Sensorless Position Control and Speed Estimation Techniques of Permanent Magnet Synchronous Motors

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ABSTRACT

This research article presents a review regarding the various techniques used for sensorless position and speed of estimation of permanent magnet synchronous motor drives. Permanent-magnet synchronous machines (PMSMs) are widely used in high performance applications because of their compact size, high-power density, high efficiency, free maintenance etc. Mechanical sensors are normally required for speed control of PMSM in sensing rotor position and speed to achieve drive system. However, these sensors increases the overall system cost, size, weight, and wiring complexity thereby reducing the mechanical robustness and the reliability of the overall PMSM drive systems. Sensorless drives are becoming more and more important as they can eliminate speed sensors maintaining accurate response; hence sensoreless methods have gained much attention. This paper presents different sensorless position and speed estimation techniques of PMSM motor drives system and their corresponding advantages and disadvantages are described.

KEYWORDS
PMSM,
Field Oriented Control,
High frequency signal injection,
Sensorless

1. Introduction

Permanent Magnet Synchronous Motors (PMSM) are widely used in high performance applications such as industrial robots, submarine propulsion, electric vehicle, home appliances, electric-drive vehicle systems, wind energy conversion systems and machine tools due to their compact size, high-power density, high air-gap flux density, high-torque/inertia ratio, high torque capability, high efficiency, ease of control and free maintenance [1-2]. Speed control of PMSM usually requires the mechanical sensor for sensing rotor position and speed to achieve the drive system. Therefore it is of great significance importance to investigate the dynamic control methods of this kind of drives system. Sensorless drives are becoming more and more important as they can eliminate speed sensors maintaining accurate response [3]. However, position sensors such as resolvers, optical encoders, and Hall Effect sensors, are commonly used to obtain rotor position/speed in PMSM drives. The use of these sensors is undesirable in a drive because it increases the cost, size, weight, hardware wiring complexity of drive systems and reliability problem, besides the need for a shaft extension and mounting arrangement. In order to overcome all these drawbacks of using position sensors, much research effort has gone into the development of sensorless drives that have comparable dynamic performance with respect to the sensor-based drives during the last decades [4-5]. It is possible to estimate the position from machine terminal voltages and currents with the help of an intelligent controller.

The advances in microprocessor and power electronics gives permission to implement modern techniques for PMSM machines such as field oriented control also known as vector control. This provides higher efficiency; lower operating costs and reduces the cost of drive components. In sensorless field oriented control, some internal states of dynamic system are available, measured or estimated but the output measurements are however unknown. In PMSM, outputs such speed and position are the principal control variables, and are not measured directly; their values are estimated using other parameters such as phase voltages and current, that is measured directly. In the last decade, many researches have been carried on the design of sensorless control schemes of the PMSM Motor. In [6] the authors gave a detail review of prior work in the field of control of PMSM drive, especially techniques using the stator voltages or currents and flux- or back-EMF based position estimators has been presented.

2. Classification of Permanent Magnet Synchronous Machines

A simple classification can be seen in Figure 1. PM machines can be divided in two groups: AC and DC machines. The only difference between Permanent Magnet DC (PMDC) and conventional DC machines is the use of permanent magnets in the place of field windings.

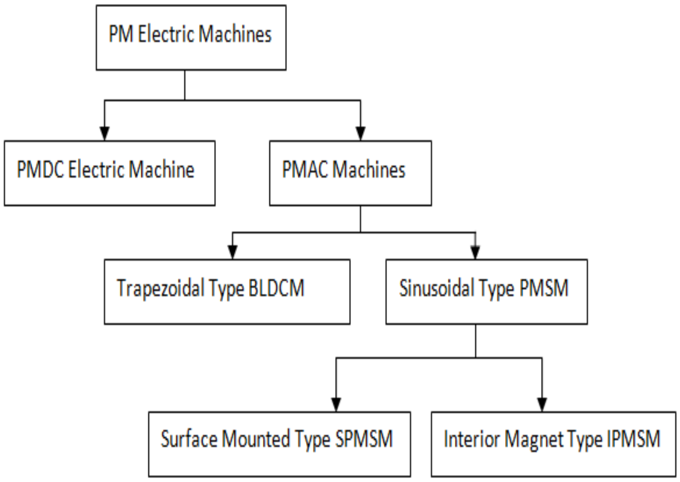

Fig. 1. Classification of Permanent Magnet Synchronous Machine [7].

