Torque Ripple Minimization of a FOC-Fed PMSM with MRAS Using Popov's Hyper-Stability Criterion

N. Krishna Kumari and D. Ravi Kumar

Abstract This paper focuses on Field-Oriented Control (FOC) of a Permanent Magnet Synchronous Motor (PMSM). Model Reference Adaptive Control System (MRAS) is selected to estimate the speed of a drive. Electrical torque distortion of the machine under dynamic performance is relatively high, and if proper measures are taken, it can be significantly decreased. The first anticipated solution here is to combine FOC with the Sinusoidal Pulse Width Modulation (SPWM) technique. The intention of the sensorless control is to get better speed control performance with reduced torque ripples under load variations in MATLAB/Simulink/Simpower environment.

Keywords Permanent magnet synchronous motor (PMSM)
Field-oriented control (FOC) · Model reference adaptive system (MRAS)
Sensorless control · Sinusoidal pulse width modulation (SPWM)

1 Introduction

Due to the availability of rare earth permanent magnet materials, PMSMs are used in applications where it requires fast torque response with better dynamic operation [1]. As rotor cage is absent in PMSM, it gives quick response with applied load torque [2]. And the outstanding features of PMSM are high torque to inertia, high power density, reliability, and high efficiency; it is used in high-performance applications such as electric vehicles, servo, robotics, machine tools, and traction applications [3–7]. In general, the high-performance operation can be obtained with surface-mounted magnets fixing on a rotor, and this gives minimum armature effect with large air gap [8].

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The most renowned control techniques for PMSM are field-oriented control (FOC) and direct torque control (DTC) [9, 10]. The objective of both the control techniques is to control the flux and torque effectively. In spite of variations in parameters of the motor and external disturbances, the motor forces to follow command trajectory [11]. To achieve the requirement of high-performance characteristics obtained by DC drives, variable speed AC drives employing PMSM with FOC have been expanded in recent years [12].

In FOC, the torque- and flux-generating components are made orthogonal so that independent control of torque and flux is possible as in separately excited DC motor [4]. That means flux control is obtained through d-axis stator current and torque control through q-axis stator current [13].

To design an advanced control system with better performance and accuracy, an adaptive control method is one of the extensively employed control methods. Model Reference Adaptive System (MRAS) is a powerful adaptive controller with adaptive mechanism and adjustable controller parameters [14]. MRAS method is adopted with AC drives to estimate the speed of the rotor for PMSM drive, and has advantages such as easy execution and simple formation. Also, it ensures the system stability through adaptive adjustable model and reference plant model [15]. The main disadvantages of AC drives are its torque pulsations, especially at low speeds. These pulsations result in periodic speed oscillations of the drive. This leads to poor performance of the drive, particularly in high-precision applications. In addition, the torque pulsation leads to acoustic noise along with mechanical vibrations [7].

This paper adopts the MRAS scheme with PI controller, which uses the PMSM itself as the reference model to estimate the speed of the motor. To minimize the torque ripples, MRAS is applied for FOC of PMSM using PI controller [16].

The organization of the paper is given as follows: Sect. 2 discusses the modeling of FOC of PMSM. Section 3 explains the FOC of PMSM drive with sensorless control and MRAS based on Popov's Hyper-Stability Criterion. Section 4 discusses the dynamic behavior of PMSM. Finally, the concluding remarks are given in Sect. 5.

2 Field-Oriented Control of Permanent Magnet Synchronous Motor

The aim of FOC is to perform real-time control of torque and the flux components separately to control the rotor mechanical speed and also to regulate phase currents in order to avoid current spikes during transient phases.

The principle idea of FOC is to introduce decoupling between field- and torque-producing components. This makes PMSM behave like a separately excited DC motor. If the magnets are placed inside the rotor, then $L_q > L_d$; otherwise, if the magnets are placed on the surface of a rotor, then $L_q = L_d$. The block diagram of FOC for PMSM is shown in Fig. 1.

