Review of Parameter Identification and Sensorless Control Methods for Synchronous Reluctance Machines*

Chengrui Li, *Gaolin Wang**, *Guoqiang Zhang*, *Nannan Zhao and Dianguo Xu*
(School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150000, China)

Abstract: Synchronous reluctance machines (SynRMs) have drawn increasing attention in recent years owing to their advantages such as low cost, simple structure, ease of manufacture, and high robustness. The main obstacle to the promotion of SynRMs is severe parameter nonlinearity, which deteriorates drive performance. Sensorless control methods for SynRMs are critical technologies that can broaden the industrial applications of SynRMs. Various methods of parameter identification and sensorless control strategies are reviewed and discussed, including self-commissioning, which is analyzed in detail. Furthermore, sensorless control strategies that can improve the industrial application of SynRMs are described. Finally, future research trends concerning SynRMs are analyzed and discussed.

Keywords: Synchronous reluctance machines, parameter identification, sensorless control

1 Introduction

Synchronous reluctance machines (SynRMs) were first introduced in 1923 [1]. The coupling effect developed between the rotating sinusoidal magnetic field, which is generated by the stator, and the special rotor structure generates a reluctance torque. With the restrictions on rotor materials and manufacturing techniques in earlier days, the saliency ratio, power density, and power factor of SynRMs were relatively low, which limited the promotion of these machines. With the rapid development of power electronics and modern control theories, as well as the extensive use of microprocessor technology, SynRMs have overcome the problem of synchronous control that enables them to be applied to electrical drives [2].

SynRMs are attracting more research interests in recent years. There are many advantages of SynRMs versus other types of machines, which make them a powerful competitor for general purpose applications such as pumps, fans and traction machines in electric vehicles [3-5]. The industrial community is considering the possibilities of industrial solutions based on SynRMs. ABB has developed products including SynRMs and drives that can achieve super-premium efficiency (IE4) per the standards of the International Electrotechnical Commission (IEC).

Given the variation of motor parameters along with the change in the operating environment, the precise calculation or identification of motor parameters is the primary problem and limitation in realizing higher driving performance [6-9]. The rotor position estimation is another essential part that needs to be designed optimally for the sensorless controlled SynRMs, which can further maximize the advantage of low cost and promote the application of SynRMs for cost-sensitive applications [10-21]. In addition, the precise knowledge of motor parameters is favorable for the improvement of sensorless control performance of SynRMs. Parameter identification methods and sensorless control strategies of SynRMs are two key technologies that can increase the competitiveness of SynRMs for industrial applications.

This paper aims at presenting a comprehensive discussion on state-of-the-art research in parameter

Manuscript received January 2, 2020; revised February 15, 2020; accepted March 12, 2020. Date of publication June 30, 2020; date of current version May 16, 2020.

* Corresponding Author, Email: WGL818@hit.edu.cn

* Supported by the National Natural Science Foundation of China (51807037) and the Power Electronics Science and Education Development Program of Delta Group (DREG2019003).

Digital Object Identifier: 10.23919/CJEE.2020.000007

identification and sensorless control strategies for SynRM drives. This paper is organized as follows. Section 2 introduces the parameter identification technologies concerning SynRMs. The sensorless control methods for SynRMs are reviewed and compared in Section 3. Furthermore, future trends concerning SynRMs drives are discussed in Section 4. Finally, Section 5 discusses the conclusions of this paper.

2 Parameters identification of SynRMs

In high-performance control of SynRM drives, the precise knowledge of motor parameters, including inductances and resistance, is highly advantageous. The accuracy of the parameters applied for control strategies is closely related to drive performance. For industrial applications, time spent on parameter identification results in loss of production. Hence, accurate and fast parameter identification and self-commissioning are essential for the industrial applications of SynRMs. Apart from the thermal influence, the stator resistance of SynRMs can be regarded as a constant value. For the inductances, the constant value cannot fully describe their characteristics. Inductances as a function of current or flux-current map models are mostly adopted and are more reliable to fit the magnetic characteristics of SynRMs well. Different aspects of parameter identification for SynRMs, adopted by various studies, will be discussed and reviewed in this section.

2.1 Finite element analysis (FEA) and analytical model methods

FEA is the basic method that can obtain the parameters based on the motor structure during the design process. The magnetic flux density distribution of a typical SynRM FEA model is shown in Fig. 1 [22]. However, the application of the FEA based method has some limitations since the detailed design data can only be accessed by the motor designer and producer, which are protected trade secrets and hinder the industrial applications of FEA based method.

The winding function is adopted in Refs. [6-7] to calculate the SynRMs inductances. The analytical model is a simpler way to compute the SynRMs parameters, which are then compared to the results obtained from the FEA in Ref. [8]. A combination of analytical equations and FEA is used for inductance identification for a machine model in terms of stator quantities in Ref. [23]. The numerical analysis tools give valuable initial information about machine parameters. However, the deviations from actual parameter values cannot be predicted and prevented as they depend on manufacturing tolerances and final material properties.

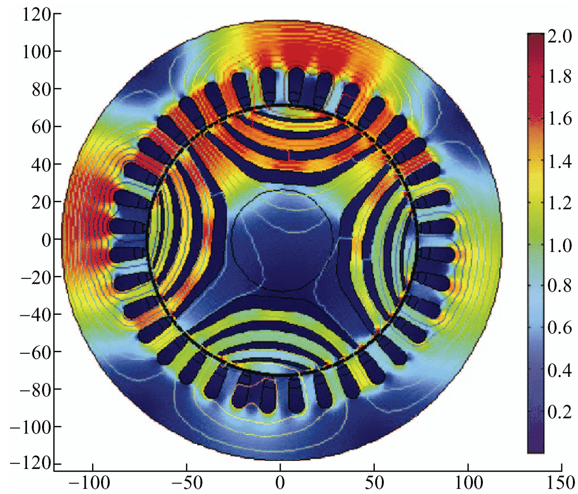


Fig. 1 Magnetic flux density distribution of a typical SynRM FEA model

2.2 Offline identification using signal injection and monitoring equipment

This type of identification method adopts different signals to excite the SynRMs and observe the response to estimate the parameters. A typical test bench for SynRMs parameter identification is shown in Fig. 2 [24].

