Model reference Adaptive Controller Based Speed Estimation Technique for the Vector Controlled Permanent Magnet Synchronous Motor Drive

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Abstract— In recent years, much endeavor has been made to improve the performance of speed sensor less permanent magnet synchronous motor drives, especially at low speeds, by identifying stator resistance together with speed. Model-based speed and stator resistance estimators are the most common schemes used in the literature. There are several other methods for estimating the rotor speed and stator resistance. One popular method among them is Model Reference Adaptive System (MRAS). This work corresponds to estimating the speed and stator resistance using active and reactive power based MRAS. Several speed estimation methods for sensor less PMSM drives have been proposed. Performance of them is not satisfactory at low speed. When the stator resistance value in the speed estimator is incorrect, the estimator does not work satisfactorily. The stator resistance varies with the temperature of the machine, so it should be estimated adaptively. Due to the high efficiency and good controllability, PMSM drives are largely used in many industrial applications. At the present classic PID controller is mostly used, whose performance is affected dramatically by parameters of motor. In addition, in order to reduce cost and avoid the limitation of mechanical sensor. People proposed sensor less techniques which are arousing great interest. They aim at eliminating mechanical sensor, which are rather expensive and delicate, especially if accurate mounting and calibration are necessary, and at obtaining rotor position and angular velocity from the measurement of only electrical quantities. But the precision of position estimation often depends on motor’s parameters. Naturally, the precise determination of PMSM parameters is of great significance. Much identification of the motor’s parameters is proposed to increase the performance of controllers and precision of position estimation. To control PMSM position and speed sensors are indispensable because, the current should be controlled depending on the rotor position. The vector control drive provides wide range of speeds, high torque capability and high efficiency. Also the vector control of PM motors is much simpler than of induction motors because there is no need to consider the slip frequency as in the induction motor drive. Conventional vector control of PM motor requires a motor position sensor to correctly orient the current vector orthogonally to the flux, because the rotor flux is obtained from the permanent magnets. It is possible to control the torque by acting simply on the amplitude of the stator current. Thus we can achieve a high degree of torque control over a wide speed range including the standstill can be achieved. Because there is no need to consider the slip frequency as in the induction motor drives. Conventional vector control of PM motor requires a motor position sensor to correctly orient the current vector orthogonally to the flux, because the rotor flux is obtained from the permanent magnets. It is possible to control the torque by acting simply on the amplitude of the stator current. Thus we can achieve a high degree of torque control over a wide speed range including the standstill can be achieved.

Keywords— model reference adaptive system, reactive power speed estimation, vector control permanent magnet synchronous motor.

I. Introduction

This report presents a parameter estimation technique for the permanent magnet synchronous motor drive. A model reference adaptive system (MRAS) has been formed by using the instantaneous and steady state reactive powers to estimate the q-axis inductance (Lq). Instantaneous and steady state active powers are used in the active power based MRAS to estimate the stator resistance. It has been shown that such unique MRAS offers several desirable features. The reactive power based MRAS method is completely independent of stator resistance (Rs) and is less parameter sensitive, as the estimation algorithm is only dependent on q-axis stator inductance. Also, the method requires less computational effort as the simplified expressions are used in the MRAS. The stability of the proposed system is achieved through Popov’s hyper stability criteria. Extensive simulation results are presented to validate the proposed technique. The system is tested at different speeds including zero speed and a very satisfactory performance has been achieved. Recently PMSM drives have received increased attention due to having several desirable features. Vector controlled PMSM drive widely used in applications like machine tools, electric vehicles etc. Indirect vector controlled system requires the information of the speed: either from the speed encoder or from an estimator/observer. Elimination of the speed encoder is highly encouraged to increase the mechanical robustness of the system and to make the drive cheaper. In some applications there is no room to put the speed sensor. This has made speed sensor less drive very attractive.
Many speed estimation techniques have been reported in literature [5–17]. They are broadly categorized as:

A. State observer-based method [5, 6]

Reported estimation method also includes Extended Kalman Filter (EKF), Extended Luenburger observer (ELO), sliding mode observer, etc. The computational complexity, parameter sensitivity and the need of initial conditions degrade the superiority of the EKF based speed estimation technique. However, one good side is that the parameter can also be treated as the state and that can be estimated along with the speed. The sliding mode observer based technique is available in [9]. The method is simple and robust against parameter variation. However, it has the demerit of the chattering phenomenon. In [9], a low pass filter (LPF) has been used to overcome the problem. However, this is at the cost of system dynamics.

B. Signal injection based method [7]

Some techniques exploited the saliency in the machine to extract the speed information. Note that the phase inductance varies for different rotor positions due to the saliency present in the rotor side. To extract the position from inductance profile, a high frequency voltage signal is fed to the motor phases. The merit of this method is that the technique is reliable at zero speed. A combination of signal injection based and the back-emf based methods for speed estimation is reported in literature, where the former is used at zero or very low speed and the later for high speed. However, the accuracy of this method is highly influenced by the geometry of the rotor (i.e., positioning of the permanent magnets). This makes the technique unsuitable for the surface mounted PMSM. The main drawbacks of signal injection based methods are the adverse effect of injecting signal on motor dynamics and the requirement of extra hardware for the purpose of signal injection.