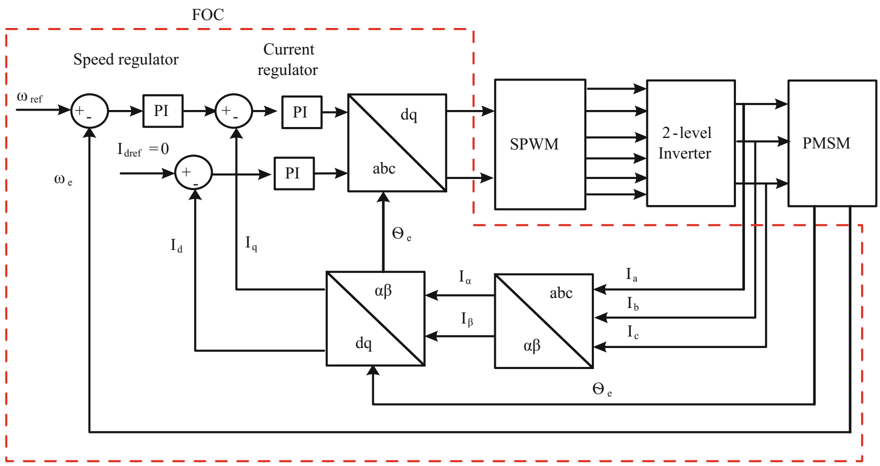

Fig. 1 Block diagram of field-oriented control for PMSM

The modeling of PMSM with rotor reference frame is considered in this work. Modeling equations for PMSM are given in Eqs. (1)–(13). With rotor reference frame, the stator *a*, *b*, *c* voltages are converted into *d*, *q* voltages using Park's transformation. Now, let *S* represent any of the variables (current, voltage, and flux linkage) to be transformed from the *abc* frame to *d*-*q* frame. The Park's transformation in matrix form is given by:

$$\begin{bmatrix} s_d \\ s_q \\ s_0 \end{bmatrix} = (2/3) \begin{bmatrix} \cos\theta & \cos(\theta - 120) & \cos(\theta + 120) \\ \sin\theta & \sin(\theta - 120) & \sin(\theta + 120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

From Eq. (1), the following equations are obtained:

$$v_q = -\frac{2}{3}\left[v_a \sin\theta + v_b \sin\left(\theta - \frac{2\pi}{3}\right) + v_c \sin\left(\theta - \frac{4\pi}{3}\right)\right] \quad (2)$$

$$v_d = \frac{2}{3}\left[v_a \cos\theta + v_b \cos\left(\theta - \frac{2\pi}{3}\right) + v_c \cos\left(\theta - \frac{4\pi}{3}\right)\right] \quad (3)$$

Here, S_0 component is called the zero sequence component, and under balanced three-phase system, this component is always zero. Since it is a linear transformation, its inverse transformation exists and is as follows:

$$\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} = (2/3) \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120) & \sin(\theta - 120) & 1 \\ \cos(\theta + 120) & \sin(\theta + 120) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} \quad (4)$$

From Eq. (4), the following equations are obtained:

$$i_a = i_d \cos\theta - i_q \sin\theta \tag{5}$$

$$i_b = i_d \cos\left(\theta - \frac{2\pi}{3}\right) - i_q \sin\left(\theta - \frac{2\pi}{3}\right) \tag{6}$$

$$i_c = i_d \cos\left(\theta - \frac{4\pi}{3}\right) - i_q \sin\left(\theta - \frac{4\pi}{3}\right) \tag{7}$$

Now, by applying the transformation of Eqs. (5), (6), and (7) to voltages, flux linkages, and currents, Eqs. (8) and (9) are obtained as follows:

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds} \tag{8}$$

$$V_{ds} = R_s i_{ds} + p\lambda_{ds} + \omega_r \lambda_{qs} \tag{9}$$

where

$$\lambda_{ds} = L_{ds} i_{ds} + \lambda_f \tag{10}$$

$$\lambda_{qs} = L_{qs} i_{qs} \tag{11}$$

The produced torque T_e by electrical currents can be represented as follows:

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(L_{ds} - L_{qs}\right) i_{ds} i_{qs} + \lambda_f i_{qs}\right] \tag{12}$$

The produced torque T_e, which is power divided by mechanical speed, can be represented as follows:

$$J\frac{\mathrm{d}\omega_m}{\mathrm{d}t} + B\omega_m + T_L = T_e \tag{13}$$

3 Implementation of FOC for PMSM Drive with MRAS

The concept of MRAS is that it employs a reference model to generate a reference input. In this work, the adaptive laws are derived from Popov's Hyper-Stability Criterion. FOC of PMSM with MRAS is given in Fig. 2. The sensorless speed control of MRAS-based FOC of PMSM is executed in this paper. Here, speed estimation is obtained from MRAS.

