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Sensorless Speed Estimation of Direct Field Oriented Control of Dual Induction Motor Drives Connected in Parallel

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Abstract—*The speed sensorless vector control method is primarily used in single inverter two motor drive system of same parameters and ratings connected in parallel. In this paper a new observer design technique, called the natural observer, is used which is employed to estimate the rotor speeds and rotor fluxes of both the induction motors. It also estimates the load torques of both the motors by load torque adaptation. The simulation work has been reported for different step changes in speed for balanced and unbalanced load condition. To make the system stable under the unbalanced load, the speed difference between the induction motors is lessened by considering the average and differential motor parameters and currents flowing in the stator windings. The estimation of rotor angle is achieved by direct vector control technique. Rotor flux control scheme is used to maintain the mean rotor flux constant.*

Keywords*: Induction Motor, Natural Observer, Sensorless Control, Torque Estimation, Direct Vector Control, PI Control*

1. INTRODUCTION

The elemental configuration of AC drives system is of inverter-motor type, where single inverter drives a multi-motors system which is connected in parallel such as electric railway traction system and steel process on account of cost-effectiveness, compactness and lightness etc. [1]. Earlier, various encoders or tacho-generators is used to sense the speed of the induction motor and hence speed can be controlled [2] [3]. In these days, several type of sensorless control schemes have been developed for variable speed ac drives because of there are low maintenance requirements; higher reliability; reduction of hardware complexity; overall ruggedness; increased noise immunity and elimination of sensor cables. Based on the information of line voltages and currents, speed can be estimated. If it is found that the speed-torque characteristics are same for both motor then speeds are equal and torque-sharing rates are same for all operating conditions [4].

In the case of balanced load conditions, the speed of both induction motors are same and hence the system is stable.it is because the rotor speed and the current taken by both induction motors are same, so the circulating current is zero. But if there is a change in the shaft velocity of induction motors, the current drawn by both motors differ and hence the circulating current increases. The reason behind the differences in rotor angular speed of motor are [5] mismatch between machine parameters and wheel diameters.

In the case of unbalanced load conditions, the speed of induction motor having low load decreases and the speed of other motor having high load increases up to a certain limit. So the system becomes unstable. To make the system again in stable condition, average and differential current are considered and the reference currents can be determined by knowing rotor fluxes [4]. Further, any difference between the two speeds of induction motors feedback may be fed to another PI controller which makes the system stable under unbalanced load conditions.

2. OPERATING PRINCIPLE OF SENSORLESS VECTOR CONTROLAND SPEED ESTIMATOR

A. SPEED ESTIMATION USING NATURAL OBSERVER

The natural observer, shown in Fig. 1 for the system described by (1) and (2) is in exactly the same form as the actual induction model and has no external feedback [6] [7] i.e., for the same conditions of input voltage and load torque, the observer state converges to the induction motor state. Such an observer will be a natural observer and its convergence will be as fast as that of the motor in reaching its steady state, which is fast enough for most applications.To achieve the convergence starting with, $\hat{T}_L \neq T_L$, a new load torque estimation scheme is proposed. The proposed scheme can be used with various induction motor models. In this paper, the fourth-order model is used [6] [8]. The state-space representation of the system is as follow

$$\frac{dX}{dt} = AX + BU \quad (1)$$

$$Y = CX \quad (2)$$

$$A=\begin{bmatrix} \frac{-1}{T_s} & 0 & \frac{MS_r}{\sigma L_s L_r} & \frac{M\omega_r}{\sigma L_s L_r} \\ 0 & \frac{-1}{T_s} & \frac{-M\omega_r}{\sigma L_s L_r} & \frac{MS_r}{\sigma L_s L_r} \\ S_r M & 0 & -S_r & -\omega_r \\ 0 & S_r M & \omega_r & -S_r \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad C=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

Where $T_s = \frac{\sigma L_s}{R_s + (R_r M / L_r^2)}$, $\sigma = 1 - \frac{M^2}{L_s L_r}$

$$S_r = \frac{1}{T_r}, \quad T_r = \frac{L_r}{R_r}$$

$$X = \begin{bmatrix} i_{ds} & i_{qs} & \phi_{dr} & \phi_{qr} \end{bmatrix}^T$$

$$U = \begin{bmatrix} v_{ds} & v_{qs} \end{bmatrix}^T, \quad Y = i_s = \begin{bmatrix} i_{ds} & i_{qs} \end{bmatrix}^T$$