C. Model reference adaptive system (MRAS) based techniques [10–14]

Theoretically MRAS computes a desired state (called as the functional candidate) using two different models (i.e. reference and adjustable models). The error between the two models is used to estimate an unknown parameter. Reference 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 (x_r,est), which is used for the tuning in adjustable and also for feedback. The stability of such closed loop estimator is achieved through Popov’s hyper stability criterion [17]. The method is simple and requires less computation. Depending on the quantity (i.e. the functional candidate) used to formulate the error signal; various kinds of MRAS are possible. In [10], an MRAS is developed with d- and q-components of flux. However, the method is heavily dependent on stator resistance variation and suffers from the integrator related problems like drift and saturation. To overcome the first problem, an MRAS with on-line stator resistance estimation is reported in [11]. Reactive power-based MRAS are presented in [12, 13]. In [14], Neural Network (NN) based MRAS is also reported. Among all of these methods, reactive power based MRAS is more popular for speed estimation as it is independent of stator resistance.

This paper deals with an MRAS, where the reference model utilizes instantaneous reactive power and the adjustable model uses steady-state reactive power. This means that the two different versions of the same quantity are used to formulate error signal. This type of approach rewards a speed estimator that depends only on Lq. A mechanism for on-line estimation of Lq will make the drive parameter independent. Such MRAS with instantaneous and steady-state reactive power was reported in [12] for the speed and parameter estimation of induction motor drive. This work applies the concept to PMSM drive for the first time. The scheme is simulated in MATLAB/SIMULINK. It is observed that the proposed technique is working well with different possible situations under load and speed variation. Extensive simulation results are presented to highlight the performance of the estimation algorithm.

II. MODEL REFERENCE ADAPTIVE SYSTEM (MRAS) METHOD

MRAS computes the desired state (called as the functional candidate) using two different models (i.e., reference and adjustable models). The error between the two models is used to estimate an unknown parameter.

A condition to form the MRAS is that adjustable model should only depend on the unknown parameter. Reference model is independent of unknown parameter. The error signal is fed to the adaptation mechanism. The output of the adaptation mechanism is estimated quantity, which is used for tuning the adjustable model and also for feedback. The stability of such closed loop estimator is achieved through Popov’s hyper stability criterion. This method is simple, accurate and requires less computation.

![Fig.1 Basic MRAS structure](image-url)
The reference model computes instantaneous reactive power \( Q_{\text{ref}} \) and adjustable model computes steady-state reactive power \( Q_{\text{est}} \). Both the reactive powers are then compared to form the error signal. The error signal is passed through the adaptation mechanism to estimate rotor speed.

In the successive section it will be proved that a PI controller is sufficient for adaptation mechanism. The estimated rotor speed used to tune the adjustable model until the two reactive powers \( Q_{\text{ref}} \) and \( Q_{\text{est}} \) become same. It is important to mention that in the proposed MRAS, continuous monitoring of speed error signal \( (e) \) and reactive power error signal \( (e) \) is required; otherwise instead of negative feed-back positive feed-back may takes place and the system may become unstable.

A. Proposed scheme

A block diagram of the proposed MRAS-based rotor speed estimator is shown in Fig. 2. The reference model computes instantaneous reactive power \( Q_{\text{ref}} \) and the adjustable model computes steady-state reactive power \( Q_{\text{est}} \). Both the reactive powers are then compared to form the error signal. The error signal is then passed through an adaptation mechanism to estimate rotor speed. In the successive section it will be proved that a PI controller is sufficient for adaptation mechanism. The estimated rotor speed is used to tune the adjustable model until the two reactive powers \( Q_{\text{ref}} \) and \( Q_{\text{est}} \) become same. It is important to mention that in the proposed MRAS, continuous monitoring of speed error signal \( (e) \) and reactive power error signal \( (e) \) is required; otherwise instead of negative feed-back positive feed-back may take place and the system may become unstable. The complete vector controlled sensorless PMSM drive with MRAS based speed estimator is available in Fig. 3.

The instantaneous reactive power can be expressed as

\[
Q = v_i - v_d i
\]

Substituting \( V_d \), \( V_q \) values in equation (16), the new expression for \( Q \) becomes:

\[
Q = \omega \left( L_i^2 + L_q^2 \right) + \left( Li \dot{i} - Li \dot{i} \right) + \omega i \lambda
\]

At steady-state derivative terms are zero and the new expression for \( Q_2 \) becomes:

\[
Q = \omega \left( L_i^2 + L_q^2 \right) + \omega i \lambda
\]

Now the condition for vector controlled PMSM drive \( (i_{sd} = 0) \), therefore, the simplified expression for \( Q \) is:

\[
Q = \omega L_i^2
\]
Equation (27) is independent of q-axis inductance \( L_q \). So, \( Q \) is used in reference model.

Equation (28) is dependent on q-axis inductance. So, \( M \) is used in adjustable model.

