Review and Comparison of Sensorless Techniques to Estimate the Position and Speed of PMSM

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ABSTRACT

Sensorless technique becomes popular nowadays in electrical drive applications specificially for AC motor drive. It is applied to determine and estimate the rotor position especially for PMSM motor. This paper presents the comparison sensorless technique to determine and estimate the position and rotor of PMSM motor. PMSM motor is widely used in industrial and automation due to its high performance motor drive. However, the location of PMSM motor in humidity and harsh environment causing the accuracy of motor is inaccurate due to deterioration of position sensor. Therefore, many sensorless techniques have been proposed by previous researchers in order to solve the problem. This paper presents the review of several categories; Model Based Method, Saliency Based Method and Signal Injection, and Artificial Intelligence Based Estimator. In addition, sensorless techniques on each category have been compared and described in terms of their advantages and disadvantages.

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1. INTRODUCTION

Nowadays, Permanent Magnet Synchronous Motor (PMSM) or Brushless AC motor (BLAC) has been recently used in industrial area due to its high performance motor drive. PMSM provide several advantages such as high-efficiency, high torque, low-cost maintenance and robust despite the price of PMSM is more expensive compare to others AC motor [1]-[2]. Basically, a brushless DC motor and PMSM motor consist of permanent magnet that works to create the magnetic field in DC motor which generally converts electrical energy to mechanical energy.

The permanent magnet is located at the inner side of stator frame. Different between the motors are depending on the view of researcher. Generally, BLDC motor is defined as permanent magnet with trapezoidal back-electromotive force (BEMF), while BLAC is permanent magnet with sinusoidal back-electromotive force (BEMF). The drive technique for BLDC and PMSM also are quite different depending on the shape of BEMF. In PMSM, a rotor shaft is function as moving element that attached together with sensor in order to detect the rotor position and speed of the motor. There are several sensors used in industry such as resolver, absolute encoder and Hall Effect. According to the characteristic of resolver and encoder, those two elements act in different way regarding the accuracy and environmental issued although they play the same function on determining speed and rotor position. Since the higher demand of goods in daily life, it makes the company to push the industry to produce and work for 24 hours to supply the product. Therefore, PMSM motor needs to work hard in order to fulfill the order. In hot, humidity and oily place, resolver is the better choice for system because it is durable to any environment compare to encoder, while to get the good accuracy from the motor, encoder is the best choice for system. However, encoder cannot act at certain temperature and be exposed to dirt, oil and dust contaminates. In the harsh environment in industry, the resolver and encoder do not give the best accuracy. Due to aforementioned problems, the industrial decides to remove the sensor and replace it with a new and good drive system as it uses the motor fundamental equations to gain the position and speed of motor concurrently reducing the overall cost of actuating devices. Basically, there are three categories for sensorless method such as fundamental excitations/ model based method, saliency and signal injection and artificial intelligence. Hence, various methods and techniques are introduced for each category proposed by the researchers to control the speed and position of motor sensor. This paper presents the review of speed and position estimation method for PMSM Drives based on several methods. Basically, this paper is organized as follows. In Section II, the three categories for sensorless position estimation of PMSM is explained and machine model of PMSM is presented in Section III. In Section IV, the comparison among the categories is showed and analyzed based on their advantages and disadvantages. Finally, the analysis results based on research and observation using PMSM machine are showed in Section V.

2. RESEARCH METHOD

2.1. There Categories for Sensorless Position Estimation

The flow chart or classification above shows the three categories of sensorless position estimation of PMSM which are called Model Based, Saliency Based Method and Signal Injection and Artificial Intelligence (AI) [1]-[5].

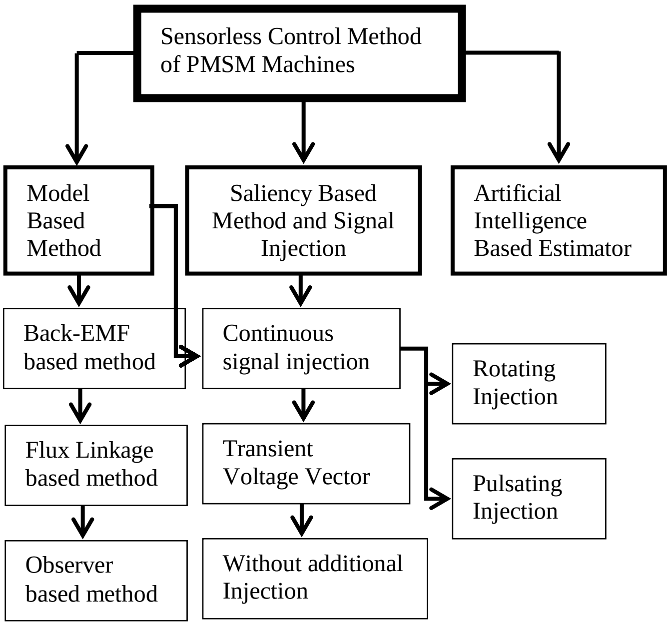

Figure 1. Classification of sensorless control method of PMSM

2.1.1. Model Based Method

For model based categories, there are two methods which are called non-adaptive and adaptive methods [5]. Non-adaptive method can be divided into three sections of method:

