Sensorless Permanent Magnet Synchronous Motor Drive : A Review

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ABSTRACT
Vector control has been widely used in control of permanent magnet synchronous motors (PMSM) where the information of rotor position is required. Shaft position sensor such as an optical shaft position encoder or Hall Effect sensor is fitted to provide a signal that is used to maintain an appropriate space angle between the stator and rotor fields in the motor. Even though this method is very precise but the cost of mechanical sensors and the difficulty to incorporate them make it necessary to avoid their uses and to study the mechanical sensorless control. There are many methods which vary in principle and observer structure. The authors cover a wide range of topics related to the speed sensorless control of permanent magnet synchronous motor (PMSM) drives including their fundamental, limitations, present advances and future trends. In this paper conventional techniques are reviewed and recent developments in this area are introduced with their inherent advantages and drawbacks.

Keywords
Permanent magnet synchronous motor, speed estimator, observer.

1. INTRODUCTION
In the field of power electronics and drive applications, controllers are getting increasingly sophisticated [1]. Sensorless control of both induction motors and permanent magnet (PM) synchronous motors (PMSMs) has been an important subject in the last decade [2], [3]. This paper begins by reviewing briefly the trends in electric drives, focusing on ac-driven machines and then discussing the various control techniques for drives. Currently AC motors are favorably used in many industrial applications. Squirrel cage induction motors are particularly popular because of their simple structure, low production cost and less maintenance. However, the limitation of the induction motors is the working speed which is lower than the speed of rotating magnetic field and the changing slip depends on load torque. That is, an increase in load torque results in the drop in working speed. Hence, the induction motors are not suitable for applications which require an accurate control of speed and position such as servo systems. Also squirrel cage induction motors suffer from poor power factor and efficiency as compared to synchronous motors [4]. On the other hand, speed of synchronous motors can be accurately controlled by varying the frequency of the rotating magnetic field which is called synchronous speed. However, the synchronous motors and dc commutator motors have limitations such as noise problem; wear etc due to the use of commutator and brushes. Also they suffer from high production and maintenance costs. These problems have led to the development of PMSM with PM excitation on the rotor. Permanent magnet synchronous motors (PMSM) have been widely used in many industrial applications. Due to their compactness, high efficiency [5], [6], high power factor and high torque density, the PMSMs are particularly used in high-performance drive systems such as the submarine propulsion, electric vehicle, home appliances, wind generation systems, subway transportation, etc. The permanent magnet synchronous motor eliminates the use of sliprings for field excitation, resulting in low losses in the rotor and low maintenance. The PMSMs are appropriate for high performance drive systems, some typical applications are CNC machine, servo drives, electric vehicles, actuators, hard disk drivers, fiber spinning mills, rolling mills, cement mills, robotic and automatic production systems in the industry. The use of permanent magnet (PM) in electrical machines in place of electromagnetic excitation results in many advantages such as no excitation losses, more flexibility in selection of appropriate rotor construction to suit the requirements of applications, simplified construction, fast dynamic performance and high torque or power per unit volume [7]. Therefore, selection of the particular PM material is application specific; however, Neodymium-Iron-Boron (Nd-Fe-B) rare earth magnets are more in demand because they provide the highest energy density and higher residual flux density than others [8]. The popularity of PMSMs are increasing day by day due to the availability of high energy density and cost effective rare earth PM materials like Samarium Cobalt (Sm-Co) and Nd-Fe-B which enhance the performance of PMSM drives and reduce the size and losses in these motors. This paper gives an overview of the extensive research on sensorless operation of PMSM. This paper presents a review about conventional methods and current trends in sensorless control of permanent magnet synchronous motor drive. At the end a brief note about future trends is also included.

2. CLASSIFICATION OF PERMANENT MAGNET SYNCHRONOUS MOTORS
The PMSMs are classified as follows.

1. On the basis of the direction of field flux [9]
   i. Radial field : the flux direction is along the radius of the machine.
   ii. Axial field: the flux direction is parallel to the rotor shaft.
2. Depending on the wave shape of induced emf [10]
   i. brushless dc machines with trapezoidal emf waveforms.
   ii. PMSM with sinusoidal waveform.