This work proposes a sensorless speed control based on MRAS, which is based on the comparison between outputs of two estimators. This estimated error is used

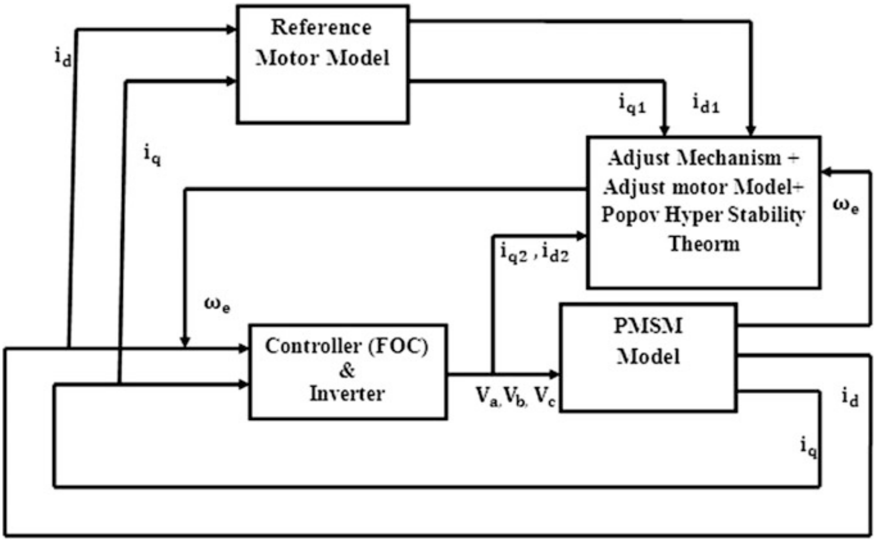

Fig. 2 Block diagram of FOC of PMSM with MRAS

to drive PMSM with a suitable adaptive mechanism to estimate the error speed. In this work, MRAS is based on i_d, i_q of a PMSM since FOC is used as a speed controller. As the control variables in this controller method (FOC) are i_d and i_q, there is a need to represent these variables as state variables. Hence, i_d, i_q is selected as a state variables, and the equations are given by:

$$p\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e \frac{L_q}{L_d} \\ -\omega_e \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_d} \\ \frac{v_q}{L_q} - \omega_e \frac{\lambda_f}{L_q} \end{bmatrix} \tag{14}$$

Define i_d* i_q* v_d* v_q* for FOC of a PMSM are as follows:

$$i_d^* = i_d + \frac{\lambda_f}{L_d}, \quad i_q^* = i_q, \quad v_d^* = v_d + \frac{R_s}{L_d}\lambda_f, \quad v_q^* = v_q \tag{15}$$

So Eq. (14) can be converted into Eq. (16):

$$p\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e \frac{L_q}{L_d} \\ -\omega_e \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} v_d^* \\ \frac{1}{L_q} v_q^* \end{bmatrix} \tag{16}$$

According to Eq. (16), the state equation of adjustable model of PMSM with speed angle as the adjustable parameter is obtained and it is given in Eq. (17)

$$p\begin{bmatrix} \widehat{i_d^*} \\ \widehat{i_q^*} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \widehat{\omega_e} \\ -\widehat{\omega_e} & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} \widehat{i_d^*} \\ \widehat{i_q^*} \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} \widehat{v_d^*} \\ \widehat{v_q^*} \end{bmatrix} \tag{17}$$

In SPM, $L_d = L_q = L_s$, so the adaptive mechanism can be simplified as follows:

$$\widehat{\omega_e} = \left(K_P + \frac{K_i}{p}\right)\left[i_d\widehat{i_q} - i_q\widehat{i_d} - \frac{\lambda_f}{L_s}(i_q - \widehat{i_q})\right] + \widehat{\omega_e}(0) \tag{18}$$

4 Results and Discussion

The motor is operated with constant torque up to its rated speed and flux weakening mode of operation is adopted beyond its rated speed. The motor model is tested for three different cases:

(i) Dynamic modeling of motor under balanced supply,
(ii) FOC, and
(iii) MRAS along with FOC.