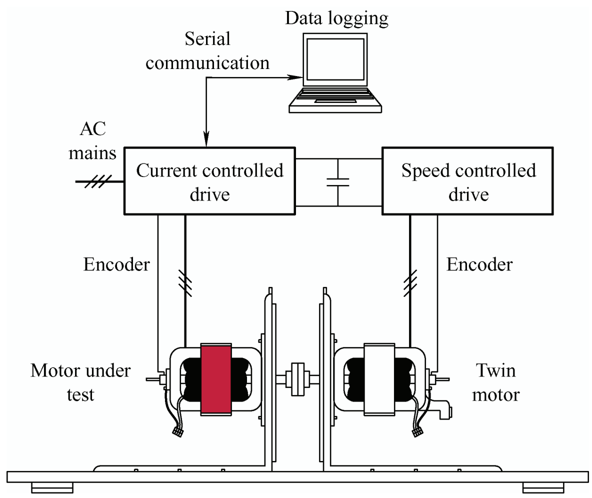


Fig. 2 Dedicated test bench diagram for SynRMs parameter identification

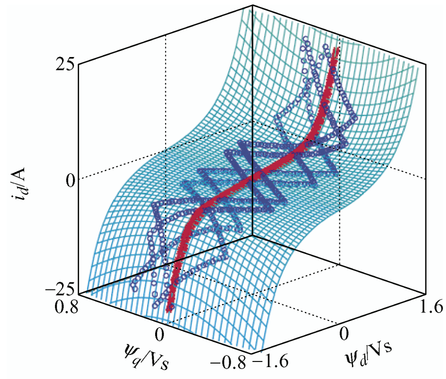
Since power converters are mostly applied to control SynRMs, the influence of space and time harmonics on machine parameters must be considered. A detailed review of the identification methods for the synchronous reactance of permanent magnet synchronous motor (PMSM) is presented in Ref. [9]. Most methods designed for PMSM parameter identification can also be applied to SynRMs, especially ones that work at standstill conditions. The sinusoidal supplybased methods and vector-controlled drive based methods are compared in Ref. [25]. The DC decay tests are performed to measure the SynRMs parameters. In Ref. [26], the authors proposed load tests for the machine and the acquired data are processed using linear regression and artificial intelligence-based techniques to obtain reliable estimates of the machine parameters. These methods are more suitable for laboratories where the equipment necessary for testing is available.

2.3 Identification based on power converters

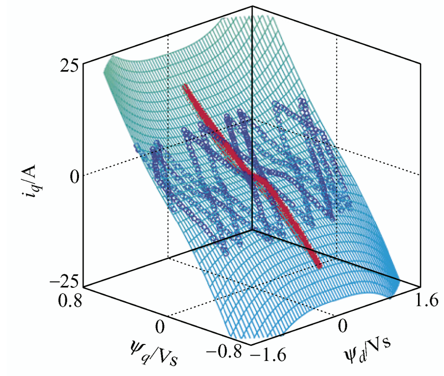
Power electronics converters are more competitive and practical for SynRM parameter identification. The precise rotor position information from the encoder or resolver makes it more competitive for improving identification accuracy. Similar to the methods introduced in the previous subsections, different signal patterns are generated using the converters and are applied to the SynRMs. Unlike the identification procedure for PMSMs, the current or voltage vector can be injected along both axes without locking rotor, since there is no additional torque produced due to the absence of permanent magnets. Since the cross-coupling effect is relatively severe for SynRMs, the injection of both d,q-axis current at the same time is necessary, and the rotor locking is acceptable to guarantee the stability of the rotor. The tested SynRMs should be characterized through the entire d,q-axes current plane to cover the saturation and cross-coupling region.

A typical current-flux model characteristic is shown in Fig. 3[27]. Both the positive and negative current along both axes are effected to emulate motoring and generating modes and lower the influence of the stator resistance thermal effect and inverter nonlinearity. To fit the multiple current-flux models, artificial intelligence methods are proposed in Ref. [28]. However, these kinds of methods require higher computation ability, which needs to record and process the data offline.

In Refs. [29-31], the principles are similar, with the rotor rigidly fixed or free to rotate, current or voltage signals are injected along each axis and then to both axes. The sampled voltage or current signals can then be processed to compute the SynRMs flux to fit the characteristic models. The typical parameter identification setup including injecting signals and monitoring responses is shown in Fig. 4 [27]. For some tests in these studies, the detachment of the load or additional rotor blocking is the principal limit of wide industrial applications.



(a) i_d



(b) i_q

Fig. 3 Currents as functions of the fluxes(the mesh surfaces correspond to the fitted model, and the stars and circles show the measured sample test)

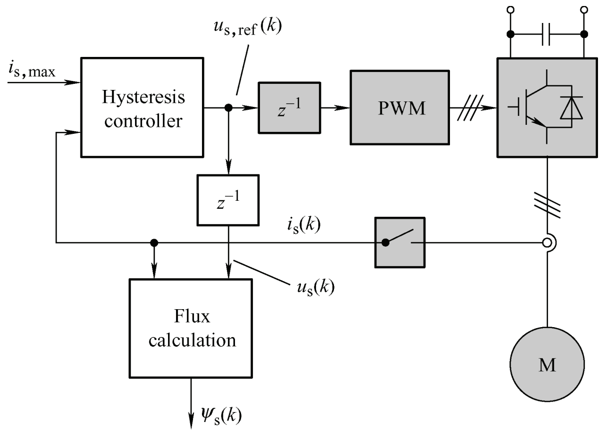


Fig. 4 Parameter identification setup with signal injection and flux calculation scheme