a. Estimator using monitored stator voltages, or currents
b. Flux based position estimator
c. Position estimator based on back-EMF

As for adaptive method, it is divided into two categories of method such as Model Reference Adaptive System (MRAS) and Observer-based estimator [5]. For MRAS, in order to get the smaller value of error, the output of reference model must be compared with the output of adjustable adaptive model. Basically, this method is used to adjust the state variable of a system and to minimise the error between two models in order to get the estimation value of quantity.The next section is observer-based estimator [5] which it is consist of:

a. Luenberger Observer

b. Reduced Order Observer
c. Sliding Mode Observer
d. Kalman Filter

Luenberger Observer and Extended Kalman Filter is estimator that uses plant model and a feedback loop with measured plant variables. Basically, the Luenberger Observer is a deterministic observer that produces zero noise compare to the Extended Kalman Filter where its signal is corrupted with noise. The noise produced in EKF will be considered in measurement and modeling inaccuracies in order to get the desired signal.

2.1.2. Saliency Based Method and Signal Injection

High signal injection is also a sensorless method to get the position estimation. Machine saliency or signal injection techniques give the best position estimator from standstill to minimum speed [6]. Generally, saliency based method can be classified into three parts:

a. Continuous signal injection
b. Transient voltage vector injection
c. Without additional injection

For continuous signal injection method, a high frequency signals are superimposed on the fundamental excitation. An observer is required for saliency tracking when using a continuous high voltage injection. According on the principle of signal injection method, all the signal injection method must be used or processed based on machine saliency. It is due to dominant effect caused by magnetic flux from permanent magnet creating the saturation of the stator [7].

Acontinuos us signal injection method can be classified into two signal injections named as rotating injection and pulsating injection [7]. Since most high frequency injection methods inject voltages, thus rotating injection can also be named as rotating voltage vector or revolving carrier while pulsating injection is named as pulsating voltage vector or alternating carrier. Rotating injection method happens when a voltage vector at constant carrier frequency is superimposed on the reference voltages produced by the machine control in stationary reference frame.

Pulsating voltage vector is injected on an estimated either d-axis or q-axis reference frame. Hence, sensorless operation is depending on the estimated dq-axis reference frame position. However, in order to get the perfect orientation, the injection of high frequency only occurs at d-axis while zero injection at q-axis. Injection high frequency will produce high frequency current ripple that affects mostly the flux producing fundamental. Generally, pulsating voltage vector injection method can be used for any type of permanent magnet motor. Firstly, high frequency method with alternating carrier takes place in interior PM motor with single-layer [8]. Next, it is injected into the there-layer interior PM motor and amazingly, the results of two sinusoidal high frequency injections are same. However, some researcher suggested the high frequency using alternating carrier give the better results for PMSM motors because the high frequency current does not produce torque, and reduce noise and vibration. When an impulse voltage vector is applied, the current transient response is produced and it gives affects to the saliency position information. This injection is called as transient signal injection.

2.1.3. Artificial Intelligence Based Estimator

Artificial intelligence based vector controlled is also used as sensorless technique by using fuzzy logic and fuzzy-neutral controller. This is one of the successfully technique that has been implemented for PMSM application. It has been applied to minimize the tuning efforts and also to improve the estimated response. Artificial intelligence based system does not require the mathematical model of motor and fuzzy neutral system can only perform with linguistic rules from the expert or other method.

2.2. Mathematical Modelling of PMSM Motor

A study of permanent magnet synchronous machine (PMSM) operation is made to understand the dynamic behavior of FOC drive. To control the PMSM motor, the d-q PMSM model is needed while field oriented control (FOC) algorithm is applied to control the flux and torque independently, similar with DC machine.

Basically, in FOC control drive, torque and flux component will aligned with the q and d coordinate respectively for having the constants as input reference. FOC is a complex control method due to numerous transformations involving three-phase reference frame to two-axis orthogonal stationary reference frame or vice versa. The transformations are known as Clark transformation, Park transformation and inverse Clark-Park transformation. This section will discuss more detail about the transformation and mathematical modeling of PMSM those is simpler compared to the mathematical modeling of induction machine.