4.1 Analysis of Speed Response

At first, the motor starts on no-load, and after reaching to a rated speed of 1500 rpm, the load of 2 Nm is applied at 0.1 s on motor. In the first case, the dynamic modeling of motor under balanced phase supply is modeled in MATLAB/Simulink and the result of speed is shown in Fig. 3.

In this case there are many transients in reaching steady state at no load. And also there are many transients when load 2 Nm is applied at t = 0.1 s.

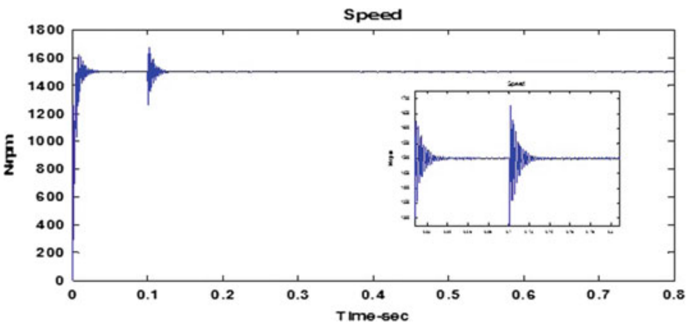

Fig. 3 Speed response with balanced supply

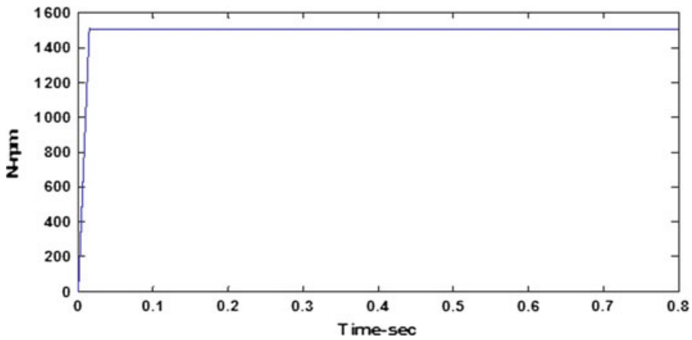

Fig. 4 Speed response with FOC

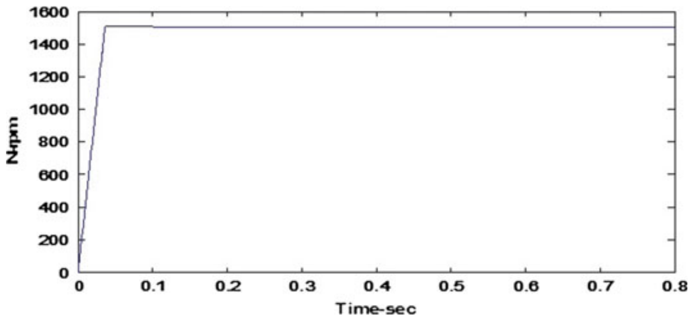

Fig. 5 Speed response with FOC and MRAS

In the second case the motor is tested for the same load conditions with FOC. Here the speed response has no disturbances and it is shown in Fig. 4.

In the third case, there are two sub-models that differ in adaptive mechanism. In adaptive block of sensorless control, two types of controllers are used to minimize the error and to regulate the speed at different rotor positions. At first, the traditional PI controller is used in sensorless control to estimate the speed as feedback. The speed response is plotted in Fig. 5 and it is noticed that the speed response is very smooth as compared to the previous two cases.

4.2 Analysis of Torque Response

In the first case, the load torque of 2 Nm is applied to the motor. The results are shown in Fig. 6. The results show that there are many ripples, harmonics, and disturbances in reaching the steady state.

In the second case, the FOC is modeled and a load torque is applied at 0.1 s. The result is shown in Fig. 7. The average torque ripple is 0.2986. The ripple of this model is less compared to the above case. The electromagnetic torque follows the command torque with less ripples.