The intense requirement for research concerning self-commissioning is attracting increasing attention over the past several years. Self-commissioning has become an essential feature for modern electric drives used in general purpose applications. Several studies are focused on self-commissioning methods of SynRMs. Several methods use bipolar voltage steps as excitation signals. The stator flux linkage is estimated using the measured currents and the reference (or measured) voltage. In Refs. [30-33], the applied voltage steps are selected sufficiently low that the steady-state is achieved, making the flux computation highly sensitive to the stator resistance and inverter voltage. The higher the test voltage, the lower is the effect of the stator resistance and offset errors on the estimated flux. The method proposed in Ref. [34] uses bipolar voltage steps with a larger magnitude (up to the rated voltage) compared with the ones used in Refs. [30-33]. The whole range of currents is scanned during a single voltage step, and the steady-state is not reached. A piecewise mathematical function is fitted to the measured samples. Overall, the method in Ref. [34] works well for self-axis identification, but the number of parameters for the cross-coupling model makes the fitting process too tedious for practical applications. The test signals pattern in Ref. [34] and the fitted model of Ref. [35] are combined in Ref. [27] with consideration of the cross-coupling effect and the number of parameters needed to describe the cross-coupling effect is only one. For the algorithms proposed in Ref. [36], tens of parameters, as well as separate postprocessing and interpolation algorithms, would be needed. The relatively high test voltage makes the rotor almost still during the cross-coupling test. The results obtained using Ref. [27] are comparable to the ones obtained from the constant speed identification in Ref. [29]. To improve the accuracy of the method proposed in Ref. [27], the effects of the variation of stator resistance, inverter voltage distortion, iron losses, and undesired rotor movements are further investigated in Ref. [37]. The method is also combined with the high-frequency signal injection to cover a wider range of inspected currents in Ref. [38]. Even though the inspection area for the self- and cross-coupling tests was increased, it demonstrated that the observed flux characteristics maintained a constant state. The application of multiple self-commissioning methods is still limited for practical industrial applications owing to the relatively high requirement of processors. However, the increasing use of fast digital signal processors in modern variable speed drives will be an enabling factor for the application of these methods on a larger scale. In addition, online parameter identification methods of PMSMs have been reported in some studies. In addition, more investigation concerning SynRM online parameter identification is still required, it is an important developing trend for SynRM drive strategies.

3 Position sensorless control of SynRM drives

One of the most important advantages of SynRMs is low cost and robustness. Hence, position sensorless control of SynRMs is a further improvement to reduce cost, downsize the system volume and enhance the system reliability. Position sensorless control is driving increasing attention from academic to industrial applications. In this section, we compare and present major sensorless techniques for the entire speed range from low to high speed. There are mainly two categories of sensorless control methods: fundamental frequency model-based sensorless methods applied to the middle and high-speed range, and saliency-based sensorless control applied to the low-speed range. The model-based method is investigated and comercialized earlier. However, it may fail when the speed is too low owing to the low signal to noise ratio (SNR) caused by parameter inaccuracy and inverter nonlinearity. The saliency-based methods have recently been widely investigated to broaden the effective operational range of sensorless SynRMs drives. The common types of SynRMs sensorless control methods are listed as in Tab. 1.

Tab. 1 Summary of SynRMs sensorless control methods

Model-based	EEMF		
	DFO		
Saliency-based	Signal injection	Rotating injection	
		Pulsating injection	Sinusoidal signals
			Square-wave signals
	PWM based		
	Stator current variation based		

3.1 Fundamental-frequency model-based sensorless control methods

The model-based sensorless control methods are recommended once the operational speed is over a certain threshold value since there are no additional losses, torque ripples, and audible noise. The maximum output torque limit caused by the injected signals could be released. Mostly, the model-based sensorless methods of SynRMs is categorized into extended electromagnetic force (EEMF) based methods and direct flux observer (DFO) based methods.

3.1.1 EEMF model

The EEMF methods are based on the tracking of extended back EEMF since the rotor positional information is contained in the EEMF signals [10-14]. The rotor position can be directly calculated as

$$\theta_e = \arctan\left(\frac{e_\beta}{e_\alpha}\right) = \arctan\left(\frac{u_\alpha - R_s i_\alpha - L_d p i_\alpha + \omega_e (L_d - L_q) i_\beta}{u_\beta - R_s i_\beta - L_q p i_\beta - \omega_e (L_d - L_q) i_\alpha}\right) \tag{1}$$

where θ_e is the estimated rotor position, e_α, e_β, u_α, u_β, i_α and i_β are the EEMF, voltage, and current of the SynRM in an α,β-reference frame, respectively. R_s is the stator resistance, L_d and L_q are self-inductance in the d,q-axes reference frame. ω_e is the electrical speed of the SynRM. The EEMF method is based on voltage estimation that is more suitable for higher speeds. The influence of model uncertainty containing parameter uncertainty and measurement error on position estimation accuracy is analyzed in Ref. [39]. For the relatively severe nonlinearity of the SynRM, the magnetic saturation is investigated in Ref. [10]. The observer should ensure a stable and sufficiently fast estimation of error dynamics at different speeds and loads. A robust adaptive speed observer is designed for estimating the rotor position without voltage sensors [40]. The proposed observer structure could improve the robustness against parameter variation. The design method for the full order EEMF observer is analyzed in Ref. [41]. To reduce the observer complexity, a reduced-order position observer with stator resistance adaption is introduced in Ref. [42]. The effect of the observer gain on the noise reduction is studied using eigenvector analysis. Sliding mode observers are based on variable structure design with a sign function that is commonly applied for EEMF [43]. A Luenberger observer-based state-space model of the SynRM is presented with phase current and EEMF as states [44]. The effect of stator iron loss on position estimation using extended Kalman filter is investigated in Ref. [45].

3.1.2 DFO model

Similar to the EEMF methods introduced in the previous subsection, the flux linkage can be calculated based on the voltage integration, where the rotor position can be computed by the inverse tangent calculation of the flux linkage in the stationary reference frame [18,46-48]. The rotor position estimation based on DFO can be expressed as

$$\theta_e = \arctan\left(\frac{\psi_\beta}{\psi_\alpha}\right) = \arctan\left(\frac{\int (u_\beta - R_s i_\beta)\mathrm{d}t}{\int (u_\alpha - R_s i_\alpha)\mathrm{d}t}\right) \tag{2}$$

where ψ_α and ψ_β are the flux of the SynRM in an α,β-reference frame. The accuracy of the DFO method is less precise as compared to EEMF. The phase-locked loop (PLL) is found effective for many applications owing to its high precision, high reliability, low complexity, and low computational burden. PLL is adopted for flux position estimation in Ref. [49]. For specially designed SynRM windings with thermistor cablings as search coils for monitoring motor temperature, the position tracking performance is independent of the motor parameters [50]. The closed-loop flux observers adaptively combining the machine voltage and current models are commonly adopted. The DC drift and initial value problem associated with the pure integrator used in the observer can be addressed. The solution to damp DC offsets caused oscillation was illustrated in Ref. [51]. Similar to the methods based on EEMF, the sensitivity of the estimation accuracy on motor model uncertainty is analyzed in Ref. [39]. The system mismatch, including resistance, inductance, voltage, and current measurement, could deteriorate estimation performance to some extent. An online tracking algorithm can improve the DFO based method estimation performance.

