Volume 8, Issue 5
October 2019

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Sensorless Control of Synchronous Reluctance Motor- A literature Review

[1]Priya Rani Jose and [2]Mariamma Chacko

[1]Department of Ship Technology, Cochin University of Science & Technology, India

[2]Department of Ship Technology, Cochin University of Science & Technology, India

E-mail: [1]priyatelly@gmail.com, [2]mariammachacko@cusat.ac.in

ABSTRACT

This paper reviews the recent developments in the field of sensorless control of Synchronous Reluctance Motor (SyRM). The elaborated aspects include advantages of SyRM, basic vector control and direct torque control schemes and different sensorless techniques to find out rotor position.

Keywords: *SyRM, Vector control, Direct torque control, Rotor position estimation, Sensorless control*

1. INTRODUCTION

The simple and rugged structure and non-magnetic rotor of Synchronous reluctance motor makes this motor a reliable alternative to other ac motors in medium-performance drive applications. This motor finds applications in day-to-day life such as metering pumps, wrapping and folding machines, proportioning devices on pumps or conveyors, synthetic fibre manufacturing equipment, processing continuous sheet or film materials, etc. This also finds application in low-power and middle-power applications of ships [1]. Much research work is being carried out in redesign of rotor and also for proper position estimation of rotor for the better efficiency and robust performance of SyRM under disturbances and uncertainties.

The converter-fed SyRM uses two control schemes to obtain high dynamic performance that include vector control scheme and direct torque control scheme. The SyRM requires the rotor position information to synchronize the inverter output voltages with the rotor position for starting and closed-loop control of the motor. Thus, it is important to determine the rotor position of SyRM. The rotor position of SyRM can be determined by two methods: one is by the use of sensors [10]-[13] where mostly rotor position transducer is used, and other is by sensorless methods. Position sensorless control technology saves cost, space, maintenance, etc. and it becomes one of the most promising trends of SyRM control system.

This review paper presents the research efforts carried out by different researchers on rotor position estimation and performance improvement of SyRM by different control schemes.

2. VECTOR CONTROL

The electromagnetic torque of SyRM as in equation (1) directly depends on the direct and quadrature axis inductances and stator current components which are expressed in rotor reference frame.

$$T_e = \frac{3}{2} P (L_{sd} - L_{sq}) i_{sd} i_{sq} \tag{1}$$

where P is the number of pole pairs

The stator current components in rotor frame can be obtained from stator currents (i_{SD}, i_{SQ}) in the stationary reference frame as expressed in equation (2), where θ_r is the rotor angle, which implies the necessity of finding out rotor position in vector control.

$$\bar{I}_s = i_{sd} + j i_{sq} = (i_{SD} + j i_{SQ}) \exp(-j\theta_r) \tag{2}$$

The rotor oriented vector control method is of two types which are constant direct axis current control and constant current angle control. Different control objectives of constant current angle vector control include MTPA (Maximum Torque per Ampere), MPFC (Maximum Power Factor Control) and MTPF (Maximum Torque per Flux).

Longya Xu et al. [2] analysed the role of saturation and iron loss in establishing optimal rotor angles for vector control of a SyRM and found that the optimal angles for maximum torque/ampere and maximum efficiency are larger than the theoretical 45 degree angle predicted by a linear, lossless model. The assumption of iron loss in SyRM is produced in equivalent eddy current windings on d-q axis made vector control of SyRM simple as that of DC machine [3]. Ahamad and Tsuyoshi [4] presented a very low speed sensorless vector control of synchronous reluctance motor with a novel start-up by the use of extended programmable cascaded low pass filter (EPCLPF). Sorin et al. [5] presented a hybrid, motion sensorless control of an Axially Laminated Anisotropic (ALA) Reluctance Synchronous Machine which improved performance at zero and very low speeds.

The main disadvantage of vector control is to require a large amount of on-line computation if torque response quickness, robustness, and precision are to be secured.

