compared with the IPMSM, the SPMSM has a relatively limited flux-weakening capability. The cross-section of a typical SPMSM is shown in Figure 1.1. The surface-mounted rotor configuration is simple enough for manufacturing and assembly. However, the PMs are exposed directly to the armature reaction field and at the risk of demagnetization. Due to the surface-mounted rotor structure, the shaft rotating speed should be limited in order to restrain the PMs on the rotor surface against the effect of the centrifugal force. Therefore, SPMSMs are commonly used in low-speed applications, such as in home appliances.

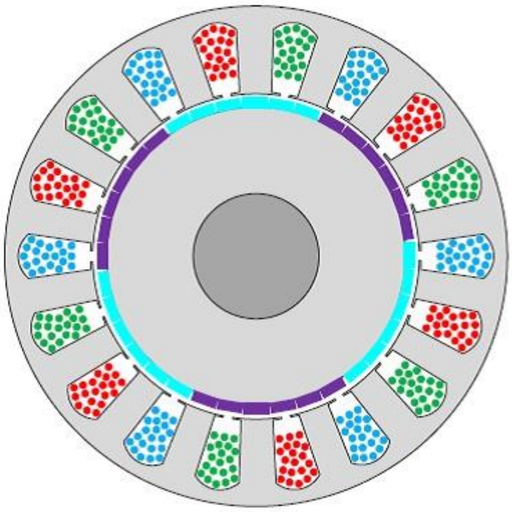

Figure 1.1 Cross-section of SPMSM

1.3 Speed sensorless control of PMSM drives

In the vector control scheme, information about the rotor position angle is important because it is used to determine the following parameters accurately:

i. Calculate component currents i_d and i_q using Park transformation
ii. Calculate component voltages v_α^* and v_β^* using the inverse Park transformation
iii. Rotor speed calculation

Therefore, the rotor position is indispensable for high performance space vector control of PMSM drives. Inaccurate rotor position information will not only degrade the control performance but also cause instability in the control system.

To obtain the information about rotor position angle, conventionally, electromechanical position sensors, e.g., resolvers, optical encoders, and hall-effect sensors, are commonly used in PMSM drives. The drawbacks are the increase in cost, size, weight, and hardware wiring complexity in the drive systems. In terms of system reliability, mounting electromechanical sensors on rotor shafts will degrade mechanical robustness of the electric machines. Furthermore, the electromagnetic interference (EMI) noise in the wiring harness, due to switching events or broken wires, may be fatal to the controller’s operation. Besides, sensors are often subject to high failure rates in harsh environments, such as excessive ambient temperature, super high-speed operation, and other adverse or heavy load conditions. To overcome these drawbacks of using position sensors, much research effort has gone into the development of sensorless drives that exhibit comparable dynamic performance with respect to the sensor-based drives during the last decades (Pacas, 2011).

1.4 Problems and Motivations

To ensure that the PMSM can be controlled with fast dynamic response with accurate speed regulation and high efficiency, it is important to get accurate rotor position before executing field oriented control (FOC). Traditional methods, such as optical encoders mounted shaft, resolver or hall sensor can be used to get the information of the rotor position accurately. However, there are disadvantages using these traditional methods. The drawbacks are increase in cost, size, weight, and hardware wiring complexity in the drive systems. Besides that, mounting electromechanical sensors on rotor shafts will degrade mechanical robustness of the electric machines.

Many speeds sensorless methods in literature have a crucial step in determining the parameters that will affect the performance, convergence and stability of the systems. Some of the tuning parameters of the model and measurement is rough & requires skilled operators. Previous study conducted by (Saad et al., 2017) used MRAS method to observe the motor speed and rotor position angle of PMSM where the motor itself was used as the reference model and the current model in the rotor reference used as the adjustable model (Bao et al., 2017) and (Kumar et al., 2017). Most of them have implemented PI controller based on Popov Hyperstability theorem as their adaptation technique. The problem with this technique is the response will be sluggish when there is sudden increase in speed and load disturbance.

1.5 Research objectives

The main aim of this research is to develop a new speed sensorless system to observe the motor speed and rotor position information that has performance comparable to the sensor-based control system for PMSMs over their entire operating speed range.