3.2 Saliency-based sensorless control methods

Estimation methods relying on the model of SynRMs fail to estimate the position at lower speeds. As the SynRMs are inherently salient, methods estimating the position, even at standstill condition, are readily applicable. These methods can be roughly categorized as signal injection methods [15-21], modified PWM based methods [52-53], and methods based on stator current variation without additional signal [11,54-56]. Signal injection-based sensorless control methods are based on the principle of tracking the saliency of the SynRMs that are effective in the zero and low-speed region of sensorless control operation [57-61]. The signal injection-based sensorless control methods can be categorized into rotating and pulsating signal injection based on the injection pattern. The pulsating signals can be either sinusoidal or square-wave signals. The SynRMs high frequency (HF) models in the low-speed region can be expressed in the rotor or stator reference frame as

$$\begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix} = \begin{bmatrix} L_{dh} & 0 \\ 0 & L_{qh} \end{bmatrix} p \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} u_{\alpha h} \\ u_{\beta h} \end{bmatrix} = \begin{bmatrix} L_1 + L_2\cos(2\theta_e) & L_2\sin(2\theta_e) \\ L_2\sin(2\theta_e) & L_1 - L_2\cos(2\theta_e) \end{bmatrix} p \begin{bmatrix} i_{\alpha h} \\ i_{\beta h} \end{bmatrix} \tag{4}$$

where the subscript h indicates the HF components, L_{dh} and L_{qh} are the d,q-axes incremental self-inductances, $L_1 = (L_{dh} + L_{qh})/2$, $L_2 = (L_{dh} - L_{qh})/2$. The most applied signal injection-based sensorless control scheme is as shown in Fig. 5. The pulsating signal injection and rotating signal injection are injected into d,q-axes and α,β-axes reference frame, respectively.

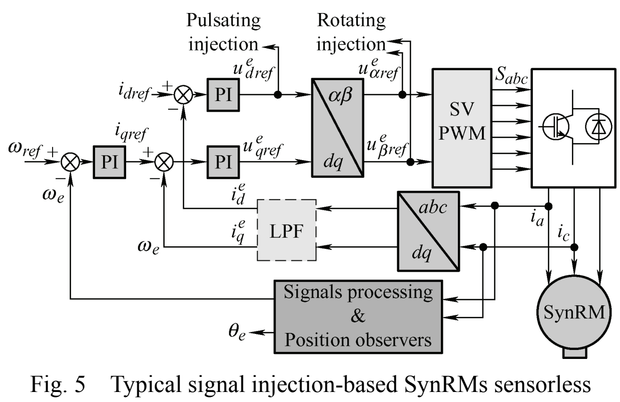


Fig. 5 Typical signal injection-based SynRMs sensorless control methods

The saliency-based sensorless control methods of SynRMs are similar to those applied to interior PMSMs (IPMSMs). The main principle is tracking the saliency of the rotor according to the induced current HF components by injecting different patterns of signals [62]. The critical parameters in the injection mechanism are analyzed in Ref. [63]. The saliency-based sensorless control methods applied for IPMSM has been well-reviewed and concluded in Ref. [62]. Hence, this paper focuses on the unique characteristics of SynRMs such as relatively severe nonlinearity and cross-coupling effects that need to be noted explicitly during the injection design procedure.

3.2.1 Parameter nonlinearity of SynRMs

The parameters of SynRMs show evident nonlinearity, as illustrated in Section 2. The d-axis flux component saturates severely as a function of the corresponding current component, and the d-axis saturation is coupled with the q-axis saturation. There are saturation dependent estimation errors of anisotropy based sensorless control algorithms [64].

A new position sensorless control method for SynRMs involving the superimposing of a HF current using a HF current control system is proposed in Ref. [65]. The amplitude of the superimposed HF current can be controlled within the range of a small constant value with the proposed method, which can improve the robustness of the parameter variation. The HF test voltage and HF test current injection methods are compared in Ref. [66]. The adopted 2DoF current control and adaptive tracking controllers in the paper can lower the effect of parameter nonlinearity to a certain extent. It is proved that the HF test current and HF test voltage injection achieved quite a similar behavior and need nearly the same implementation effort. The parameter adaption laws are proposed in Ref. [67], where stator resistance, d-axis inductance and q-axis inductance adaption algorithms could be respectively applied according to different speed and load conditions. In Ref. [68], it is shown how saturation effects could be readily alleviated by using a digitally implemented quadrature PLL observer, together with linear regression, so that easy digital implementation, stable operation, and null parametric dependence can be achieved.

3.2.2 Cross-coupling effect of SynRMs

For the SynRMs sensorless control based on HF signal injection, when the cross-coupling effect is neglected as in the case of IPMSMs, there will be a persistent estimation error that can be expressed as

$$\theta_{err} = \frac{\arctan[2L_{dqh} / (L_{qh} - L_{dh})]}{2} \tag{5}$$

where L_{dqh} is the cross-coupling mutual inductance. The position estimation error caused by the cross-coupling effect is analyzed in Ref. [69] as shown in Fig. 6. This error deteriorates the performance of the sensorless drive when the estimated position is used instead of the actual one.

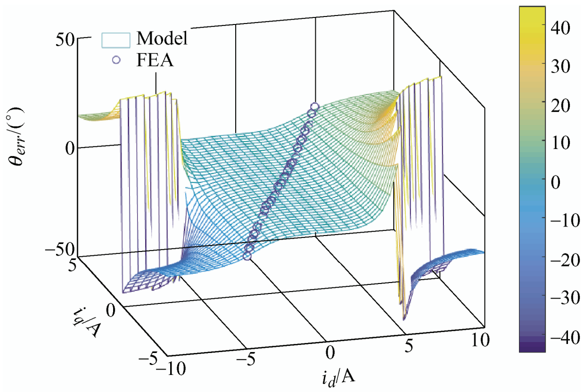


Fig. 6 Rotor position estimation error caused by the cross-coupling effect

Normally, the estimation error caused by the cross-coupling effect can be simply compensated based on the FEA results or offline measurement using a lookup table (LUT) [66,70]. However, the uncertainty and inaccuracy of the test results and disturbance may further worsen drive performance. The impact of the position error as a function of the working point and the technique to minimize the influence is introduced in Refs. [71-72]. Stable operation of the SynRMs with a load at a very low speed can be guaranteed. In Ref. [69] and Ref. [73], a cross-coupling factor is proposed to combine both d,q-axes current HF component information to extract the rotor position in the measured reference frame. The measured reference frame is defined to lag the estimated reference frame by 45 degrees, where the current signals containing position information can be maximized. In addition, the injected signals were set to be discontinuous, which can suppress voltage errors and improve the stability of the estimation. However, the dynamic performance of the proposed method is lower owing to the delay of FOC commands. Instead of the commonly used current demodulation, the position error feedback was extracted at the output of the observer's flux maps in Ref. [74], which resulted in immunity toward the cross-coupling effect caused position error.