Volume 8, Issue 5
October 2019

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

3. DIRECT TORQUE CONTROL

The basic principle of the direct torque control is to bind the torque error and the flux error in hysteresis bands by properly choosing the switching states of the inverter. In this scheme the rotor position is not used, or detected, and it relies purely on orientation of stator flux linkage and torque control.

Rolf Lagerquist [6] implemented direct torque control using a high-speed digital processor DSP96002. Field weakening method was also used here to keep the voltage constant above base speed. Highly dynamic torque controller could be implemented based on the current vector [7]. Direct torque control, along with Lyapunov stability theorem [8] achieved fast response and a good disturbance rejection capability. In this method the speed and current errors are used to form a Lyapunov function and the controller is designed by the method of the Lyapunov and adaptive theory. Zarchi et al. [9] used the well-known adaptive input–output feedback-linearization (AIOFL) technique for SynRM torque control without using mechanical position and voltage sensor. The overall stability of the proposed control and the persistency of excitation condition are proved based on Lyapunov theory.

Although the direct torque control is very simple, it shows good dynamic performance in torque and flux regulation. The performance of the drive system may deteriorate by the presence of high frequency ripples of the flux and torque which is the main disadvantage of direct torque control. In addition, the controller is not easy to apply due to the large torque pulsation of the motor.

4. RESEARCH EFFORTS ON ROTOR POSITION SENSING BY SENSORLESS TECHNIQUES

Rotor position estimation from electrical measurements without use of any position sensor is the technique used in a synchronous reluctance motor sensorless drive. Various existing technologies that are being adopted in the sensorless control of SyRM are shown in Fig. 1.

The various methods of rotor position detection at different speeds even at zero-speed along with its advantages and disadvantages, have been found in literature are described below.

4.1 Estimation using stator voltage and current

It is possible to estimate the rotor angle and the speed in both the transient and steady state of the SyRM by utilising the estimated stator flux-linkage components. The estimation of the stator flux linkage requires the stator voltages and currents in the direct and quadrature axes and also the stator resistance. In the steady state, the speed of the stator flux-linkage space vector is equal to the rotor speed. However, in the transient state, when there is a change in the torque reference, the stator flux-linkage space vector moves relative to the rotor to produce the desired new torque [33]. Accordingly, Lagerquist et al. [15] implemented the closed loop speed control by estimating the rotor speed by differentiating the position of the flux-linkage vector. In reference [16] the speed is assessed utilizing the stator voltage and current. The rotor position is acquired by the speed integral. Jung-Ik et al. [17] proposed a combined position sensorless control scheme of a synchronous reluctance motor in which at low speed region, a high-frequency current injection method and at the high-speed region, the flux estimation method based on the stator voltages is adopted.. This rotor position estimation scheme can just work in medium-speed and high speed regions, in light of the fact that the voltage adequacy is excessively little in low speed region.

4.2 Estimation using the spatial saturation third harmonic voltage component

In a wye connected SyRM, the resultant of sum of the stator voltage is a spatial saturation third- harmonic voltage component and is due to saturation effects. Accordingly, Kreindler et al. [18] located the fundamental component of air gap flux from the third-harmonic voltage component induced in the stator phase voltages. By the use of zero crossing