In the third case, sensorless control with the adaptive block minimizes the error between actual one and reference one. In this, at first, traditional PI controller is used to minimize the error. The torque result is shown in Fig. 8. The average torque ripple is reduced compared to FOC. The average torque ripple is 0.04522.

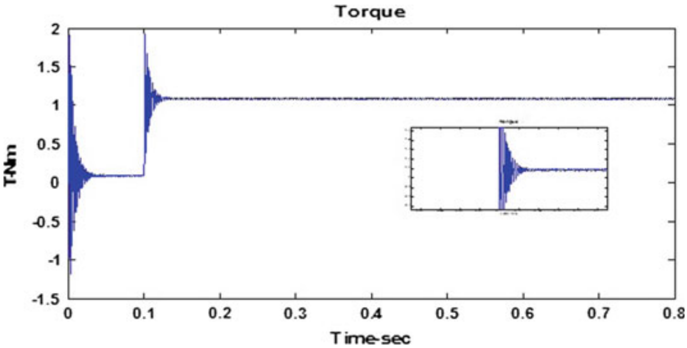

Fig. 6 Torque response with balanced supply

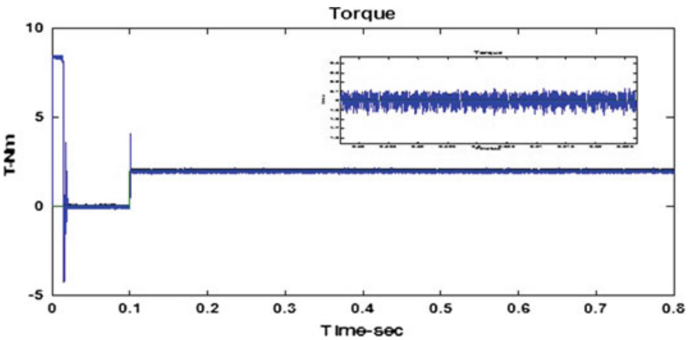

Fig. 7 Torque response with FOC

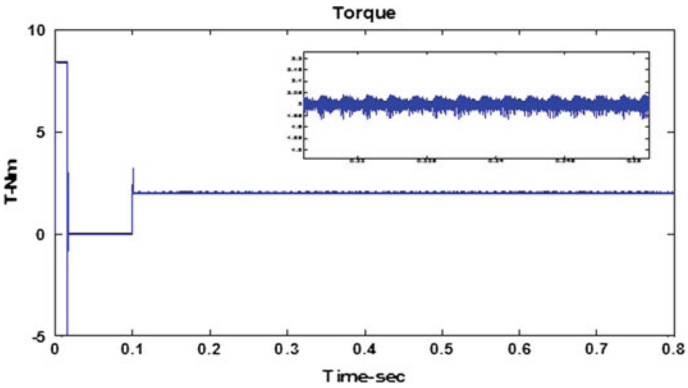

Fig. 8 Torque response with FOC and MRAS

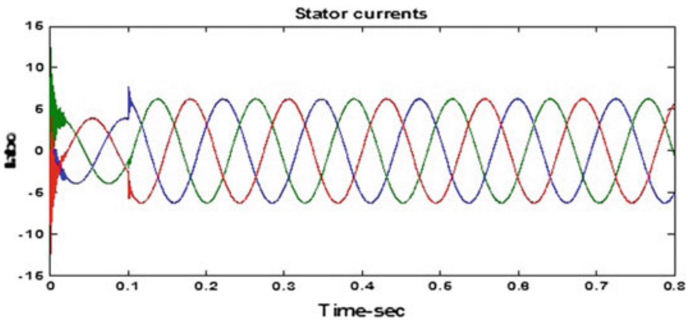

Fig. 9 Stator current response with balanced supply

4.3 Analysis of Three-Phase Stator Currents

The currents are obtained using Park's reverse transformation. It is clear that the current is non-sinusoidal at the starting and becomes sinusoidal when the motor reaches the controller command speed at steady state, as shown in Fig. 9. The steady-state error is reduced in FOC compared to stator currents under balanced supply as shown in Fig. 10.