2.2.1. d-q Reference Cordinate System

FOC can be classified into two coordinate systems such as static coordinate system and revolving coordinates system [10]. The two phase stator *(a-B)* coordinate system is a static coordinate system consisted of *a*-axis fixed on *x*-axis and *B*-axis at *y*-axis which vertical 90 degree to *a*-axis. Meanwhile, d-q coordinate system with d-axis fixed on the rotor is called revolving coordinate system. Figure 2 shows the relationship between *a-B* coordinate system and d-q coordinate system while Figure 3 shows the relationship between three-phase quantities either voltage or current named as A, B, C with $\alpha - \beta$ coordinate system. In Figure 3, it shows the A coordinates axis is equal to the *a*-axis and the angle between A, B, and C axis is 120 degree.

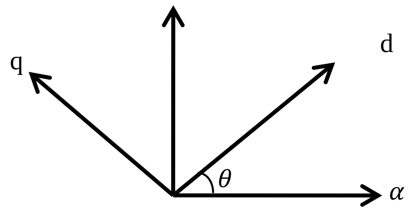

Figure 2. Relationship between $\alpha - \beta$ and d-q coordinate system

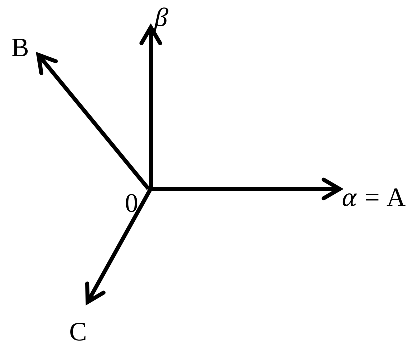

Figure 3. Relationship between $\alpha - \beta$ and A-B-C coordinate system

The angle (θ) between d and α-axis in Figure 1 is knows as rotor flux position. In both Figures, the Equation (1) and equation (2) used the Clark and Park transformation where it involve the transformation between $\alpha - \beta$ and A-B-C coordinate system and between $\alpha - \beta$ and d-q coordinate system respectively.
The transformations in matrix are given below:

$$\begin{bmatrix} i_a \\ i_B \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_a \\ i_B \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2)$$

2.2.2. PMSM Mathematical Model Based on d-q Coordinate System

In order to get the accurate estimated position and speed, it is important to know and solve the mathematical modeling because PMSM modeling plays the bigger role in the experiment. The aims of its modeling are to present the d-q axis Equation in terms of currents and voltage. The voltage equation of PMSM can be expressed as follow:

$$V_d = i_d(R + sL_d) - \omega_e L_q i_q \qquad [V] \qquad (3)$$

$$i_d = \frac{V_d + \omega_e L_q i_q}{R + sL_d} \qquad [A] \qquad (4)$$

$$V_d = i_q(R + sL_q) + \omega_e L_d i_d + \omega_e \lambda_{PM} \quad [V] \tag{5}$$

$$i_q = \frac{V_q - \omega_e L_d i_d - \omega_e \lambda_{PM}}{R + sL_d} \quad [A] \tag{6}$$

Where λ_{PM} comes from flux linkage equation:

$$\lambda_d = \lambda_{PM} + L_d i_d \tag{7}$$

$$\lambda_{PM} = L_d i_d - \lambda_{PM} \tag{8}$$

The total electromagnetic torque of the PMSM can be presented in (9):

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{PM} i_{sq} - (L_q - L_d) i_{sq} i_{sd}\right. \tag{9}$$

The torque equation is shortened in (10) and the mechanical Equation is presented in (11):

$$T_e = T_m = \frac{3}{2}\frac{P}{2}\lambda_{PM} i_{sq} \tag{10}$$

Mechanical equation:

$$T_e = T_L + BW_m + J\frac{dw_m}{dt} \tag{11}$$

3. RESULTS AND ANALYSIS

3.1. Analysis and Comparison of Advantages and Disadvantages of Sensorless Technique

This section will discuss about the sensorless technique that has been done by researchers regarding the advantages and disadvantages of the technique proposed. The table below has been made by following the three categorized of sensorless position estimation as discussed at section II.

3.1.1. Model Based Method

Table 1 shows the techniques, advantages and disadvantages for model based method. There were several methods introduced thus the popular methods among researchers were back-EMF and Extended Kalman Filter (EKF) technique. According to the Table 1, all methods gave the best results at the initial rotor position and had simple systems which there were easy to design. It could also be extended to detect the position of rotor at low speed. However, since these techniques used the fundamental and model based method, it was important to know the machine mathematical model of the machine with stator voltages and currents accurately in order to get the accurate results. Failure to do so would affect the values of rotor position from low speed to standstill [17].