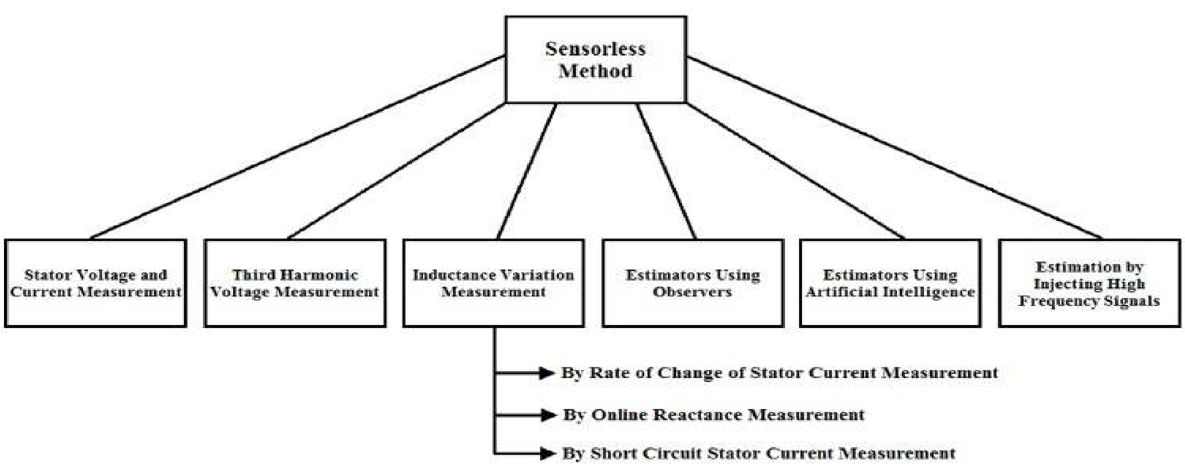

Fig. 1: Various existing technologies in the sensorless control of SyRM

detection of third- harmonic voltage, the position of air gap flux is determined and direct torque control scheme is implemented. Usage of this strategy requires the stator to be star-connected with access to the neutral connection. This technique, tragically, had poor outcomes at low speed. An estimation of 2.7 Hz was the most minimal working frequency.

4.3 Estimation based on inductance variation due to geometrical and saturation effects

Due to rotor saliency, the stator self and mutual inductances of the SyRM depend on the rotor position. Thus in a SyRM drive, the rotor position can be estimated by using inductance variations due to geometrical effects. The following techniques are used for the estimation of rotor position indirectly by using inductance variation

4.3.1 Estimation using the measured rate of change of the stator currents.

In a SyRM drive, where the SyRM is supplied by a hysteresis current-controlled inverter, the rate of change of the stator currents which is related to the inverter switching is also position dependent. At low speed or at zero speed, the rate of change of stator currents expression contains known value of inductances and rotor angle only. Therefore, it is possible to plot the rate of change of current as a function of rotor angle. Thus if the measured values of rate of change of stator currents are known ,then it is possible to be estimate the rotor position from the curves indirectly [19]-[21]. The estimation scheme can be used at low rotor speed, including zero speed, but the estimation accuracy decreases radically at higher speeds.

4.3.2 Indirect flux detection by the on-line reactance measurement method (INFORM method)

In this method, appropriate stator test voltages are applied to the motor and the rate of change of the stator currents is measured. At standstill, and neglecting the ohmic drops, the test voltage space vector is equal to the product of rate of change of stator flux linkage and rate of change of stator currents. Due to geometrical saliency, the voltage space vector and the rate of change of the current space vector are related via a complex inductance, which is a function of twice the rotor angle [33]. This method is suitable in low speed region only. Therefore Schroedl et al. [22] proposed a hybrid model in which INFROM method was used in low-speed region and back EMF method for rotor position detection used in high-speed region.

4.3.3 Indirect rotor position estimation at free-wheeling modes of inverter

If the inverter supplying the SyRM is forced for a short time into one of the zero switching states ((0 0 0) or (1 1 1)) ,where the stator windings got short- circuited, then it is possible to extract the rotor position indirectly by measuring the rate of change of the stator currents. This technique cannot he used at zero and low speed and at low values of the stator reference current. This estimation technique effectively implemented in reference [23]

4.4 Estimators using Observers

Extended Kalman Filter (EKF) is an optimal recursive estimation algorithm for nonlinear systems that are disturbed by random noise. In reference [24] the EKF estimator was implemented to estimate the machine parameters which are used for the high efficiency position controller and the current controller. M. Rizwan and Iqbal [25] used Extended Luenberger Observer algorithm for speed estimation in an indirect rotor flux-oriented synchronous reluctance machine, with current control in the stationary reference frame. The combination of Extended Kalman Filter (EKF), Adaptive Filter (AF) and quadrature Phase-Locked Loop (PLL) are used for better estimation of the non-sinusoidal back EMF, elimination of the high order harmonics, and the accurate estimation of position and speed of rotor, respectively for a Permanent Magnet-Assisted Synchronous Reluctance Motor [26].These algorithms will optimally reduce the effects of stochastic disturbances, and will also yield an accurate estimate of the load torque and rotor speed.