The stator current error is more reduced with MRAS sensorless control. The MRAS based on stator currents of PMSM is used to estimate the speed at different load conditions. The results are shown in Fig. 11. In MRAS, current ripples are highly reduced and steady-state error is almost reduced to small value.

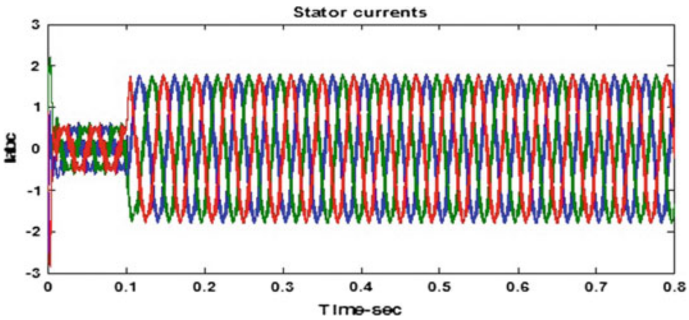

Fig. 10 Stator current response with FOC

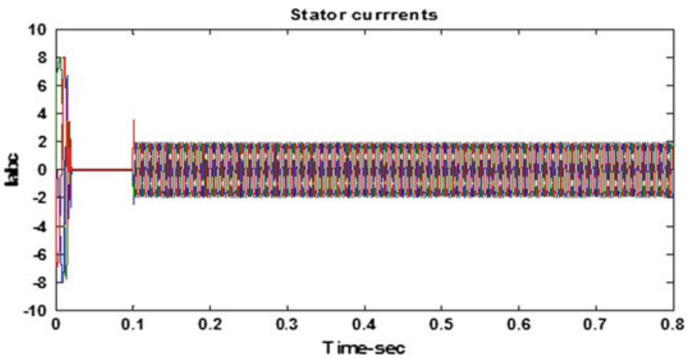

Fig. 11 Stator current response with FOC and MRAS

4.4 Analysis of Stator Flux Response

The total stator flux in three cases is shown in Figs. 12, 13 and 14. The rotor flux is $\lambda = 0.1750$, and the flux is increased with balanced supply but the flux ripples are more in FOC. Whereas in sensorless, the ripples are reduced to small magnitude due to correct estimate of speed and reduction torque harmonics.

4.5 Dynamic Performance of PMSM

The dynamic performances of PMSM with MRAS and without MRAS are shown in Figs. 15, 16, 17 and 18 for two cases:

(i) Dynamic response with constant speed and variable loads applied at different instants;

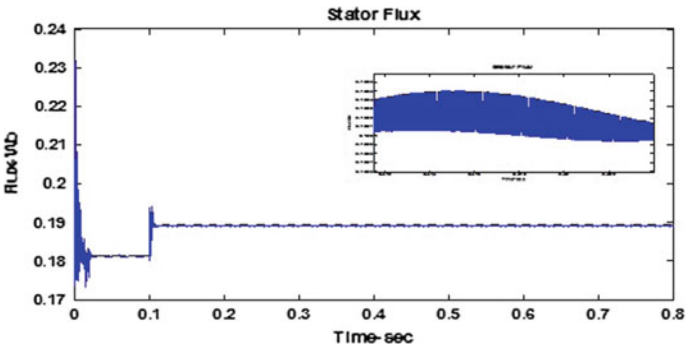

Fig. 12 Flux response with balanced supply

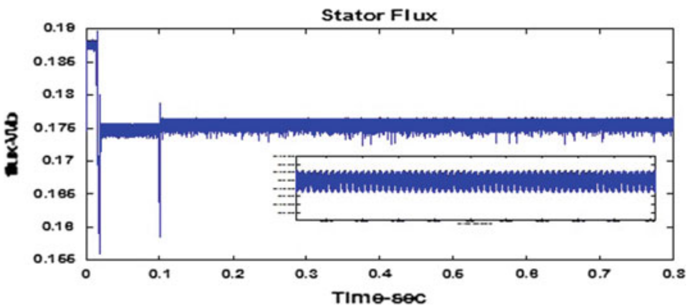

Fig. 13 Flux response with FOC

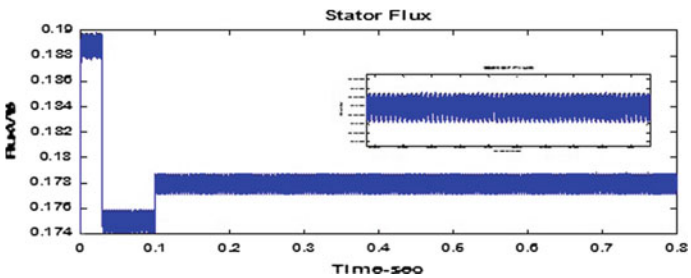

Fig. 14 Flux response with FOC and MRAS

(ii) Dynamic response with constant load and variable speeds applied at different instants.