4 Future trends of SynRMs drives

The SynRMs are promising alternative candidates for industrial applications. To further improve the competitiveness of this type of machine, there are several aspects concerning drive technologies that can be further investigated and developed.

(1) Low cost but also effective inverters should be developed for applications to maximize the low-cost advantages of SynRMs. The corresponding control methods that need less digital calculation and signal processing should be investigated as well.

(2) Online parameter identification and observer self-adaption tuning are the future developing trends since the accuracy of identified parameters, and flux-current models of SynRMs are fundamental to multiple advanced control strategies.

(3) The position estimation for sensorless control of SynRMs needs to be further improved and consummated using adaptive and artificial intelligence methods to increase the robustness concerning parameter nonlinearity and uncertainty. Furthermore, the problem of intrusive noise caused by widely used HF injection-based methods should be ameliorated.

(4) The efficiency/torque optimized control strategies need further investigation. The transition performance of online searching based methods is supposed to be improved. The methods to obtain more precise equivalent circuit models of SynRMs demand prompt solutions.

(5) Another obstacle to the promotion of SynRMs is the torque ripple. At present, most efforts to lower torque ripple that have been made are focused on designing procedure. The ripple suppressing from the control side should be investigated.

5 Conclusions

SynRMs have drawn increasing attention in recent years with the development of technologies. With lower cost, simpler rotor structure, and competitive performance versus IMs and PMSMs, SynRMs are promising and could be widely applied in domestic and industrial applications. State-of-the-art SynRMs drive strategies covering parameter identification and sensorless control were discussed. The advantages and disadvantages of various approaches were concluded and compared. Finally, the authors provided some advice concerning future research trends and interests for reference.

References

[1] J K Kostko. Polyphase reaction synchronous motors. *Journal of the American Institute of Electrical Engineers*, 1923, 42(11): 1162-1168.

[2] P R Ghosh, A Das, G Bhuvaneswari. Performance comparison of different vector control approaches for a synchronous reluctance motor drive. *International Conference on Computer Applications In Electrical Engineering-Recent Advances*, October 5-7, 2017, Roorkee, India. New York: IEEE, 2018: 320-325.

[3] C Li, D Xu, G Wang. High efficiency remanufacturing of induction motors with interior permanent magnet rotors and synchronous reluctance rotors. *IEEE Transportation Electrification Conference and Expo*, *Asia-Pacific*, August 7-10, 2017, Harbin, China. New York: IEEE, 2017: 1332-1337.

[4] C Oprea, A Dziechciarz, C Martis. Comparative analysis of different synchronous reluctance motor topologies. *International Conference on Environment and Electrical Engineering*, June 10-13, 2015, Rome, Italy. New York: IEEE, 2015: 1904-1909.

[5] S Talebi, P Niazi, H A Toliyat. Design of permanent magnet assisted synchronous reluctance motors made easy. *Annual Meeting of the IEEE Industry Applications Society*, September 23-27, 2007, New Orleans, LA, USA. New York: IEEE, 2007: 2242-2247.

[6] E S Obe. Direct computation of AC machine inductances based on winding function theory. *Energy Conversion & Management*, 2012, 50(3): 539-542.

[7] E S Obe. Calculation of inductances and torque of an axially laminated synchronous reluctance motor. *IET Electr*. *Power Appl*., 2010, 4(9): 783-792.

[8] T Lubin, T Hamiti, H Razik, et al. Comparison between finite-element analysis and winding function theory for inductances and torque calculation of a synchronous reluctance machine. *IEEE Trans*. *Magn*., 2007, 43(8): 3406-3410.

[9] Y Gao, R Qu, C Yu, et al. Review of off line synchronous inductance measurement method for permanent magnet synchronous machines. *IEEE Transportation Electrification Conference and Expo*, *Asia-Pacific*, August 31-September 3, 2014, Beijing, China. New York: IEEE, 2014.

[10] S Ichikawa, M Tomita, S Doki, et al. Sensorless control of synchronous reluctance motors based on extended emf models considering magnetic saturation with online parameter identification. *IEEE Trans*. *Ind*. *Appl*., 2006, 42(5): 1264-1274.

[11] M Hofer, M Nikowitz, M Schroedl. Application of a position sensorless control to a reluctance synchronous drive including flux weakening. *International Exhibition and Conference for Power Electronics*, *Intelligent Motion*, *Renewable Energy and Energy Management*, May 16-18, 2017, Nureberg, German. New York: IEEE, 2017: 631-635.

[12] H Marko, S S Erkki, A H A Ali, et al. Observers for sensorless synchronous motor drives: Framework for design and analysis. *IEEE Trans*. *Ind*. *Appl*., 2018, 54(6): 6090-6100.

[13] A Iwata, S Ichikawa, M Tomita, et al. Position and velocity sensorless control of SynRMs using online parameter identification. *Annual Conference of the IEEE Industrial Electronics-Society*, November 2-6, 2003, Roanoke, VA, USA. New York: IEEE, 2003: 2156-2161.

[14] S Ichikawa, M Tomitat, S Doki, et al. Sensorless control of synchronous reluctance motors based on an extended EMF model and initial position estimation. *Annual Conference of the IEEE Industrial Electronics Society*, November 2-6, 2003, Roanoke, VA. New York: IEEE, 2003: 2150-2155.

[15] S C Agarlita, I Boldea, F Blaabjerg. High frequency injection assisted “active flux” based sensorless vector control of reluctance synchronous motors, with experiments from zero speed. *IEEE Trans*. *Ind*. *Appl*., 2012, 48(6): 1931-1939.