4.5 Estimators using Artificial intelligence

By using artificial intelligence (AI) techniques, it is possible to estimate any non-linear function with great accuracy. The rotating angles of the rotor identification by the use of artificial neural network (ANN) are proposed in reference [27].Neural networks are trained to associate between the measured phase voltages and currents and the rotor positions. The networks perform independently to identify the rotor positions based on the measured voltages and currents once this association is established.

4.6 Estimation using high frequency signal injection (HFSI)

High frequency signal injection method based on the anisotropy of SyRM. The d and q stator current injection and the appropriate signal demodulation techniques are used in reference [28] for the rotor angle calculation. The difference between the real rotor angle and the estimated angle is got from the output of modulated signal .Continuous rotor position estimation is made possible by adjusting the estimated angle with the modulated signal. The rotor position can also be estimated from the measurement of an additional high-frequency stator current component by the application of high -frequency synchronous stator voltage component [29].Toshiya et al. [30] proposed a method for rotor position detection in which a constant low- amplitude current injection was used in order to avoid flow of large high frequency current. This method is useful even at low speeds. Machine parameter information is not required mostly in HFSI based implementation and thus it is easy to achieve machine parameter independent sensorless control. Seog-Joo Kang et al. [31] implemented a combined form of high-frequency current injection in a low-speed region and the flux estimation based on the stator voltages in a high- speed region. However, the disadvantage of this method was the requirement of a second order low pass filter. The traditional high frequency voltage injection techniques are to superimpose high-frequency voltage signals onto the fundamental stator voltage vector. Accordingly, the extent of the voltage utilized for machine torque creation is sacrificed and these strategies are not applicable for high speed operation range. Injecting a high-frequency signal at half of the switching frequency [32] has overcome these disadvantages.

5. CONCLUSION AND FUTURE SCOPE

A review of vector control and direct torque control techniques used in SyRM and various sensorless techniques used in SyRM rotor position detection has been presented in this paper, along with their merits and demerits in detail in order to have a clear understanding. The rotor position estimation in the medium speed and high speed can be achieved either by measurement of stator voltage and current or by the measurement of the spatial saturation third - harmonic voltage component and also possible by indirect rotor position estimation at free-wheeling modes of inverter. Estimation using the measured rate of change of the stator currents suitable in low rotor speed, including zero speed. In the low-speed to medium -speed region, high frequency signal injection method is very useful for rotor position estimation. The combination of these methods also is used in SyRM to achieve rotor position estimation in entire speed region. The application of sensorless techniques reduces the size, maintenance, and cost. Most of the motors used artificial intelligence technique for rotor position estimation but from the available literature the use of AI is very less in the case of SyRM. The AI methods can use in future for the rotor position estimation of SyRM for the entire speed region.

REFERENCES

[1] Ioannis Ch. Proimadis, Dionysios V. Spyropoulos, and Epaminondas D. Mitronikas, “An Alternative for All-Electric Ships Applications: The Synchronous Reluctance Motor”, Hindawi Publishing cooperation, 2013.

[2] Longya Xu, Jiping Yao, “A Compensated Vector Control Scheme of a Synchronous Reluctance Motor Including Saturation and Iron Losses”, IEEE Transactions on industry applications, vol. 28, no. 6, November / December 1992

[3] Yoshikatsu Tomori, Tomonobu Senjyu, Katsumi Uezato, “Vector Control of Synchronous Reluctance Motors Including Stator Iron Loss with On-Line Parameter Measurement”, Proceedings of 1994 Power Electronics Specialist Conference - PESC'94

[4] Ghaderi Ahmad, Hanamoto Tsuyoshi, “Very Low Speed Sensorless Vector Control of Synchronous Reluctance Motors with a Novel Startup Scheme “,APEC 07 - Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition

[5] Sorin-Cristian Agarliţă, I. Boldea,Frede Blaabjerg, “High Frequency Injection Assisted —Active Flux Based Sensorless Vector Control of Reluctance Synchronous Motors, with Experiments from zero speed “,2011 IEEE Energy Conversion Congress and Exposition.