The specific objectives of this research are:

i. To design a speed sensorless method for PMSM based on MRAS scheme.

ii. To develop a new adaptation technique of MRAS that can track the motor speed and rotor position precisely.

iii. To implement and model the new adaptation technique into FOC in order to control the motor speed accurately in Matlab Simulink.

iv. To verify the performance of the proposed design so that the effectiveness of the new adaptation technique can be measured, tested and validated.

1.6 Research scope

In order to achieve the objectives of this research, the following research scope is carried out:

i. Speed sensorless control scheme:

A variety of methods to control the speed sensorless of PMSM conducted by previous researchers such as extended Kalman Filter (EKF), sliding mode observer (SMO), flux linkage observer and model reference adaptive system (MRAS) are critically reviewed. However, the focus of this research is limited to the MRAS due to its ability to control the speed and position of the PMSM with good performance.

ii. Adaptation scheme.

Generally, traditional controller that used for MRAS adaptation scheme is the proportional-integral PI controller. Due to this study intend to control the speed sensorless of the PMSM for high speed and position estimation performance, the Fuzzly logic controller based on Takagi-Sugeno Fuzzy Inference System is applied. Therefore, this study is limited to modelling the TS-FIS. However, PI controller is also developed in order to benchmark the performance of the proposed work.

iii. Development of adaptation technique for MRAS based on Takagi Sugeno Fuzzy Inference System (TS-FIS).

A TS-FIS is developed in order to replace the conventional method of adaptation technique for MRAS which is (PI) controller. TS-FIS algorithm is able to track the motor speed and rotor position angle of PMSM during various dynamic conditions of the motor. The proposed algorithm is validated with various speeds and loads applied to the PMSM. Its performance is evaluated based on the accuracy to track the motor speed and rotor position angle of the PMSM. For comparative evaluation, its tracking performance is compared with conventional adaptation technique of MRAS.

iv. Hardware Implementation

A hardware prototype of the drive system for PMSM that can be used to validate the performance of the proposed algorithm is designed and constructed. Main components of the hardware setup are PMSM, three-phase inverter, dc motor as a load, ac/dc power supply and controller. The dSPACE DS1104 digital signal processing (DSP) board is utilised as the controller in which the proposed MRAS algorithm is implemented.

1.7 Research contributions

This work authenticates the viability of the proposed speed sensorless control of PMSM by using MRAS scheme. The new technique for adaptation scheme is proposed by using TS-FIS. The tests and results demonstrate that the proposed method is capable of effectively and accurately tracking the motor speed and rotor position angle of PMSM. The main contributions of this research work are summarized as follows:

i. The work has proposed a new technique used in the adaptation scheme for MRAS to replace the classical PI controller used in MRAS speed estimation. The new technique is based on Takagi-Sugeno Fuzzy Inference System (TS-FIS) where it is more compact and computationally efficient representation. Besides that, the proposed technique is computationally efficient, can adapt well together with linear techniques, optimization and adaptive techniques which can guarantee continuity of the output surface.

ii. The proposed technique has been tested for several motor conditions. It deals with various conditions of speed and load torque. In addition, it has also been implemented into FOC to control the motor speed and torque.

iii. The effectiveness of the TS-FIS to tune the errors in MRAS scheme is compared with the conventional PI controller. The proposed method clearly indicates an improved motor performance over a wide range of operating speeds since it is capable of tracking the motor speed effectively.

iv. The other contribution of this PhD work is to propose systematic step by step methodology on how to design TS-FIS controller (e.g., membership function shapes and number, rules types and input

/output scaling gain). The goal is to provide some basic design guidelines that are generic to all fuzzy controllers.

v. This research work implements the proposed drive system in full digital form. The implementation is carried out on DS1104 DSP board. It plays an important role in proving the effectiveness of the designed method.

1.8 Outline of the thesis

This thesis consists of six chapters, covering the introduction, methodology, results and discussions and conclusions of the research.

CHAPTER ONE presents the research background, the importance of Sensorless control of PMSM. This chapter also explains the research problems that lead to the motivations of this research, with the stipulated research objectives and scope. The contributions of the PhD thesis are also highlighted this chapter.

CHAPTER TWO presents a review of the speed sensorless method for PMSM. Many researches undertaken by other researchers have been discussed and compared. Various methods and techniques used for speed sensorless control are given. The advantages and disadvantages of each technique are explained and compared. The problems of the current technique are highlighted and analysed in this chapter. Moreover, this chapter also covers a review of various conditions and research gaps in observing the motor speed and rotor position angle for PMSM.