[16] A Consoli, F Russo, G Scarcella, et al. Low- and zero-speed sensorless control of synchronous reluctance motors. *IEEE Trans*. *Ind*. *Appl*., 1999, 35(5): 1050-1057.

[17] H W D Kock, M J Kamper, O C Ferreira, et al. Position sensorless control of the reluctance synchronous machine considering high frequency inductances. *Power Electronics and Drive Systems*, November 27-30, 2007, Bangkok Thailand. New York: IEEE, 2007: 1017-1021.

[18] J I Ha, S J Kang, S K Sul. Position controlled synchronous reluctance motor without rotational transducer. *IEEE Trans*. *Ind*. *Appl*., 1999, 35(6): 1393-1398.

[19] E Capecchi, P Guglielmi, M Pastorelli, et al. Position sensorless control of the transverse laminated synchronous reluctance motor. *IEEE Trans*. *Ind*. *Appl*., 2001, 37(6): 1770-1776.

[20] T H Liu, H S Haslim, S K Tseng. Predictive controller design for a high frequency injection sensorless synchronous reluctance drive system. *IET Electr*. *Power Appl*., 2016, 11(5): 902-910.

[21] U K Madawala, T H Liu, P C Pan. Adaptive controller with an improved highfrequency injection technique for sensorless synchronous reluctance drive systems. *IET Electr*. *Power Appl*., 2016, 10(4): 240-250.

[22] V Mukherjee, J Pippuri, S E Saarakkala, et al. Finite element analysis for bearingless operation of a multi flux barrier synchronous reluctance motor. *International Conference on Electrical Machines and Systems*, October 25-28, 2015, Pattaya, Thailand. New York: IEEE, 2015: 688-691.

[23] E S Obe, A Binder. Direct phase variable model of a synchronous reluctance motor including all slot and winding harmonics. *Energy Conversion & Management*, 2011, 52(1): 284-291.

[24] S A Odhano, P Pescetto, H A A Awan, et al. Parameter identification and self-commissioning in AC motor drives: A technology status review. *IEEE Trans*. *Power Electron*., 2019, 34(4): 3603-3614.

[25] R Dutta, M F Rahman. A comparative analysis of two test methods of measuring d- and q-axes inductances of interior permanent magnet machine. *IEEE Trans*. *Magn*., 2006, 42(11): 3712-3718.

[26] M A Jabbar, J Dong, Z Liu. Determination of parameters for internal permanent magnet synchronous motors. *IEEE International Conference on Electric Machines and Drives*, May 15, 2005, San Antonio, TX, USA. New York: IEEE, 2005: 149-156.

[27] M Hinkkanen, P Pescetto, E Molsa, et al. Sensorless self-commissioning of synchronous reluctance motors at standstill without rotor locking. *IEEE Trans*. *Ind*. *Appl*., 2017, 53(3): 2120-2129.

[28] L Kan, J Feng, S Guo, et al. Identification of flux linkage map of permanent magnet synchronous machines under uncertain circuit resistance and inverter nonlinearity. *IEEE Transactions on Industrial Informatics*, 2018, 14(2): 556-568.

[29] G Pellegrino, B Boazzo, T M Jahns. Magnetic model self-identification for PM synchronous machine drives. *IEEE Trans*. *Ind*. *Appl*., 2015, 51(3): 2246-2254.

[30] E Armando, R I Bojoi, P Guglielmi, et al. Experimental identification of the magnetic model of synchronous machines. *IEEE Trans*. *Ind*. *Appl*., 2013, 49(5): 2116-2125.

[31] B Stumberger, G Stumberger, D Dolinar, et al. Evaluation of saturation and cross magnetization effects in interior permanent magnet synchronous motor. *IEEE Trans*. *Ind*. *Appl*., 2003, 39(5): 1264-1271.

[32] G Stumberger, T Marcic, B Stumberger, et al. Experimental method for determining magnetically nonlinear characteristics of electric machines with magnetically nonlinear and anisotropic iron core, damping windings, and permanent magnets. *IEEE Trans*. *Magn*., 2008, 44(11): 4341-4344.

[33] G Zanuso, P Sandulescu, L Peretti. Self-commissioning of flux linkage curves of synchronous reluctance machines in quasi standstill condition. *Electric Power Applications Iet*, 2015, 9(9): 642-651.

[34] N Bedetti, S Calligaro, R Petrella. Stand still self-identification of flux characteristics for synchronous reluctance machines using novel saturation approximating function and multiple linear regression. *IEEE Trans*. *Ind*. *Appl*., 2016, 52(4): 3083-3092.

[35] Z Qu, T Tuovinen, M Hinkkanen. Inclusion of magnetic saturation in dynamic models of synchronous reluctance motors. *International Conference on Electrical Machines*, September 2-5, 2012, Marseille, France. New York: IEEE, 2012: 994-1000.

[36] G Stumberger, T Marcic, B Stumberger, et al. Experimental method for determining magnetically nonlinear characteristics of electric machines with magnetically nonlinear and anisotropic iron core, damping windings, and permanent magnets. *IEEE Trans*. *Magn*., 2008, 44(11): 4341-4344.

[37] P Pescetto, G Pellegrino. Sensorless standstill commissioning of synchronous reluctance machines with automatic tuning. *IEEE International Electric Machines and Drives Conference*, May 21-24, 2017, Miami, FL, USA. New York: IEEE, 2017:1-8.

[38] P Pescetto, G Pellegrino. Sensorless commissioning of synchronous reluctance machines augmented with high frequency voltage injection. *IEEE Energy Conversion Congress and Exposition*, October 1-5, 2017, Cincinnati,

OH, USA. New York: IEEE, 2017: 1909-1916.

[39] S Bolognani, L Ortombina, F Tinazzi, et al. Model sensitivity of fundamental-frequency based position estimators for sensorless PM and reluctance synchronous motor drives. *IEEE Trans. Ind. Electron.*, 2018, 65(1): 77-85.

[40] M Amin, G A A Aziz, J Durkin, et al. A hardware-in-the-loop realization of speed sensorless control of pma-synrm with steady-state and transient performances enhancement. *IEEE Trans. Ind. Appl.*, 2019, 55(5): 5331-5342.

[41] S Nohara, M Tomita, M Hasegawa, et al. A new design method of full-order extended electromotive force observer for position sensorless control of IPMSM. *39th Annual Conference of the IEEE Industrial Electronics Society*, November 10-14, 2013, Vienna, Austria. New York: IEEE, 2013: 2512-2517.