The speed response is smooth with FOC, whereas torque response, flux response, and quadrature current responses are smooth with MRAS using FOC even though distortion is present; i.e., the magnitude of flux and torque ripples are less with MRAS than without MRAS (Figs. 7, 8, 13 and 14).

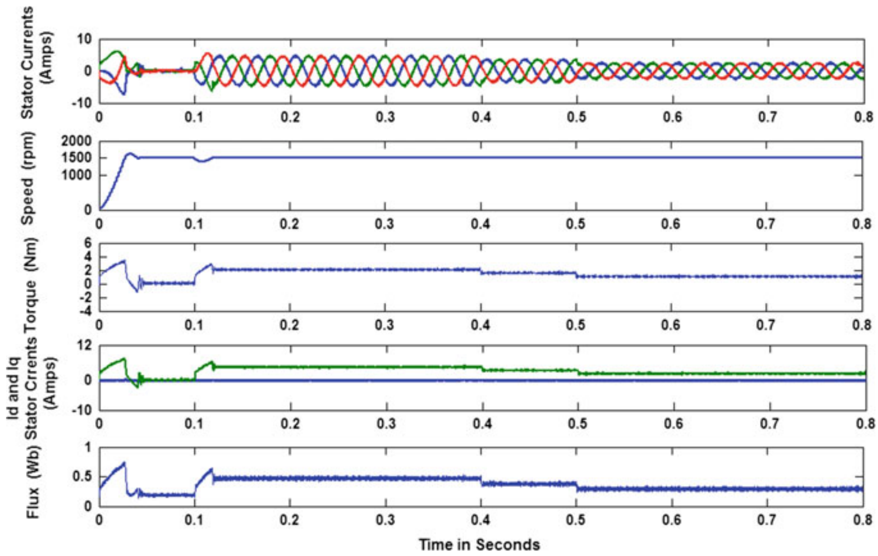

Fig. 15 Dynamic response of stator currents, speed, torque, direct current, quadrature current, and flux with FOC for constant speed

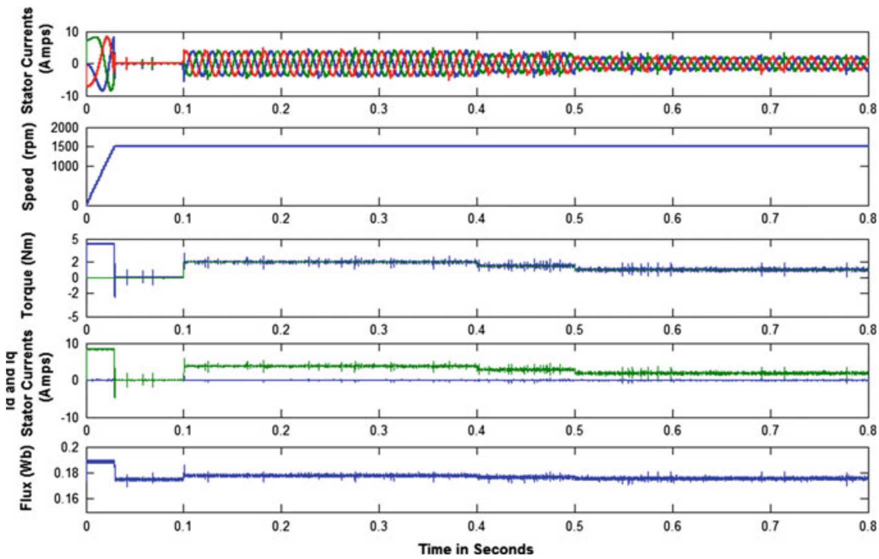

Fig. 16 Dynamic response of stator currents, speed, torque, direct current, quadrature current, and flux with FOC and MRAS for constant speed