CHAPTER THREE explains the research methodology to achieve the research objectives as given in chapter one accordingly. The PMSM drive system was derived based on FOC to implement with the MRAS scheme.

CHAPTER FOUR is the most contribution part in this thesis which is Fuzzy Logic based on Takagi Sugeno Fuzzy Inference System is revealed and derived in details. Method used to achieve the speed sensorless control is expressed by using MRAS scheme by adopting the PI controller. Then, a new technique for the adaptation scheme is derived in details. This technique is then adapted into the FOC in order to drive the PMSM efficiently.

CHAPTER FIVE provides detailed analyses and discussions on all results obtained from the simulations and experiments. Various conditions of PMSM are tested in order to verify the effectiveness of the system. In the simulation analysis, the comparison between conventional and proposed design is presented. The experimental results are analysed, discussed and compared with the simulated results. The hardware and assembly as well as the experimental test benches are discussed in details.

Finally, conclusions and future work recommendations are presented in CHAPTER SIX.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Currently, speed sensorless control techniques for permanent magnet synchronous motor (PMSM) drives is being widely investigated among the researchers. Speed sensorless control has become an alternative approach due to its ability of dynamic response at very low frequencies to sense the rotor position and motor speed, which eliminate the use of traditional methods, such as optical encoders mounted shaft, resolver or hall sensor. The great advantages offered by speed sensorless control including compactness and robustness make it attractive for many industrial applications. This chapter provides a comprehensive review of different strategies employed for speed sensorless control of PMSM drives with particular focus given to MRAS. Problems affecting adaptation scheme of MRAS schemes are discussed and different methods are employed in the literature to tackle these problems as illustrated in Table 1. Besides that, the vector control of is PMSM also discussed in this chapter.

Table 2.1 Review of speed sensorless method

No	Authors (year)	Technique	Methods
1	(Iizuka et al., 1985)	Back electromotive force (EMF)	Indirect positioning
2	(Ogasawara & Akagi, 1990)	Back electromotive force (EMF)	Indirect positioning
3	(Moreira, 1994)	Third harmonic back emf method	Indirect positioning
4	(E. S. Park et al., 2015)	Third harmonic back emf method	Indirect positioning
5	(Said et al., 2015)	back-EMFs using dual-inverter open-end winding	Indirect positioning

No	Authors (year)	Technique	Methods
6	(Profumo et al., 1994)	Third harmonic back emf method	Indirect positioning
7	(Shen et al., 2004)	Third harmonic back emf method	Indirect positioning
8	(Tan et al., 2018)	Third harmonic back emf method	Indirect positioning
9	(J. M. Liu & Zhu, 2014)	Third harmonic back-EMF	Indirect positioning
10	(D. Yousfi ; M. Azizi ; A. Saad, 1999)	Back-EMF	Indirect positioning method
11	(Briz et al., 2004)	Frequency estimation	Saliency-based method
12	(Bianchi & Bolognani, 2007)	High-frequency stator voltage	Saliency-based method
13	(Jang et al., 2003)	High-frequency signal injection	Saliency-based method
14	(Garcia et al., 2011)	High frequency resistance	Saliency-based method
15	(Briz & Degner, 2011)	High frequency method	Saliency-based method
16	(Briz et al., 2004)	Saliency based method	Saliency-based method
17	(Bianchi & Bolognani, 2007)	Super imposition of a high-frequency stator voltage (IPMSM)	Saliency-based method
18	(Jang et al., 2003)	High-frequency voltage signal injection (PMSM)	Saliency-based method
29	(Garcia et al., 2011)	High frequency method	Saliency-based method
20	(Briz et al., 2004)	Saliency based method	Saliency-based method
21	(Jang et al., 2003)	High-frequency voltage signal injection (PMSM)	Saliency-based method
22	(Corley & Lorenz, 1998)	Rotor position and velocity estimation	Saliency-based method
23	(Jansen & Lorenz, 1996)	Saturation-induced saliencies in induction machines	Saliency- based method
24	(Ha et al., 2003)	Saliency or impedance difference (IPMSM)	Saliency-based method
25	(Yoon et al., 2011)	Square-Wave-Type Voltage Injection	Saliency-based method
26	(Robeischl & Schroedl, 2004)	Optimized INFORM measurement sequence	Saliency-based method
27	(Hua et al., 2007)	Standard Space Vector PWN	Saliency-based method
28	(Jansen & Lorenz, 1996)	Saturation-induced saliencies in induction machines	Saliency-based method
29	(Corley & Lorenz, 1998)	Rotor position and velocity estimation	Saliency-based method
30	(Jansen & Lorenz, 1996)	Saturation-induced saliencies in induction machines	Saliency-based method
31	(Agrawal & Bodkhe, 2016)	High frequency signal injection	Saliency-based method
32	(Kulkarni & Ehsani, 1992)	Inductance-Based Method (IPMSM)	Model-based methods. Open loop
33	(Chi et al., 2009)	SMO	Model-based methods.