[42] T Tuovinen, M Hinkkanen, J Luomi. Analysis and design of a position observer with resistance adaptation for synchronous reluctance motor drives. *IEEE Trans. Ind. Appl.*, 2013, 49(1): 66-73.

[43] A K Chakali, H A Toliyat, H Abu-Rub. Observer-based sensorless speed control of PM-assisted SynRM for direct drive applications. *IEEE International Symposium on Industrial Electronics*, July 4-7, 2010, Bari, Italy. New York: IEEE, 2010: 3095-3100.

[44] F P Scalcon, C J Volpato, T Lazzari, et al. Sensorless control of a SynRM drive based on a Luenberger observer with an extended EMF model. *45th Annual Conference of the IEEE Industrial Electronics Society*, October 14-17, 2019, Lisbon, Portugal. New York: IEEE, 2019: 1333-1338.

[45] T Senjyu, K Kinjo, N Urasaki, et al. Sensorless control of synchronous reluctance motors considering the stator iron loss with extended Kalman filter. *Power Electronics Specialist Conference*, June 15-19, 2003, Acapulco, Mexico. New York: IEEE, 2003: 403-408.

[46] P Sun, D Zhang, Z Bai, et al. Comparison study of MRAS and EEMF-based sensorless control for synchronous reluctance motor. *International Conference on Electrical Machines and Systems*, August 11-14, 2019, Harbin, China. New York: IEEE, 2019: 331-335.

[47] X Dianguo, J Xinhai, C Wei. Sensorless control of synchronous reluctance motors. *IEEE Transportation Electrification Conference and Expo, Asia-Pacific*, August 7-10, 2017, Harbin, China. New York: IEEE, 2017: 431-434.

[48] T Hanamoto, A Ghaderi, M Harada, et al. Sensorless speed control of synchronous reluctance motor using a novel flux estimator based on recursive Fourier transformation. *IEEE International Conference on Industrial Technology*, Febrary 10-13, 2009, Churchill, Australia. New York: IEEE, 2009: 261-266.

[49] I Isakov, V Popović, I Todorović, et al. Application of phase-locked loop in sensorless SynRM drives. *International Symposium on Industrial Electronics* (*INDEL*), November 1-3, 2018, Banja Luka, Bosinia&Herceg. New York: IEEE, 2018: 361-364.

[50] L D Tornello, G Scelba, G Scarcella, et al. Combined rotor position estimation and temperature monitoring in sensorless synchronous reluctance motor drives. *IEEE Trans. Ind. Appl.*, 2019, 55(4): 3851-3862.

[51] D Wang, L Kaiyuan, R P Omand. Improved closed-loop flux observer based sensorless control against system oscillation for synchronous reluctance machine drives. *IEEE Trans. Power Electron.*, 2019, 34(5): 4593-4602.

[52] M Schroedl, P Weinmeier. Sensorless control of reluctance machines at arbitrary operating conditions including standstill. *IEEE Trans. Power Electron.*, 1994, 9(2): 225-231.

[53] R Morales-Caporal, M Pacas. Encoderless predictive direct torque control for synchronous reluctance machines at very low and zero speed. *IEEE Trans. Ind. Electron.*, 2008, 55(12): 4408-4416.

[54] M Y Wei, T H Liu. A high performance sensorless position control system of a synchronous reluctance motor using dual current-slope estimating technique. *IEEE Trans. Ind. Electron.*, 2012, 59(9): 3411-3426.

[55] T Matsuo, T A Lipo. Rotor position detection scheme for synchronous reluctance motor based on current measurements. *IEEE Trans. Ind. Appl.*, 1995, 31(4): 860-868.

[56] M Wei, T Liu. A high performance sensorless position control system of a synchronous reluctance motor using dual current-slope estimating technique. *IEEE Trans. Ind. Electron.*, 2012, 59(9): 3411-3426.

[57] M Tamaoki, M Tomita, Z Chen, et al. Position and velocity control of sensorless synchronous reluctance motor using disturbance observer based on high frequency current. *Power Conversion Conference*, April 2-5, 2002, Osaka, Japan. New York: IEEE, 2002: 695-698.

[58] S Kondo, Y Sato, T Goto, et al. Position and velocity sensorless control for synchronous reluctance motor at low speeds and under loaded conditions using high

frequency extended EMF observer and heterodyne detection. *International Conference on Electrical Machines*, September 2-5, 2014, Berlin, Germany. New York: IEEE, 2014: 857-863.

[59] K Kato, M Tomita, S Doki, et al. Position estimation for sensorless control of synchronous reluctance motor at low speed using disturbance observer. *International Conference on Electrical Machines and Systems*, October 10-13, 2010, Incheon, South Korea. New York: IEEE, 2010: 716-720.

[60] K Kawai, M Tomita, S Ichikawa, et al. Position estimation of synchronous reluctance motor at standstill using disturbance observer. *30th Annual Conference of IEEE Industrial Electronics Society*, November 2-6, 2004, Busan, South Korea. New York: IEEE, 2004: 2874-2878.

[61] T Mabuchi, A Makimura, M Tomita, et al. Position sensorless control of synchronous reluctance motors at very low speeds region using high frequency current control system. *International Conference on Electrical Machines and Systems*, August 11-14, 2017, Sydney, Australia. New York: IEEE, 2017: 641-646.

[62] G Wang, M I Valla, J A Solsona. Position sensorless permanent magnet synchronous machine drives: A review. *IEEE Trans*. *Ind*. *Electron*., 2019, DOI: 10.1109/TIE. 2019.2955409.

[63] S Shih-Wei, K Hu, C Liaw, et al. Development of a position sensorless synchronous reluctance motor drive. *IEEE 3rd International Future Energy Electronics Conference and ECCE Asia*, June 3-7, 2017, Kaohsiung, Taiwan, China. New York: IEEE, 2017: 1199-1204.

[64] S Kuehl, P Landsmann, R M Kennel. Compensating angle estimation errors caused by magnetic saturation in anisotropy-based sensorless control schemes. *Sensorless Control for Electrical Drives*, September 21-22, 2013, Milwaukee, WI, USA. New York: IEEE, 2013: 1-6.