Both types are found in Hybrid Electric Vehicles (HEV) such as the Honda In sight, in which a brushless dc machine is used or the Toyota Prius which utilizes a PMSM. PMSM as the name indicates must rotate at synchronous speed; that is the speed is uniquely related to supply frequency. In a permanent magnet synchronous machine, the dc field winding of the rotor is replaced by permanent magnets. The advantages of elimination are reduced field copper loss, lower rotor inertia, higher power density and more robust construction of the rotor. The demerits of using permanent magnets are loss of flexibility of field flux control and possible demagnetization effect. PM machines, particularly at low power range, are widely used in industry. PMSMs can be categorized based on the mounting of the permanent magnets.

i) Surface-mounted magnets (without saliency, SM).
ii) Internal-mounted magnets (with saliency, IM).

We can distinguish between two main kinds of PMSM: The main difference is that the IM machine has a variable reluctance which varies with the rotor angle, while the SM machine has quite a fixed reluctance for any rotor angle. Therefore this leads to an uniform air gap, resulting in an equal magnetizing inductance for the direct and quadrature axis (L_d and L_q).

3. SPEED CONTROL OF PMSM DRIVE USING A SENSOR

Operation of permanent magnet synchronous motors requires position sensors in the rotor shaft when operated without damper winding. This is shown in Fig 1. The need of knowing the rotor position requires the development of devices for position measurement. It is necessary to avoid the inaccurate estimation of rotor position because, if estimated inaccurately, then the starting torque of the motor decreases, and the motor may temporarily rotate in the wrong direction [11]. Four main devices are there for the measurement of position, the potentiometer, linear variable differential transformer, optical encoder and resolvers. The ones most commonly used for motors are encoders and revolvers. Depending on the application and performance desired by the motor a position sensor with the required accuracy can be selected. Many approaches to sensorless PMSM operation have been reported as sensors present several disadvantages [12] such as reduced reliability, increased cost, weight & size and increased complexity of the drive system. In many industrial installations, the presence of this shaft sensor may substantially reduce the overall ruggedness of the drive. In others, it may add significantly to the drive cost [13].

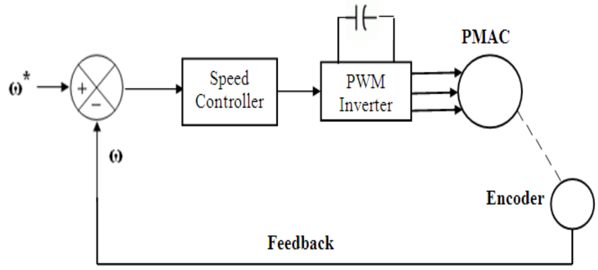

Fig 1. Sensored operation of PMAC motor drive

4. PMSM SENSORLESS CONTROL METHODS

The methods to determine the position of the rotor in electric machines by measuring only their voltages and currents, evolved significantly in recent years [14]. These methods are usually designated as sensorless, encoderless, or self sensing [15], [16]. The torque control of a PMSM requires knowledge of the rotor position to perform an effective stator current control [17]. Furthermore, for speed control, the speed signal is also required. Motor drives without a speed or position sensor have received much research attention in recent years, both for induction motors and PM brushless motors. In a PMSM, the position of the rotor can be determined by the back electromotive force (EMF) or by the position dependence of the inductances, flux linkage sensing etc, each of which is described in Section IV. Among various sensorless control strategies which have been investigated for PMSMs, the model-based methods using adaptive observers are very popular. The observer-based estimation has several advantages over the others because it does not assume steady-state conditions, and stability of the estimation can be analyzed via rigorous control theory [18]. Fig. 2 shows a schematic of a sensorless scheme.

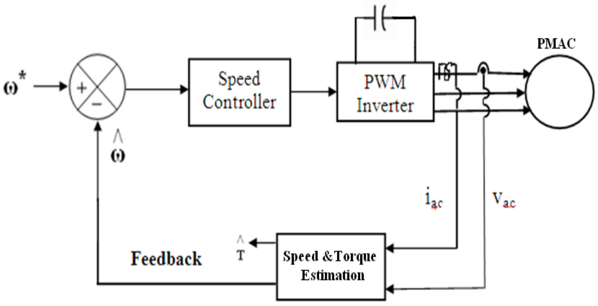

Fig.2. Sensorless operation of PMAC motor drive

The sensorless approach has several advantages [19]:
1) More compact drive.
2) Absence of connecting leads prevents corruption of position data by electromagnetic interference.
3) Cost of position-encoding device is avoided.
4) Increases mechanical robustness.
5) Suitable for hostile environments including temperature.
6) Ensure that the inertia of the system is not increased.
7) Low maintenance.