No	Authors (year)	Technique	Methods
			Closed loop
34	(Qiao et al., 2012)	SMO-Wind turbine	Model-based methods. Closed loop
35	(Kim et al., 2011)	SMO	Model-based methods. Closed loop
36	(Foo & Rahman, 2010)	SMO	Model-based methods. Closed loop
37	(J. Liu et al., 2005)	SMO (IM)	Model-based methods. Closed loop
38	(Xi et al., 2005)	MRAS (IPMSM)	Model-based methods. Closed loop
39	(Shi et al., 2012)	MRAS (IPMSM)	Model-based methods. Closed loop
40	(Peng & Fukao, 1994)	MRAS (IM) – Popov hyperstability	Model-based methods. Closed loop
41	(Kojabadi & Ghribi, 2006)	MRAS (PMSM)	Model-based methods. Closed loop
42	(Bolognani et al., 2002)	EKF (IPMSM)	Model-based methods. Closed loop
43	(Bolognani et al., 2003)	EKF (IPMSM) avoid try and error method	Model-based methods. Closed loop

2.2 PMSM Drives system

In order to achieve a high-performance motion control of permanent magnet synchronous machine (PMSM), it should be drive in smooth rotation and accurate torque control over the entire speed range (including standstill) and fast acceleration and deceleration. The vector control techniques as mentioned by (Novotny & Lipo, 1996) and (Mohan, 2014) which is also referred to as the field-oriented control (FOC), can be adopted to achieve this objective. With this type of control technique, the stator current of a PMSM are decomposed into a magnetic-field-generating part and a torque-generating part, which can be controlled independently. By doing this separation method, the flux and torque can be controlled separately by using the decomposed current components. Therefore, the structure of the PMSM vector control scheme is then as simple as that of a separately excited DC machine. The overall block diagram of a PMSM drive system using a position sensor based space vector control scheme is shown in Figure 2.1.

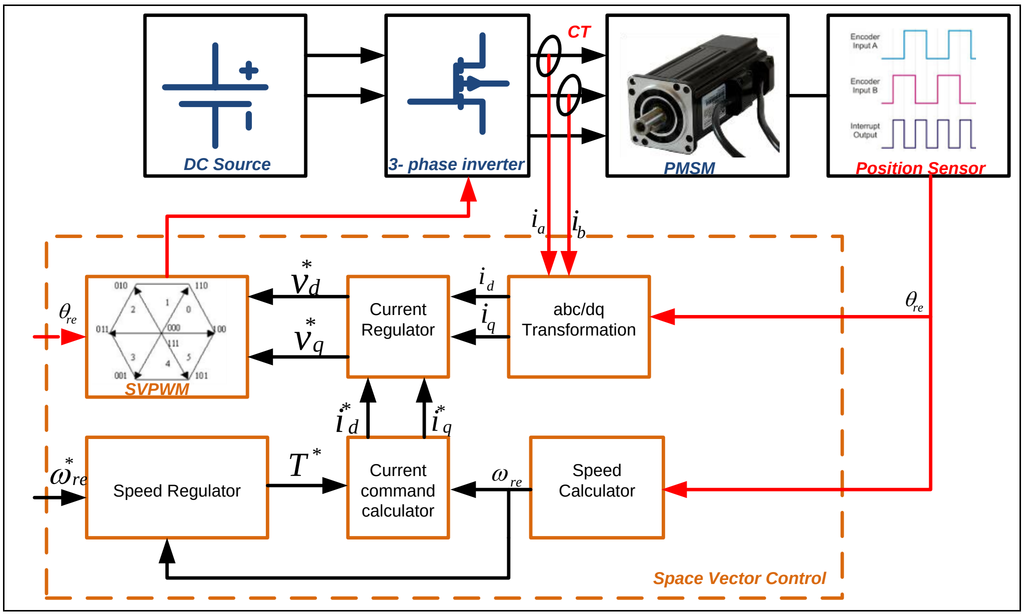

Figure 2.1 Overall block diagram of a PMSM drive system using a position sensor based on space vector control scheme.