[65] T Hatanaka, T Mabuchi, M Tomita, et al. Robust position sensorless control against inductance variations of synchronous reluctance motors in low speed region using high frequency current control. *International Conference on Electrical Machines*, September 3-6, 2018, Alexandroupoli, Greece. New York: IEEE, 2018: 1677-1683.

[66] M Bugsch, A Held, B Piepenbreier. Sensorless control of SynRMs using an adaptive 2DoF current control including a comparison of two alternating HF signal injection-based methods. *42nd Annual Conference of the IEEE Industrial Electronics Society*, October 23-26, 2016, Florence, Italy. New York: IEEE, 2016: 2910-2916.

[67] T Tuovinen, M Hinkkanen. Signal-injection-assisted full-order observer with parameter adaptation for synchronous reluctance motor drives. *IEEE Trans*. *Ind*. *Appl*., 2014, 50(5): 3392-3402.

[68] R Morales-Caporal, M Pacas. Suppression of saturation effects in a sensorless predictive controlled synchronous reluctance machine based on voltage space phasor injections. *IEEE Trans*. *Ind*. *Electron*., 2011, 58(7): 2809-2817.

[69] C Li, G Wang, G Zhang, et al. Saliency-based sensorless control for SynRM drives with suppression of position estimation error. *IEEE Trans*. *Ind*. *Electron*., 2019, 66(8): 5839-5849.

[70] T Tuovinen, M Hinkkanen. Adaptive full-order observer with high frequency signal injection for synchronous reluctance motor drives. *IEEE J*. *Emerg*. *Sel*. *Topics Power Electron*., 2014, 2(2): 181-189.

[71] P Guglielmi, M Pastorelli, A Vagati. Impact of cross saturation in sensorless control of transverse laminated synchronous reluctance motors. *IEEE Trans*. *Ind*. *Electron*., 2006, 53(2): 429-439.

[72] C Li, G Wang, G Zhang, et al. High frequency torque ripple suppression for high frequency signal injection based sensorless control of SynRMs. *IEEE Applied Power Electronics Conference and Exposition* (*APEC*), March 17-21, 2019, Anaheim, CA, USA. New York: IEEE, 2019: 2544-2548.

[73] C Li, G Wang, G Zhang, et al. Eliminating position estimation error caused by cross-coupling effect in saliency-based sensorless control of SynRMs. *21st International Conference on Electrical Machines and Systems*, October 5-8, 2018, Jeju, South Korea. New York: IEEE, 2018: 1600-1605.

[74] A Yousefi-Talouki, P Pescetto, G Pellegrino. Sensorless direct flux vector control of synchronous reluctance motors including standstill, MTPA, and flux weakening. *IEEE Trans*. *Ind*. *Appl*., 2017, 53(4): 3598-3608.

Chengrui Li received his B.S. in electrical engineering from Harbin Institute of Technology, Harbin, China, in 2015, where he is currently working towards his Ph.D. in power electronics and electrical drives in the School of Electrical Engineering and Automation.

His current research interests include parameter identification techniques, and control

of electrical drives, with a focus on sensorless field-oriented control of synchronous reluctance machines and synchronous reluctance machine design.

Gaolin Wang received his B.S., M.S., and Ph.D. in electrical engineering from Harbin Institute of Technology, Harbin, China, in 2002, 2004, and 2008, respectively.

In 2009, he joined the Department of Electrical Engineering, Harbin Institute of Technology as a Lecturer, where he has been a Professor of Electrical Engineering since 2014. From 2009 to 2012, he was a Postdoctoral Fellow at the Shanghai STEP Electric Corporation, where he was involved in traction machine control for direct-drive elevators. He has authored more than 60 technical papers published in journals and conference proceedings. He is also the holder of 10 Chinese patents. His current primary research interests include permanent magnet synchronous motor drives, high-performance direct-drives for traction systems, position sensorless control of AC motors, efficiency optimization control of interior PMSM, and digital control of power converters.

Dr. Wang serves as an Associate Editor of IET Electric Power Applications, and Journal of Power Electronics. He received the Outstanding Research Award and the Delta Young Scholar Award from the Delta Environmental and Educational Foundation in 2012 and 2014, respectively. He is currently supported by the National Natural Science of China for Excellent Young Scholars, the Program for Basic Research Excellent Talents, and the Young Talent Program from Harbin Institute of Technology.

Guoqiang Zhang received his B.S. degree in electrical engineering from Harbin Engineering University, Harbin, China, in 2011, and M.S. and Ph.D. in electrical engineering from Harbin Institute of Technology, Harbin, China, in 2013 and 2017, respectively.

Since then, he has been a Postdoctoral Fellow and a Lecturer in the Department of Electrical Engineering, Harbin Institute of Technology. His current research interests include parameter identification techniques, and control of electrical drives, with a focus on sensorless field-oriented control of interior permanent magnet synchronous machines.

Dr. Zhang serves as an Associate Editor for the Journal of Power Electronics.

Nannan Zhao received his B.S. and M.S. in control science and engineering in 2013 and 2015, respectively, and his Ph.D. in electrical engineering in 2019, all from Harbin Institute of Technology. Currently, he is a Postdoctoral Fellow and a Lecturer in the School of Electrical Engineering and Automation, Harbin Institute of Technology. He is currently supported by the Postdoctoral Innovative Talent Support Program of China. His current research interests include advanced control of permanent magnet synchronous motor drives and sensorless position control of AC motors.

Dianguo Xu received his B.S. in control engineering from Harbin Engineering University, Harbin, China, in 1982, and M.S. and Ph.D. in electrical engineering from Harbin Institute of Technology (HIT), Harbin, China, in 1984 and 1989, respectively.

In 1984, he joined the Department of Electrical Engineering, HIT, as an assistant professor. Since 1994, he has been a professor in the Department of Electrical Engineering, HIT. He was the Dean of the School of Electrical Engineering and Automation, HIT from 2000 to 2010, and was the Assistant President of HIT from 2010 to 2014. He is now the Vice President of HIT. His research interests include renewable energy generation technologies, power quality mitigation, sensorless vector controlled motor drives, high-performance servo systems. He has published over 600 technical papers.

Dr. Xu is a Fellow of IEEE, an Associate Editor of the IEEE Transactions on Industrial Electronics and IEEE Transactions on Power Electronics, and the IEEE Journal of Emerging and Selected Topics in Power Electronics. He serves as the Chairman of the IEEE Harbin Section.