The Permanent Magnet AC (PMAC) is very simple since the comutator and brushes don't exist. The field is generated by the magnets placed in the rotor. The PMAC machines are grouped in trapezoidal and sinusoidal type. They are called like this in function of the back-EMF voltage waveform induced in each stator phase [7]. In function on how the magnets are placed in the rotor, two main types can be distinguished: (i) surface magnet type (SPM) (ii) Interior magnet type (IPM).

2.1. The Surface-Magnet Synchronous Motor

The surface-magnet motor comes with the rotor magnets glued onto the surface of the rotor. The relative permeability of the magnetic material is very close to unity and thus the magnets have high reluctance and accordingly the SPM motor can be considered to have a large and uniform effective air gap. The surface mounted permanent magnet is a non-salient machine since the permeability of the magnet material is similar with air permeability. This property makes the saliency effect negligible. Consequently, the synchronous inductances along the rotor d- and q-axes, as indicated in Figure 2(a) are equal and small(i.e. Ld= Lq= La). The armature reaction in this type of motor is small [8].

2.2. Interior Magnet Type (IPM)

In interior magnet type, the magnets are buried inside the rotor as shown in Figure 2(b). Unlike the surface magnet, the effect of saliency is normally obvious in the IPM because the equivalent air gap is not uniform as well as due to its interior permanent magnet. As a result, the quadrature-axis synchronous inductance of IPM is larger than its direct-axis inductance, Lq>Ld, which significantly changes the torque production mechanism [9].

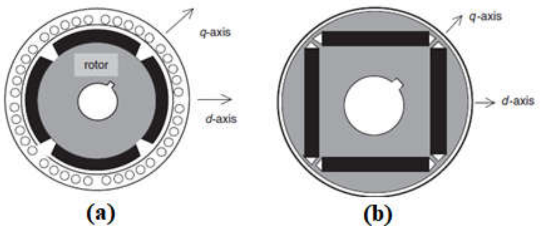

Fig. 2. (a) Surface Magnet Synchronous Motor (SPM) (b) Interior Magnet Synchronous motor

3. Field Oriented Control (FOC)

A better dynamic performance can be achieved using a more complex control scheme that needs to be applied in order to control the PMSM motor. Advanced control strategies can be implemented using mathematical transformations in order to decouple the torque generating component and the magnetizing component in PMSM motors. Such de-coupled torque and magnetization control is commonly called rotor flux oriented control, or simply Field Oriented Control (FOC). FOC control will allow us to decouple the torque and the magnetizing flux components of stator current. With a decoupled control magnetization, the torque producing component of the stator flux can now be assumed as an independent torque control. In order to achieve such decouple torque and flux, several mathematical transformations are engaged.

The Field Orientated Control consists of controlling the stator currents represented by a vector [10]. The idea behind FOC control is to transform a three phase time and speed dependent system into a two coordinate (d and q coordinates) time invariant system. These transformations lead to similar structure as that of a DC machine control. The torque component which is aligned with the q coordinate and the flux component which aligned with d coordinate are the two constant needed in FOC controlled machines. The overall sensorless control structure of PMSM is presented in Figure 3.

The advantages of FOC are: mechanical position, good torque response, accurate speed control, full torque at zero speed. The disadvantages are current feedback, many equations and transformations need to be implemented [11].