This type of control scheme consists of a PMSM, a voltage source inverter (VSI), a DC voltage source, current sensors and position sensors. The following steps usually perform the vector control technique:

a) Sensing and processing of motor currents and rotor position

i. Measure the stator phase currents of the PMSM using current transducers (CTs). Owing to the redundancy, the measurements of two phase currents, e.g., i_a and i_b , are sufficient.

ii. Measure the rotor position information θ_{re} using a rotor position sensor, e.g., a resolver or an encoder.

iii. Coordinate transformation: transform the stator phase currents i_a , i_b and i_c into the currents i_d and i_q in the synchronously rotating (rotor) reference frame using the measured rotor position information.

b) Torque command and current commands

i. Generate the torque command T^* based on the tracking error between the desired rotor speed ω_{re}^* and the measured rotor speed ω_{re} using a speed regulator.

ii. Generate the current commands, i_d^* and i_q^*, according to the relationship among i_d^* , i_q^* , T^* , and $\frac{v_{dc}}{\omega_{re}}$ (the ratio between the DC bus voltage and the rotor speed). This relationship is usually implemented by lookup tables in practical applications as mentioned by (Cheng & Tesch, 2010).

c) Current regulation and gate signals.

i. Perform the decoupling current control by using two current regulators, in which the torque- and flux-producing components of the stator currents, i_d and i_q , are controlled separately. This step will generate reference voltages, v_d^* and v_q^* , in the synchronously rotating reference frame.

ii. Perform the space vector pulse width modulation (SVPWM) based on v_d^* and v_q^* , and generate the gate signals for the voltage source inverter (VSI). In this step, rotor position information is required to transform v_d^* and v_q^* into v_α^* and v_β^* .

(Abassi et al., 2016) and (Kivanc & Ozturk, 2016) agreed that, high performance control characteristics can be achieved by FOC method. It is the one of the vector based methods that aims to control the torque and rotor flux of the PMSM effectively. FOC is efficiently capable to control the space vector of magnetic flux, currents and voltages of the machines in order to achieve the precise speed target.

By applying the FOC method, the stator currents are set as a control variable. The three-phase static reference frame of the stator current is transformed and converted into the direct (d)- quadrature (q) coordinate reference frame of the motor. The magnetic flux produced from the rotor of PMSM is locked to the vector of the rotor flux and will rotate synchronously at the stator frequency. The voltage supplied to the motor is transformed from d-q coordinate reference frame of the rotor to the three-phase static reference frame of the stator before it can be fed to SVPWM for PWM output. The implementation of vector based FOC, which is built upon stator-flux orientation, gives a better steady-state operation. All this process is illustrated in Figure 2.1.

To achieve high-performance vector control for PMSMs, accurate measurements of rotor position and motor speed are necessary. In conventional PMSM drive systems, the information of rotor position and motor speed are usually obtained by using rotary encoders or resolvers. However, the use of these sensors increases the cost, size, and wiring complexity and reduces the mechanical robustness and reliability of PMSM drive systems. Many researchers such as (Zhao et al., 2013), (Seilmeier & Piepenbreier, 2015), (Quang et al., 2015) and

(Kung et al., 2016) have gone into the development of rotor position and speed sensorless drives that have dynamic performance comparable to the position sensor-based drives during the last few decades in order to overcome the sensor problems. Several methods to estimate the rotor position and motor speed information without using a sensor have been reviewed and summarized in this chapter. The rotor position and motor speed estimation methods can be classified into three major categories:

i. Indirect position sensing methods in which the rotor position information is obtained indirectly from the sensed position-related quantities, e.g., back-EMF components or third harmonic back-EMF.

ii. Saliency-based methods in which the rotor position information is extracted from the position-dependent machine saliency and high frequency (HF) excitation is usually required.

iii. Model-based methods in which the fundamental-frequency model of PMSM, measured stator currents, and measured stator voltages are utilized to estimate the rotor position information.