Various methods of sensorless operation for PMSM motors have been seen in the literature. The sensorless techniques are categorized as: open loop methods, close loop methods and non-ideal property.

4.1 Open loop methods

4.1.1 Back-EMF based methods

In PMSM, the magnitude of the back EMF is a function of the instantaneous rotor position. Thus if this can be accurately monitored the rotor position can be accurately determined in real-time and this can be used to control the switching pattern of the inverter. In practice, it is difficult to measure the back EMF, because of the rapidly changing currents in machine windings and induced voltages due to phase switching. The back EMF is not sufficient enough at starting until the rotor attains some speed. In such a case it is possible to have a starting scheme in which two or three stator windings are energized, and the rotor will then align itself to the desired rotor position to yield the required accelerating torque. However, such a solution leads to low dynamic performance. Methods based on the EMF cannot determine the position at standstill and they have low accuracy at low speeds [20]. In **2011** methods based on phase voltages integration and the third harmonic has been suggested [20], also a method of open-loop starting and ways of determining the position of the stopped rotor is presented. At standstill or at low rotating speed, an accurate rotor-position estimation can be obtained by measuring the phase-current responses on high-frequency voltage test signals [21]. The high-frequency components that are injected in the stator windings may increase the losses in the machine [22]. There are four main methods based on back emf techniques, although all the techniques can be used for high-dynamic-performance applications, they are briefly reviewed here for better understanding.

1. The zero-crossing method, where the instant (switching point) is detected at which the back-emf of an unexcited stator phase crosses zero or reaches a pre-determined level (this is the simplest technique, but is only suitable for steady-state operation).
2. The phase-locked loop method, where the position signals are locked on to the back e.m.f. in the unexcited stator phase during each sixty-degree interval (there is automatic adjustment to inverter switching instants to changes in rotor speed).
3. The back e.m.f. integration method, where a switching pulse is obtained when the absolute value of the integrated back e.m.f. reaches a pre-set threshold value (integrator results in reduced sensitivity to high-frequency modulation noise caused by the inverter and also provides automatic adjustment to inverter switching instants to change in rotor speed).
4. The indirect estimation of the back e.m.f.s by detecting the conduction interval of free-wheeling diodes connected in anti-parallel with the power transistors of the inverter (allows detection of position at very low speeds as well, but not zero speed).

4.1.2 Method based on stator inductance calculation

The inductance-based method is popular for a motor that has severe saliency such as switched reluctance motors and interior PM motors. Inductance is a function of rotor position θr, then position can be deduced from winding current and its rate of change [16]. Based on this property, in **1992** paper [29] A B Kulkarni and M Ehsani proposed a method to calculate motor rotor position using stator phase current and voltage. Such a scheme has the important advantage that it is useful even at zero speed where there is no motional EMF. Sensing of rotor position by inductance variation in the brushless PM machine is complicated because in a machine with surface-mounted magnets, there is no inherent saliency [12], so any variation of winding inductance with rotor position arises only from magnetic saturation; at higher speed motional EMF dominates; inductance variation has two cycles per electrical cycle of the PWM, giving a sensed position ambiguity [13]. Also, this method is an open loop method; the correctness of the estimation cannot be guaranteed [1].