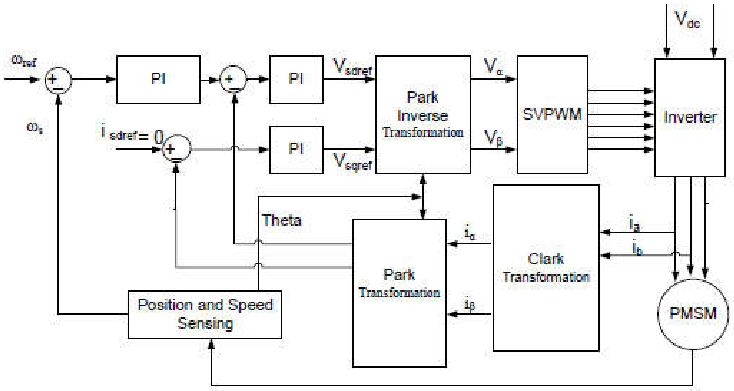

Fig. 3. Sensorless Field-Oriented Control of PMSM

4. Speed Estimation Techniques of Pmsm Motor Drives

The three most widely used techniques are classified as; Fundamental Machine Model-based method, Indirect position sensing method; and saliency based methods as shown in Figure 4.

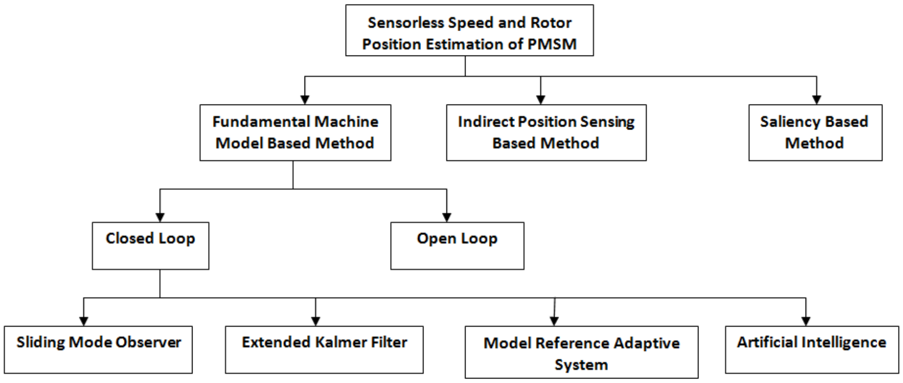

Fig. 4. Speed Estimation Techniques of PMSM Drives

4.1. Fundamental Machine Model Based Methods

This category can be classified according to the algorithm used for position and speed estimation either as an open loop or closed loop estimator. In the open loop estimator, the rotor speed and slip frequency estimators are obtained by considering the voltage equations of the PMSM machine. No feedback is used to check the correctness of the estimation. The Open-loop estimator is simple and easy to implement. Closed-loop estimators unlike the open loop estimator contain a correction form involving an estimation error to adjust the response of the estimator. These closed-loop estimators are referred to as observers. Compared to open-loop estimators, observers are more robust against parameter mismatch and also signal noise [11]. Some of the machine model based methods of speed estimation are adaptive flux observer, sliding mode observer, extended kalmer filter, model reference adaptive system, and artificial intelligence.

4.1.1. Sliding mode observer

The sliding mode observer for estimating rotor position angle is based on a stator current estimator using discontinuous control. Due to the fact that only stator currents are directly measurable in a PMSM drive, the sliding mode manifold or surface s (x) = 0 (shown in Figure 5) is selected on the real stator current trajectory. In this way, when the estimated currents, i.e., state, reach the manifold and then the sliding mode happens and has been enforced, the current estimation error becomes zero and the estimated currents track the real ones regardless of certain disturbances and uncertainties of the drive system [12]. The sliding mode current observer is designed with the same structure as Permanent Magnet machines without saliency and consists of a model based current estimator and a big-bang sliding control surface.