[6] Rolf Lagerquist, Member, Ion Boldea, Tim J. E. Miller, “Sensorless Control of the Synchronous Reluctance Motor “,IEEE Transactions on Industry Applications, vol. 30, no. 3, May/June 1994

[7] Seog-Joo Kang,Seung-Ki Sul, “Highly Dynamic Torque Control of Synchronous Reluctance Motor “, IEEE Transactions on Power Electronics Volume: 13, Issue: 4, Jul 1998

[8] Chien-An Chen, Huann-Keng Chiang, Bor-Ren Lin, Chih-Huang Tseng, Maximum Torque Control of Synchronous Reluctance Motor Speed Drive Based on the Lyapunov Function Stability Theorem , 2007 2nd IEEE Conference on Industrial Electronics and Applications

[9] Hossein Abootorabi Zarchi, Jafar Soltani, and Gholamreza Arab Markadeh, “Adaptive Input–Output Feedback-Linearization-Based Torque Control of Synchronous Reluctance Motor Without Mechanical Sensor”, IEEE Transactions on Industrial Electronics, Vol. 57, No. 1, January2010.

[10] T.J.E. Miller (SM), C. Cossar, and A.J. Hutton, “Design of a synchronous reluctance motor drive”, IEEE Transactions on Industry Applications, Vol: 27, Issue: 4, Jul/Aug 1991

[11] Y. Fu, B. Robyns, F. Labrique,” Investigation on a Fully Digital Control System for Synchronous Reluctance Machines” ISIE '93 - Budapest: IEEE International Symposium on Industrial Electronics Conference Proceedings, 1993

[12]Takayoshi Matsuo, Thomas A. Lipo, “Field Oriented Control of Synchronous Reluctance Machine”, Proceedings of IEEE Power Electronics Specialist Conference - PESC '93

[13] Betz, R. E., Lagerquist, R., Jovanovic, M., Miller, T. J. E., Member, S., & Middleton, R. H.,” Control of Synchronous Reluctance Machines”, IEEE Transactions on Industry Applications, Vol. 29, no. 6, November/December 1993.

[14] Vagati, A., Pastorelli, M., & Franceschini, G. ,” High-Performance Control of Synchronous Reluctance Motors”, IEEE Transactions on Industry Applications, Vol. 33, no. 4, July/August 1997

[15]R. Lagerquist, I. Boldea, and T. J. E. Miller, “Sensorless control of the synchronous reluctance motor”, IEEE Trans. Ind. Applicat., vol. 30, pp. 673–682, May/June 1994

[16] Jin Xinhai, Chen Wei, Xu Dianguo," Sensorless control of Synchronous Reluctance motor", IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), 2017

[17] Seog-Joo Kang, Jung-Ik Ha, Seung-Ki Sul, "Position Controlled Synchronous Reluctance, Motor Without Rotational Transducer", IEEE Transactions on Industry Applications, Volume: 35, Issue: 6, Nov/Dec 1999

[18] L. Kreindler, A. Testa and T. A. Lipo," Position Sensorless Synchronous Reluctance Motor Drive Using the Stator Phase Voltage Third Harmonic", Conference Record, ,pp. 679-686,IEEE IAS Annual Meeting, October 1993

[19] Takayoshi Matsuo, Thomas A. Lipo, "Rotor position detection scheme for synchronous reluctance motor based on current measurements", IEEE Trans. Ind. Application., vol. 31, pp. 860–868, July/Aug. 1995

[20] Milutin G. Jovanovic, Robert E. Betzt, Don Plattt , "Sensorless Vector Controller for a Synchronous Reluctance Motor" ,IEEE Transactions on Industry Applications, Vol. 34, No. 2, March/April 1998

[21] Ming-Tsan Lin,Tian-Hua Liu, "Sensorless Synchronous Reluctance Drive With Standstill Starting", IEEE Transactions on Aerospace and Electronic Systems vol. 36, no. 4 October 2000.