4.2 Closed loop methods

4.2.1 Extended Kalman filter (EKF)

The Extended Kalman Filter (EKF) is an optimal estimator in the least-square sense for estimating the states of dynamic non-linear systems, and it is thus a viable and computationally efficient candidate for the on-line determination of rotor position and speed of a PMSM. Theoretical basis and digital implementation of EKF have been deeply investigated [23]. A novel method i.e. adjustable DC bus voltage, has been proposed in **2009** [23] for low speed EKF sensorless control of permanent magnet synchronous motor (PMSM) drives. This assumes that the measurement noise and disturbance noise are not correlated. The noise sources take account of measurement and modeling inaccuracies. In the very first stage at the time of calculations, by using a mathematical model the states are predicted and in the second stage; the predicted states are continuously corrected by using a feedback correction scheme. This scheme uses actual measured states by adding a term to the predicted states which is obtained in the very first stage. The additional term contains the weighted difference of the measured and estimated output signals. Based on the deviation obtained from the estimated value, the Extended Kalman filter (EKF) provides an optimum output value at the next input instant. The EKF estimation is very sensitive to the PM flux linkage error. However, at least one major drawback of the EKF application to sensorless drives which is not yet solved, is the poor performance in low speed (<5Hz). In addition to the influence of estimation algorithm, the precision of system error estimation is mainly determined by the system observability. The observations of EKF filter are voltage and current. There is not any impact on current data in low speed. But there is one problem that is the harmonic component has a high ratio in voltage data. This estimation fluctuates severely because of the slowly changed system error information disturbed by quickly changed random error. That is why the higher ratio of signal-to-noise (SNR) of voltage, there would be a better performance in low speed. A simple method for high Signal-to-noise ratio is to reduce the voltage level of DC bus.

4.2.2 Model Reference Adaptive System (MRAS)

Many researchers have used MRAS approach to estimate rotor position [23]. It makes use of the redundancy of two machine models of different structures that estimate the same state variable (rotor speed) of different set of input variables. The estimator that does not involve the quantity to be estimated is chosen as the reference model, and the other estimator may be regarded as the adjustable model. The error between the estimated quantities obtained by the two models is proportional to the angular displacement between the two estimated flux vectors. A PI adaptive mechanism is used to give the estimated speed. As the error signal gets minimized by the PI, the tuning signal ω approaches the actual speed ω of the motor. Based on MRAS principle, [12] proposes a technique for sensorless PMSM drives in **2006** by H. Madadi Kojabadi, and M. Ghribi. In this scheme, the rotor speed is estimated with a MRAS based reduced order flux observer is used as the feedback signal for the FOC. In comparison with the full order observer, the observer feedback gain matrix is simpler. Therefore, this method consumes less computational time, and yields much easier control programming.

4.2.3 Sliding mode observer (SMO)

The rotor speed and position information can also be gained by using a siding mode observer [24], which has good robustness and can be easy to implement. The siding mode observer is built based on the mathematical model of PMSM under α-β coordinate system. The model is unceasingly revised in order to make the deviation between estimated current and measured current vanish, thus realize the angle and speed estimation.

The PMSM model in α-β coordinate can be expressed by

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L} i_\alpha + \frac{1}{L} v_\alpha + \frac{1}{L} \omega_r \varphi_f \sin\theta \qquad (1)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L} i_\beta + \frac{1}{L} v_\beta + \frac{1}{L} \omega_r \varphi_f \cos\theta \qquad (2)$$

Equations of SMO can be given by

$$\begin{cases} \dfrac{\mathrm{d}\hat{i}_\alpha}{\mathrm{d}t} = -\dfrac{R}{L}\hat{i}_\alpha + \dfrac{u_\alpha}{L} - \dfrac{k}{L}\mathrm{sgn}(\hat{i}_\alpha - i_\alpha) & (3) \\ \dfrac{\mathrm{d}\hat{i}_\beta}{\mathrm{d}t} = -\dfrac{R}{L}\hat{i}_\beta + \dfrac{u_\beta}{L} - \dfrac{k}{L}\mathrm{sgn}(\hat{i}_\beta - i_\beta) & (4) \end{cases}$$

Where, k is the SMO gain co-efficient

The main advantage of the SMO is its robustness towards parameter variation. However, the method does not work at standstill or low speeds, and the tuning of the gains is quite complicated to ensure method by properly choosing gain coefficient, aiming e convergence [28].

4.2.4 Flux linkage observer

This method is based on the phase voltage equation of the motor. Since the phase flux linkages are a function of current and rotor position, therefore, phase flux linkage can be estimated continuously by integrating the voltage after subtracting the resistive voltage drop from the phase voltage. The open-loop integration is prone to errors caused by drift, which can be reduced if pure integrator is replaced by a low pass filter or an alternative integrator structure. In most electrical machines, it is not practical to measure the phase voltages directly, because of isolation related issues; therefore, applied phase voltage is estimated from DC supply voltage of the solid-state converter [12]. Methods based on flux linkage detection fails at zero speed since the back electromotive force (EMF) which is obtained principally by model inversion becomes zero [24], [21].