The PMSM motor can be represented by its dynamic model expressed in the stationary reference frame in terms of the stator current and rotor flux by the following state equations;

$$\frac{d}{dt}\tilde{\imath}_s = \mathrm{A}\tilde{\imath}_s + \mathrm{Bu} + \mathrm{k}\,\mathrm{sgn}(\tilde{\imath}_s - i_s) \qquad (1)$$

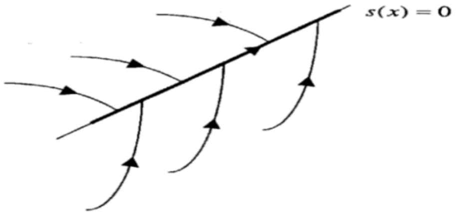

Fig. 5. Sliding Mode in Non-Linear System

Where $\mathrm{A} = \begin{bmatrix} -\frac{R_S}{L} & 0 \\ 0 & -\frac{R_S}{L} \end{bmatrix}$ $\qquad \mathrm{B} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}$

$\tilde{\imath}_s = \tilde{\imath}_{\alpha\beta s} = [\tilde{\imath}_{\alpha s}\tilde{\imath}_{\beta s}]^T$ Estimated $\alpha\beta$ currents vectors

R_S and L are the stator winding resistance and armature inductance respectively; and

$$K_1 = k[I, -I]^T = kI \qquad (2)$$

Where K1is the gain matrix and k is the switching gain. The equation of rotor speed estimation can be written in the following form based on Lyapunov theory:

$$\tilde{\omega}_r = -k\int\left[sgn(\tilde{\imath}_{\alpha s} - i_{\alpha s})\psi_{r\beta} - sgn(\tilde{\imath}_{\beta s} - i_{\beta s})\psi_{\alpha r}\right] dt \qquad (2)$$

The complete block diagram of the sliding mode observer based rotor position estimator is shown in Figure 6[13].

The main advantages of SMO are its fast dynamic response, robustness, and simplicity in design and implementation. However, the major drawback of the SMO is the effect of chattering which appears as an undesired oscillation on the system trajectory with finite frequency and amplitude, and leads to low control accuracy, high wear of moving mechanical parts, high heat loss in power circuits, and control loop instability. For chattering reduction, several suppression methods have been analyzed recently, including the use of saturation, or use of a sigmoid function instead of a sign function for chattering reduction or elimination [11].

4.1.2. Extended Kalmer Filter

The extended Kalman Filter is a recursive stochastic state estimator. The Kalman filter KF is a special kind of observer, which provides optimal filtering of noises in measurement and inside the system if the covariance matrices of these noises are known. The process and the measurement noises are both assumed to be Gaussian with a zero mean. The system step space model and its discrete measurement are described as follow [15]:

$$\dot{x}(t) = f[x(t)] + Bu(t) + \sigma(t) \tag{2}$$

$$y(tk) = h[x(tk)] \; + \; \mu(tk) \tag{2}$$

Where $\sigma(t)$ and $\mu(tk)$ are zero mean white Gaussian noises with covariance matrices (Q and R) which serve as design parameters for the convergence of the algorithm. f = state matrix, B = matrix of inputs, h = matrix of outputs. Matrix h defines the measurement relations to the state variable x. The system noise σ has a covariance matrix Q and the measurement noise μ has a covariance matrix R, which characterize the uncertainties in the states and correlations within it. The state covariance matrix P is obtained in prediction part of the algorithm. After fulfillment actual measurement, it is then corrected. The elements of their covariance matrices (Q and R) serve as design parameters for the convergence of the algorithm.

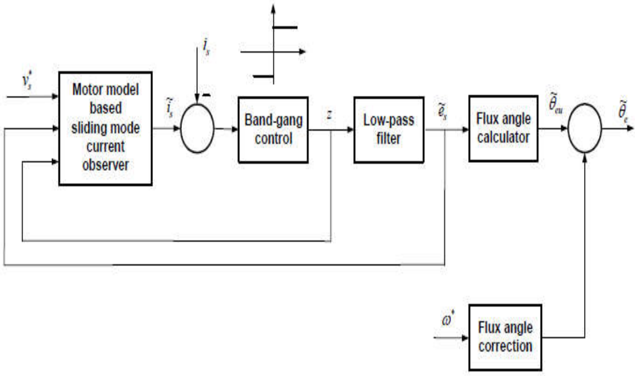

Fig. 6. Block Diagram of the Sliding Mode Observer Based Rotor Flux Position Estimator

The advantage of EKF is that is its extensions are robust and efficient observers for linear and nonlinear system respectively. It is also an optimal estimator in the least-square sense for estimating the states of dynamic nonlinear systems, and it is, thus, a viable and computationally efficient candidate for the online determination of rotor position and speed of a permanent-magnet synchronous motor (PMSM) [14]. The major drawback of the EKF application to sensorless drives, which is the design and the tuning of the covariance matrices that appear in the EKF equations, is still unsolved [16].