[22] M. Schroedl and P. Weinmeier, "Sensorless control of reluctance machines at arbitrary operating conditions including standstill," IEEE Trans. Power Electron., vol. 9, pp. 225–231, Mar. 1994.

[23] Ming-Tsan Lin,Tian Hua Liu, "Sensorless Synchronous Reluctance Drive With Standstill Starting", IEEE Transactions on Aerospace and Electronic Systems vol. 36, no. 4 October 2000

[24] Tomonobu Senjyu, Akihiro Omoda, Katsumi Uezato, "High Efficiency Control of Synchronous Reluctance Motors Using Extended Kalman Filter" ,PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference.

[25] M. Rizwan Khan, Atif Iqbal, "Speed Estimation in Five-Phase Syn-Rel Machines using ELO-Algorithm", 16th National Power Systems Conference, 15th-17th December, 2010.

[26] Ali Sarajian, Davood Arab Khaburi, Marco Rivera," Using Extended Kalman Filter and Adaptive Filter for sensorles predictive torque control of PM-Assisted Synchronous Reluctance Motor",7th Power Electronics and Drive Systems Technologies Conference (PEDSTC) ,2016

[27] M.Sadeghierad, B.Ganji, H.ImanEini, S.Afsharnia," A Neural Network Approach to Sensorless Control of Synchronous Reluctance Motor",Proceedings of the 4th WSEAS international conference on Applications of electrical engineering,March 2005

[28] Seog-Joo Kang, Jang-Mok Kim , Seung-Ki Sui," Position Sensorless Control of Synchronous Reluctance Motor Using High Frequency Current Injection" , IEEE International Electric Machines and Drives Conference Record,1997

[29] Alfo Consoli, Fabio Russo, Giuseppe Scarcella, Antonio Testa ,"Low and Zero Speed Sensorless Control of Synchronous Reluctance Motors" , IEEE Transactions on Industry Applications , Volume: 35, Issue: 5, Sep/Oct 1999

[30] Toshiya Mabuchi, Ayame Makimura, Mutuwo Tomita, Shota Kondo, Masaru Hasegawa, Shinji Doki,Shinji Kato, "Position Sensorless Control of Synchronous Reluctance Motors at Very Low Speeds Region Using High-frequency Current Control System".20th International Conference on Electrical Machines and Systems (ICEMS), 2017

[31] Seog-Joo Kang, Jung-Ik Ha, Seung-Ki Sul, "Position Controlled Synchronous Reluctance Motor without Rotational Transducer", IEEE Transactions on Industry Applications, Volume: 35, Issue: 6, Nov/Dec 1999.

[32] Dong Wang, Kaiyuan Lu, Peter Omand Rasmussen, "High Frequency Signal Injection Method Based on Duty Cycle Shifting Without Maximum Fundamental Voltage Magnitude Loss ",IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 5, No. 3, September 2017

[33] Peter Vas, "Sensorless vector and direct torque control, Oxford Science Publications.

AUTHOR PROFILES

Priya Rani Jose received her Bachelor's degree in Electrical and Electronics Engineering from Amal Jyothi College of Engineering in 2007, and Master's degree in Instrumentation and control systems from NIT Calicut in 2013. She is currently doing her research in Controller for Electrical Motors in Cochin University of Science and Technology.

Dr. Mariamma Chacko was born in 1961 at Changanacherry, India. She received her Bachelor's degree in Electrical Engineering from University of Kerala in 1985, Master's degree in Electronics from Cochin University of Science and Technology in 1987 and PhD in Computer Science from Cochin University of Science and Technology in 2012. She has been working as a faculty in the Department of Ship Technology at Cochin University of Science and Technology since 1990 and as currently Professor in the department. From 1987 to 1990 she was associated with the Department of Electronics, Cochin University of Science and Technology, as a Research Associate. She has 18 research publications to her credit and her research interests include validation and optimization of embedded software, motor control and power quality in electrical system.