4.3 Artificial-intelligence-based estimators

The application of two types of Artificial-intelligence- based estimators is briefly discussed below; these use an artificial neural network (ANN) or a 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. 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].

4.4 Methods based on motor non-ideal property

At very low speed range, however, many sensorless vector control methods couldn't work very well, because the back-EMF, which is generally used to estimate speed, becomes very small and more sensitive to parameter and sample errors. In order to improve the control performances, different methods have been proposed for sensorless control of PMSM in the low speed range [16] in **2008:**

4.4.1 HF signal injection methods

This is the most popular method [25], which takes use of the non-ideal characters of PMSM. As a result, most of them are more suitable for interior PMSM with certain rotor saliency. The HF signal injection method makes use of the magnetic saliency of IMPM caused by the injected HF signal $V_{dc}(t)=V_{inj}\sin\omega_h t$, which is injected on the estimated d axis stator voltage. After some mathematical deduction as is done in [27], the resultant steady-state HF current components on the estimated q-axis can be expressed as follows

$$\hat{i}^r_{qsh} = \frac{U_{inj}\sin 2\tilde{\theta}_r}{\omega_h L_{dh} L_{qh}}\left(L_{diff}\cos\omega_h t\right) \tag{5}$$

where L_{dh}, L_{qh} are *d* and *q*-axis HF inductances respectively and θr is the rotor position error. From equation (5), it can be seen that the HF inductances of *d*- and *q*-axis are different, so that $L_{diff} \neq 0$. In order to adjust θr to zero, some deduction is made in [25] and finally an error signal is obtained. Therefore, the exact rotor position can be obtained by adjusting error signal to zero. The HF signal injection method has larger noise problem. Also, different saliencies may become disturbances to each other and special signal processing methods are needed to separate the useful signals with noise.

4.4.2 LF signal injection methods

The LF signal injection method doesn't rely on the rotor saliency but just the fundamental-wave model, so it's very suitable for surface-mounted PM (SMPM) motor. An LF current signal $i_c(t)=\sqrt{2}I_c\cos(\omega_c t)$ is superimposed on the estimated d-axis. If there is an error between the estimated and ideal d-axis, the injected signal will induce back-EMF ripples, which could be used to estimate rotor speed. After some mathematical deduction as is done in [26] the error is adjusted to zero, and the exact rotor position can be obtained. The drawback of the above method is that the LF signal injection method needs to be combined with advanced observers to improve its dynamic response**.**

5. FUTURE TRENDS

In all existing speed sensorless methods for PMSM drives the position of rotor is determined by measuring only the stator voltages and currents. Hence, either four additional electrical sensors are used to measure the stator voltages and stator currents or in High frequency signal injection methods additional complex circuitry is needed which reduces the robustness of overall system. It is difficult to get current sensors with equal gains over the wide range of frequencies, currents and voltages used in a practical inverter. If the motor windings are not perfectly balanced or if the current sensors have some dc offset, the problem is exacerbated. These are the drawbacks of conventional methods available for sensorless control of PMSM drive. Presently amongst various sensorless control methods, the HF signal Injection method has received much research attention in recent years. These injection methods are applicable to those permanent magnet (PM) machines which have magnetic saliency variations. However, additional sensors are needed in this method for operation at very low speed and continuously at zero speed. In particular, carrier-based techniques can be divided into two further categories: rotating voltage carrier and pulsating voltage carrier. From most of the papers it has been observed that no guideline is available for the suitability of these methods based on rotor construction, control methodology, size of machine and speed range. Therefore, a new control strategy has to be investigated further which includes speed control, torque control and current regulation without using the mechanical speed sensor. The dc link current and dc link voltage can be used to implement the closed loop torque/speed control which may increases the robustness of overall system.

6. CONCLUSION

In this paper, a review of position sensorless drives for PMSM has been presented. The fundamentals of various methods have been introduced as a useful reference for preliminary investigation of conventional methods. The recent advances in the position sensorless control and the expected future research works 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. Further research is required in this area such as dc link measurement without position sensors to realize optimal performance.

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