4.1.3. Model Reference Adaptive Systems (MRAS)

The MRAS comprises a reference model, an adjustable model, and an adaptive mechanism. The general idea behind MRAS is to create a closed loop controller with parameters that can be updated to change the response of the system as shown in Figure 7.

Theoretically MRAS computes a desired state using two different models (i.e. reference and adjustable models). The error between the two models is used to estimate an unknown parameter (either rotor position or speed). A condition to form the MRAS is that the adjustable model should only depend on the unknown Parameter. Here, the reference model is independent of rotor speed, whereas the adjustable model is dependent on the same. The error signal is fed to the adaptation mechanism. The output of the adaptation mechanism is the estimated quantity, which is used for the tuning in adjustable model and also for feedback. The estimated speed, ω which is used as the adjustable model as shown in the block diagram of Figure 8 is generated by the error e between calculated and estimated state variables which is then used to drive an adaptation mechanism. The error is then fed into an adaptation mechanism, which is designed to ensure the stability of the MRAS. The stability of such closed loop estimator is achieved through Popov's Hyper stability criterion [17]

MRAS is widely accepted for speed estimation due to its simplicity and excellent stability. Also the method unlike EKF does not require any extra hardwire, signal injection or huge memory [17]. However, the major drawback of this method is that it is heavily dependent on stator resistance variation and suffers from the integrator related problems like drift and saturation [18].

4.1.4. Artificial Intelligence

The Artificial-intelligence- based estimators can be broadly classified into artificial neural network (ANN) and fuzzy-neural network. It is possible to train a supervised multi-layer feed forward ANN with back-propagation training for the estimation of the rotor position and the rotor angle. By using the back-propagation algorithm, the square of the error between the required and actual ANN output is minimized. The trained ANN can then be used in real-time applications. Such an ANN contains an input layer, an output layer and the hidden layers. However, the number of hidden layers to be used is not known in advance; this has to be determined by trial and error, although it should be noted as a guideline that in electrical engineering applications the number of hidden layers is usually one or two. Furthermore, the number of hidden nodes in the hidden layers is also not known in advance and again this has to be obtained by trial and error.

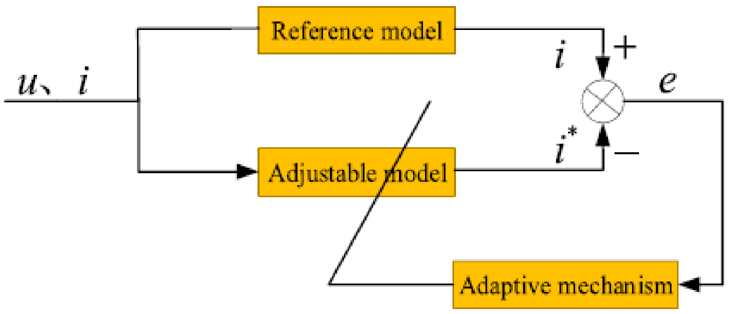

Fig. 7. Rotor position and speed estimation structure using MRAS

The number of input nodes depends on the type of PMSM (machine with surface-mounted magnets or machine with interior magnets). It is possible to construct such a neural network which also uses at its inputs the stator currents of the machine but for each of the stator currents used, there are two inputs, corresponding to a present and also to a past input. It is an advantage of such an approach that, in contrast to other conventional techniques, it does not require a mathematical model of the machine. In ANN-based approach it is difficult to relate the structure of the network to the physical process and there are no guidelines for the selection of the number of hidden layers and nodes. It is possible to overcome some of the difficulties of the ANN-based approach by using a fuzzy-neural estimator. A fuzzy neural system combines the advantages of fuzzy-logic and neural networks. Number of layers and also the number of nodes are known is the main advantage of a fuzzy-neural network [3].