The relationship among these three categories is illustrated in Figure 2.2. Each category of methods can be performed through simple and straightforward open-loop techniques. However, to improve the accuracy of the rotor position estimation, the trend in recent research is toward the design of closed-loop position estimation methods. Therefore, the observer design has become the core part of position estimation.

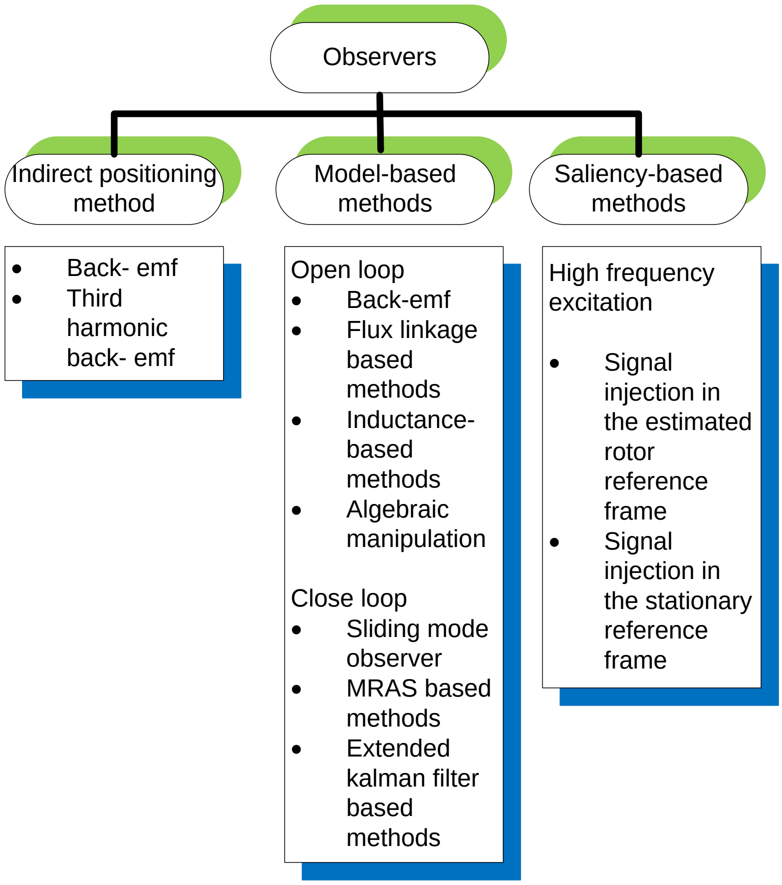

Figure 2.2 Three major categories to obtain rotor position information without using position sensors.

2.3 Indirect Position Sensing Method

The idea for this technique is to obtain the rotor position information indirectly from the sensed position related signal. This method uses measured currents and voltages as well as fundamental machine equations of PMSM. The characteristic of this method is easy to be computed, responded quickly with almost no delay. But it requires highly accurate motor parameters, more suitable for motor parameters online identifications.

2.3.1 Back-EMF Method

Based on this method, the information of rotor position angle is obtained indirectly from the sensed position related signals, e.g., instantaneous magnitude of the back-EMF, which is a function of rotor position. These methods were firstly applied to the brushless DC (BLDC) motors, which have trapezoidal back-EMF waveforms. (Iizuka et al., 1985) and (Ogasawara & Akagi, 1990) implemented the detected zero-crossing points on the back-EMF to obtain the rotor position. Due to EMF sensing cannot be used in low-speed operating conditions, the open-loop start up procedure should be used to address this problem.

The existence of armature reaction which causes distorted air gap flux distribution in Permanent magnet AC machines, especially in IPMSMs, has resulted a technique introduced by (Iizuka et al., 1985) and (Ogasawara & Akagi, 1990) which cannot be adopted to obtain the rotor position. Nevertheless, with this method, the base speed is the maximum speed that can be achieved.

2.3.2 Third Harmonic Back-Emf Method

The third harmonic component of the back-EMF waveform has a constant phase relationship with the rotor flux regardless of the machine operating mode. This type of harmonic component is extracted from the stator phase voltages while the fundamental and other higher order harmonic components are eliminated via a simple summation of the three phase voltages. (Moreira, 1994) had proposed an indirect position sensing method based on this third harmonic components.This method needs less filtering and has an improved capability to operate in a lower-speed region compared with the technique introduced by (Iizuka et al., 1985) and

(Ogasawara & Akagi, 1990). Due to this method is highly associated to the BLDCs with trapezoidal back EMFs, (J. W. Lee, 2015) and (Said et al., 2015) introduced other third harmonic back EMF-based indirect position sensing methods, which can be applicable to both BLDCs and SPMSMs.