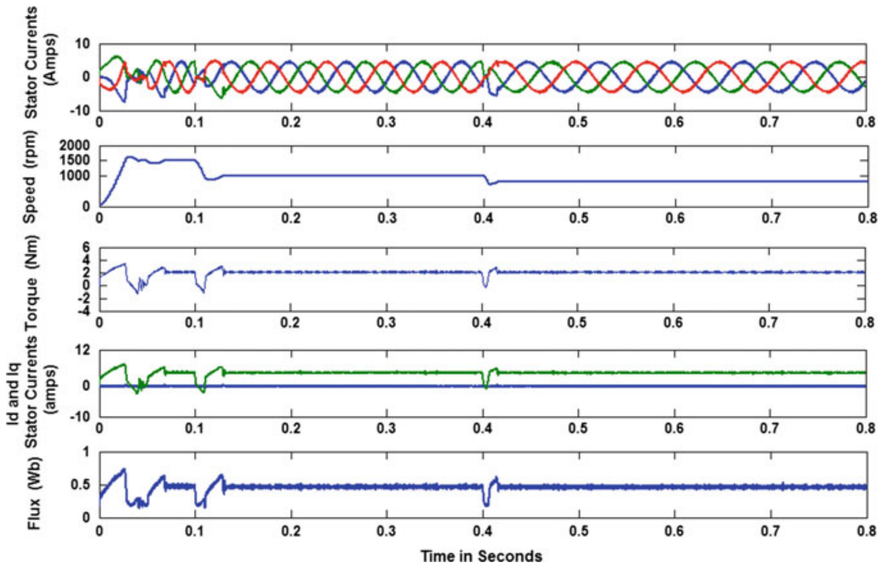

Fig. 17 Dynamic response of stator currents, speed, torque, direct current, quadrature current, and flux with FOC for constant torque

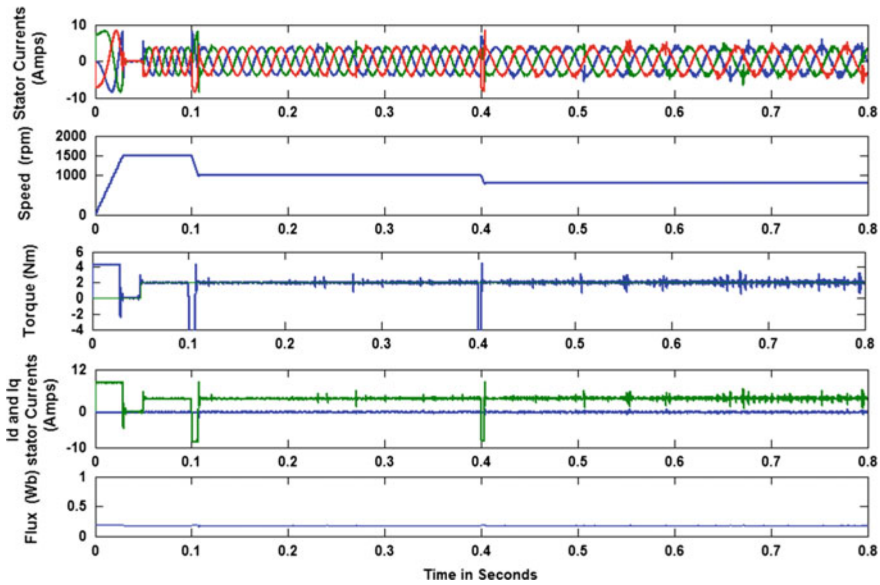

Fig. 18 Dynamic response of stator currents, speed, torque, direct current, quadrature current, and flux with FOC and MRAS for constant torque

5 Conclusion

The output of the adaptation mechanism is the estimated quantity ($\omega_{r,\mathrm{est}}$), 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. The method is simple and requires less computation. The drive is tested for three cases and also for dynamic conditions. It is found that with MRAS with PI controller, the drive performance is smooth, and torque and flux ripples are less. Further, this work can be extended with fuzzy logic controller along multilevel inverter topology.

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