C. Modeling of PMSM

The d and q-axis stator voltages for PMSM referred to rotor reference frame may be expressed as

\[
v_d = R_s i_d + \frac{d}{dt} \frac{L_d}{L_s} i_q - \omega_s L_q i_q
\]

\[
v_{q} = R_s i_{q} + \omega_s L_d i_d + \frac{d}{dt} \omega_s L_q i_{q} - \omega_s \lambda_{af}
\]

\( L_d \) and \( L_q \) are the d- and q-axis stator inductance, \( R_s \) is the stator resistance, \( \lambda_{af} \) is the mutual flux linkage, and \( \omega_s = \omega_{r} \rho \).

Where \( \rho \) is the number of pole pair, the \( \alpha \)- and \( \beta \)-axis variables in stationary reference frame are related to the rotor reference frame with the following expression

\[
\begin{bmatrix}
i_{\alpha s} \\
i_{\beta s}
\end{bmatrix} = e^{-j\theta} \begin{bmatrix}
i_{\alpha r} \\
i_{\beta r}
\end{bmatrix}
\]

Where \( \theta \) is the angle between the stationary reference frame and the rotor reference frame.

The developed electromagnetic torque can be expressed as

\[
T_e = \left( \frac{3}{2} \right) P \left\{ \lambda_{af} i_{\alpha s} + \left( L_q - L_s \right) i_{\alpha s} i_{\alpha s} \right\}
\]

The governing electromechanical equation is

\[
T_e - T_l = J \frac{d\omega_r}{dt} + B \omega_r
\]

Where \( T_l \) is the load torque.

III. SIMULATION RESULT

The proposed speed estimation algorithm for PMSM drive has been simulated in MATLAB/SIMULINK under the following operating conditions. The motor parameters as available in [2] are used for the simulation. The Q-MRAS system is extensively simulated in MATLAB/ SIMULINK and this section presents some of the simulation results.
Fig (4) shows that simulation result for speed reversal in step. The motor reference speed is changed from 100 rad/sec to -100 rad/sec at 5 sec. and 10 sec. again speed is set to 100 rad/sec at 10 sec. From the result it is observed that the actual motor speed takes 25 msec to follow the reference speed with good accuracy. Reference speed and actual speeds are plotted in the same scale to observe the accuracy of MRAS-based speed estimator.

Fig (5) shows that simulation result for speed reversal in step. The actual motor speed is changed from 100 rad/sec to -100 rad/sec at 5 sec. and 10 sec. again speed is set to 100 rad/sec at 10 sec. From the result it is observed that the estimated motor speed takes 25 msec to follow the actual speed with good accuracy. Actual speed and estimated speeds are plotted in the same scale to observe the accuracy of MRAS-based speed estimator.

In Fig (6) d, q-axis stator currents are plotted vs. time. These stator currents components are shown in fig (3.1.3) for dc generator type load. For vector controlled PMSM drive d-axis stator current should be zero and the same is observed from the simulation results and the spike at 5 sec., 10 sec. is due to speed reversal.

Fig (7) shows that Electromagnetic torque follows $i_{sq}$. Because

$$T_e = \frac{3}{2} \left( \frac{P}{2} \right) \phi_f i_{sq}$$

Where $\phi_f$ is constant. so, $T_e$ is proportional to $i_{sq}$

B. Speed with Ramp response
Fig (8) shows that the response of the drive for ramp type speed reference. The simulation is also performed for ramp type speed reference and actual speed vs. time. From the result it is observed that actual speed is not tracking the reference speed near zero stator frequency.

Fig (9) shows that the response of the drive for ramp type speed reference. The simulation is also performed for ramp type actual speed and estimated speed vs. time. From the result it is observed that actual speed is not tracking the estimated speed near zero stator frequency. It is noticed that estimated rotor speed follows the reference speed with good accuracy. This discrepancy can be overcome by proper adjustment of PI controller gains.

From the Fig (10) it is observed that the vector control operation of the drive i.e. $i_{sd}=0$ Torque component of the stator current ($i_{sq}$) is also shown for ramp reference.

From the fig (4.1.24) it is observed that $\phi_{sd}=\phi_f$. $\phi_f$ is constant and $\phi_{sq}$ is the product of $L_q$ and $i_q$.

C. Zero speed response

Fig (12) shows that $\omega_{r-ref-act}$ for zero speed response. Actual speed is tracking with the reference speed at zero speed response. Fig (13) shows that $d$, $q$-axis stator currents for zero speed response. $i_{sd}=0$ and $i_{sq}$ follows the torque component.

IV. CONCLUSIONS

The proposed MRAS method is less parameter sensitive, and it gives accurate results. Among all the speed estimation techniques, reactive power based MRAS is more popular as it is independent of stator resistance. MRAS method involves less computational complexity. The adaptation mechanism used the instantaneous power in the reference model and steady-state power in the adjustable model. The use of steady state power eliminates the need of derivative computation. So the method is less sensitive to noise, also the scheme does not need back-emf estimation and hence free from integrator related problems. This improves the performance of the estimator at very low and zero speed. Stator resistance changes due to the temperature of the machine. When the stator resistance value in the speed estimator is incorrect, the estimator does not work satisfactorily.

V. REFERENCES

Short Paper

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