The effectiveness of this sensing method was verified on both BLDCs and SPMSMs including the sensorless speed control in the flux weakening region by (Shen et al., 2004). However, an open-loop starting procedure has to be employed similar to all other EMF-based sensorless control methods. The latest improvement for position estimation method was done by (Tan et al., 2018) for PMSM. Their method combined a third harmonic back-EMF sensing method and a position observer. With this method, the error between the estimated and reference was used to compensate the motor speed estimation error where the third harmonic flux linkage was set as a reference. Then the rotor position was calculated based on this compensated motor speed. Compared to previous work, this method has been reported achieve better position estimation accuracy.

2.4 Saliency-Based Methods

A previous section has discussed the fundamental frequency model-based rotor position and motor speed estimation techniques. These methods are capable of providing highly accurate rotor position and motor speed estimations for the vector control of PMSMs in medium and high-speed regions. However, these methods will have poor performance or even fail in the low-speed region and at standstill due to low signal-to-noise ratios (SNRs) of the position-related system states. To overcome this limitation and improve the low-speed operation capability, (Briz & Degner,

2011) and (Briz et al., 2004) have proposed the machine saliency to track the rotor position and motor speed. This method is based on the excitation of HF that is normally used, where the frequency is much higher than the fundamental frequency. Using the measured response of the PMSM under the HF excitation, the position-related saliency signal can be obtained.

The rotor position is detected by tracking the variation of the position dependent stator inductance as discussed by (Bianchi & Bolognani, 2007). They have applied this method to the IPMSMs which is the salient-pole PMSMs. (Jang et al., 2003) and (Garcia et al., 2011) have studied this approach to the nonsalient-pole PMSMs. They have researched on SPMSMs, which have symmetric rotor structures and, therefore, a nearly zero spatial variation of inductance. The main flux saturation or stator leakage flux saturation-related spatial saliency is usually used for rotor position detection.

Continuous mode of HF excitation were used by (Corley & Lorenz, 1998), (Jansen & Lorenz, 1996), (Ha et al., 2003) and (Yoon et al., 2011) and discontinuous mode were proposed by (Robeischl & Schroedl, 2004) and (Hua et al., 2007). With this method, different types of HF excitation and the carrier signal can be achieved by using either a carrier signal injection method proposed by (Jansen & Lorenz, 1996), (Ha et al., 2003) and (Yoon et al., 2011) or a pulse-width modulation (PWM) pattern modification proposed by (Robeischl & Schroedl, 2004) for HF excitation. For the carrier signal, (Corley & Lorenz, 1998), (Jansen & Lorenz, 1996) and (Ha et al., 2003) have proposed the sinusoidal waveforms type and square waveforms.

Each types of HF excitation have their own measurement of the saliency-related signal. The method used for the signal processing also differs with different saliency- related signal. (Lorenz, R.D., 2015) and (Agrawal & Bodkhe, 2016) have done researches on closed-loop saliency-tracking observers to improve rotor position detection performance.

2.5 Model Based Methods

This method is based on the fundamental frequency and widely used for rotor position and motor speed estimation. It can be classified into two categories as illustrated in Figure 2.2. These methods are very effective especially for medium and high-speed applications (X. Zhang et al., 2016). The first category is the open loop rotor position and motor speed estimation method. It is straightforward and easy to implement. These methods perform like real-time dynamic models of PMSMs. Back-EMF, flux linkage based method, inductance based method and algebraic manipulations are included in this category.

On the other hand, in a closed-loop observer (Y. Liu et al., 2016), these methods can be of linear state observer, non-linear state observer, MRAS based methods or extended kalman filter. When applying these methods, both the control inputs of the plant and the output tracking error are often used as the inputs to the observer. Therefore, the output tracking error is the error between the outputs of the plant and the observer. The observer gains are designed to force the observer output to converge with the plant output. Thus, the estimated values of the states of interest are forced to converge to their actual values. From this aspect, the closed-loop observer can be viewed as an adaptive filter, which has a good disturbance rejection