Table 1. Advantages and disadvantages of model based method

Technique	Advantages	Disadvantages
Using back-EMF if the position sensor fails [11]	1) Provide initial rotor position for the proper implementation of fall-back strategy 2) Can be extended to detect position at low speeds	1) Only suitable for low current and low speed application 2) Line-to-neutral (phase) voltages are not easy to sense due to the unavailability of the neutral point
Utilizing an existing back-EMF based position sensorless [12]	1) The structure of techniques is the exceptional simplicity	1) Saturation causes a shift of saliency and magnetic axis 2) The structure is sensitive to the accuracy of the estimation of object parameters
State observer is used to detect direct and quadrature stator current [13]-[14]	1) Been successfully demonstrated for commutation needs and may be implemented using inexpensive electronics 2) The observer can be added/removed	1) Required expensive electronics components 2) The observer can be complex and lead to inadvertent performance issues.
Using Extended Kalman Fitler (EKF) [15]-[16]	1) Does not require either the knowledge of mechanical parameters or the initial rotor position 2) Consider simple system and easy to design	1) State transition model are both linear, however most of the real system are non-linear

3.1.2. Saliency Based and Signal Injection

In Table 2, there are many advantages and disadvantages for saliency based method and signal injection. Some advantages by using high frequency method claimed those techniques could give the best rotor position estimation at low range and insensitive to parameter inaccuracy. It was due to the high frequency injection did not use the mathematical modeling to estimate the rotor position. Instead, they were injected the signal into the current at stationary or rotary in order to get the rotor position. However, if the currents were measured inaccurately, therefore, the rotor position estimation was failed to achieve.

Table 2. Advantages and disadvantages of saliency based method and signal injection

Technique	Advantages	Disadvantages
High frequency voltage or current vector signal is injected into d-axis winding [18]-[19]	1) High Frequency shows good rotor position estimation at low range 2) Insensitive parameter inaccuracy 3) Possible to drive the SMPM motor in low-speed regions including zero speed, even under heavy load conditions	1) Many filter are used for signal processing 2) Produce error between the rotor estimation error and high-frequency current signal
Integration of high frequency injection (HFSI) and EMF [20]	1) Eliminates bumps generation during speed transitions 2) Provide a smooth change between both estimation methods (HFSI and EMF)	1) Complex implementation due to the combining two techniques
Injection of square-waveform high-frequency pulsating voltage signal into the stationary reference frame [21]-[22]	1) The bandwidth of the position estimation can be improved 2) The influence of winding resistance is eliminated 3) Fixed, simpler voltage signal injection and quicker demodulation from the response current.	1) Required high sampling device to capture the response current

3.1.3. Artificial Intelligence Method

As shown in Table 3, artificial intelligence is a new method proposed due to advance technologies nowadays. Many advantages had been explored and some of the techniques using simple adaptive fuzzy logic could improve the efficiency of the system. Besides, they gave a good performance for the controller regarding no-load and load condition and even they were easy computation. However, fuzzy logic or neutral network controller was hard to gain due to the unrecognized multiple numbers of rules in advance. Therefore, this method required to be determined by trial and error. Other than that, it was difficult method to be understood by an inexperience researcher due to complex rules.

Table 3. Advantages and disadvantages of artificial intelligence method

Technique	Advantages	Disadvantages
Using the fuzzy logic implementation [23]-[24]	1) Rotor position is aligned without an additional sensor 2) Stator current easily be adjusted by modulating the pulse width of the switching device 3) Flexible, uncertain and easy computation	1) It is not suitable for industrial application due to time- consuming computation. 2) Big software overhead for simple applications
Combine the intelligence of fuzzy logic with the sliding mode control technique [25]-[26]	1) The peak overshoot is completely eliminated 2) The settling time is improved and the speed of motor with load condition is minimized	1) Complex implementation due to combining two technique
Using simple adaptive fuzzy logic for PMSM [27]	1) Improve the control system's efficiency 2) Good performance of the controller in no-load and load condition	1) Give effect to system precision and the measurement of peak current of the motor

4. CONCLUSION

In conclusion, a review of position sensorless drives technique for PMSM has been presented in this paper. The sensorless techniques grouped by categories are also described. A variety of methods is introduced as a reference to researchers for doing further research. Understanding toward the conventional technique is necessary by knowing their advantages and disadvantages. It will encourage researchers for producing some ideas or concepts in the electrical drive research. Thus, the electrical drive considering the sensorless technique could be developed and sustainable in the future industrial and automation application.

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