4.2. Indirect Position Sensing Based-Method

In this type of control, the basic idea is to obtain the rotor position information indirectly from the sensed position related signals, e.g., the instantaneous magnitude of the back EMF, which is a function of rotor position. By this method, the motor terminal voltages and currents are sensed and an algorithm is used to extract the embedded data from which the rotor position can be estimated. So, this method is always called the sensorless technique in rotor position estimation. However, back EMF sensing does not work in low-speed operating conditions. To solve this problem, an open-loop starting procedure is needed. Moreover, the base speed is the maximum achievable speed using this method. In order to estimate the rotor position regardless of the machine operating mode, an indirect position sensing method based on the third harmonic component of the back EMF which has a constant phase relationship with the rotor flux is designed [19]. The third 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. This method needs less filtering and has an improved capability to operate in a lower-speed region as compared to the aforementioned back EMF sensing methods. Very recently, an improved position estimation method for a PMSM, which combined a third harmonic back EMF sensing method and a position observer, was developed [20]. In this method, the integral of the third harmonic back EMF, which is the third harmonic flux linkage, was utilized as a reference. The error between the estimated and reference third harmonic flux linkages were used to compensate the speed estimation error. The rotor position was then calculated based on the compensated rotor speed. This method has been reported to achieve better position estimation accuracy than the previous one.

4.3. Saliency Based-Method

Rotor position/speed estimation methods using machine saliency tracking have been extensively studied in order to overcome drawback and limitation of poor performance in the low-speed region and at standstill due to low signal-to-noise ratios (SNRs) of the position-related system states and improve the low-speed operation capability [21][22]. An HF excitation method, whose frequency is much higher than the fundamental frequency, is usually utilized. Using the measured response of the PMSM under the HF excitation, the position-related saliency signal can be obtained. The HF excitation-based methods can be differentiated as:-

4.3.1. The principle of the machine saliency tracking-based rotor position estimation

The rotor position can be detected by tracking the variation of the position dependent stator inductance for salient-pole PMSMs [23]. For the non salient-pole PMSMs, e.g., Surface Mounted PMSMs, 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 [24].

4.3.2. The method for HF excitation

In this method, both continuous and discontinuous HF excitations have been proposed. Different types of HF excitation can be achieved by using either a carrier signal injection or a pulse-width modulation (PWM) pattern modification. For the carrier signal injection, both sinusoidal waveforms and square waveforms are available candidates; and they can be injected into either the stationary reference frame or the estimated synchronously rotating reference frame [25].

4.3.3. The signal processing method and saliency tracking observer

The saliency-related signals measured could be different for different types of HF excitation,; and the signal processing methods used for different saliency-related signals could also vary as well. In order to improve the rotor position estimation performance, closed-loop saliency-tracking observers have been extensively studied in recent years [26].

4. Conclusion

In this paper, a prior review of speed and position sensorless drives for PMSM has been presented. The recent advances in the speed and position sensorless control were also discussed. To provide insight in sensorless drive techniques and their benefits, classification of existing sensorless methods and newer methods were presented with their merits and drawbacks. The methodology and design each scheme was discussed. There are three main classes of rotor position and speed estimator for the PMSM drives; Fundamental Machine Model-based method, Indirect Position sensing Technique and Saliency Based-Method. Robustness against parameter variations Steady state error, dynamic behavior, noise sensitivity, low speed operation, parameter sensitivity, complexity, and computation time are some of the important parameters to evaluate the effectiveness of the schemes. Finally, each rotor position and speed estimation method of sensorless PMSM drives application requires a specific design, which takes into consideration the required performance, hardware and the designer skills.

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Author Contribution

We focused on the literature review of previous papers on propulsion without speed and position sensors for PMSM having been applied.

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Conflict of Interest

The authors declare no conflict of interest.

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