The natural observer which estimates the stator current and the rotor flux is given by the following equations:

$$\frac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU \quad (3)$$

$$Y = CX \quad (4)$$

$$\hat{T}_L = K_D \dot{e}_P + K_P e_P + K_I \int e_P dt \quad (5)$$

Where $e_P = v_{ds}(\hat{i}_{ds} - i_{ds}) + v_{qs}(\hat{i}_{qs} - i_{qs})$

$$\dot{\hat{\omega}}_r = (3/2)(n_p/J)(M/L_r)[\hat{\phi}_{dr}\hat{i}_{qs} - \hat{\phi}_{qr}\hat{i}_{dr}] - \hat{T}_L/J$$

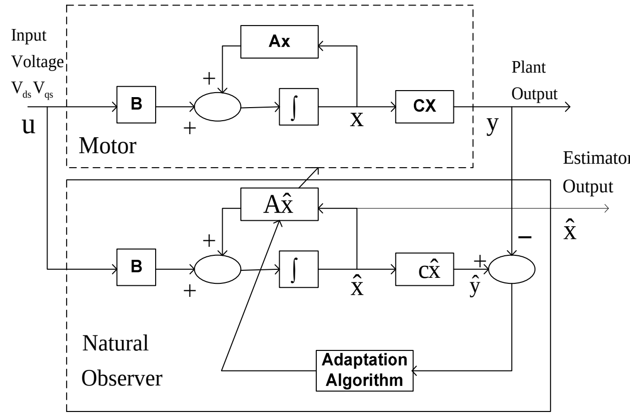

Fig. 1: Natural observer with adaptation

B. Current model of parallel-connected induction motors

The currents i_{s1} and i_{s2} are stator currents of IM 1 and IM2 respectively. In case of the unbalanced loads, i_{s1} and i_{s2} are not equal. This is because the circulating stator current flows from IM of light load to that of the heavy one. This $\overline{i_s}$ current is compared with the reference current i_s^* to produce the required control voltage for the inverter [2] [9]. Equation (6) and (7) express the average stator current and circulating stator current is respectively.

$$\overline{i_s} = \frac{i_{s1} + i_{s2}}{2} \quad (6)$$

$$\Delta i_s = \frac{i_{s1} - i_{s2}}{2} \quad (7)$$

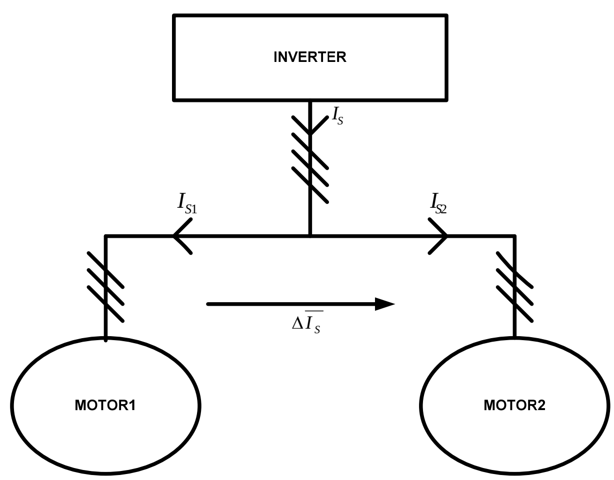

Fig. 2: Shows the current flowing in the parallel connected induction motor.

C. Calculation of Reference Current for Parallel Connected Induction Motor Drive

The current i_{ds}^* is generated by comparing the actual average rotor flux with the set reference flux and the error is given to the PI controller which gives the desired value of i_{ds}^*. The reference current i_{qs}^* is derived from the torque reference.

$$i_{qs}^* = \frac{L_r}{pL_m \hat{\overline{\phi}}_r}\overline{T}_e^* \quad (8)$$

$$\overline{T}^* = \frac{\overline{T}_e - \left(\frac{\Delta\overline{M}'}{\overline{M}'}\right)\Delta\overline{T}_e}{1-\left(\frac{\Delta\overline{M}'}{\overline{M}'}\right)^2}, \quad \overline{M} = \frac{L_{m1}+L_{m2}}{2}$$

$$\overline{M}' = \frac{1}{2}\left(\frac{L_{m1}}{L_{r1}}+\frac{L_{m2}}{L_{r2}}\right), \quad \Delta\overline{M}' = \frac{1}{2}\left(\frac{L_{m2}}{L_{r2}}-\frac{L_{m1}}{L_{r1}}\right)$$

$$\overline{i}_s^e = \frac{i_{s1}^e + i_{s2}^e}{2} \quad \hat{\overline{\omega}}_r = \frac{\omega_{r1}+\omega_{r2}}{2}$$

$$\Delta\hat{\overline{\omega}}_r = \frac{\hat{\omega}_{r2}-\hat{\omega}_{r1}}{2} \quad \Delta i_s^e = \frac{i_{s2}^e - i_{s1}^e}{2}$$

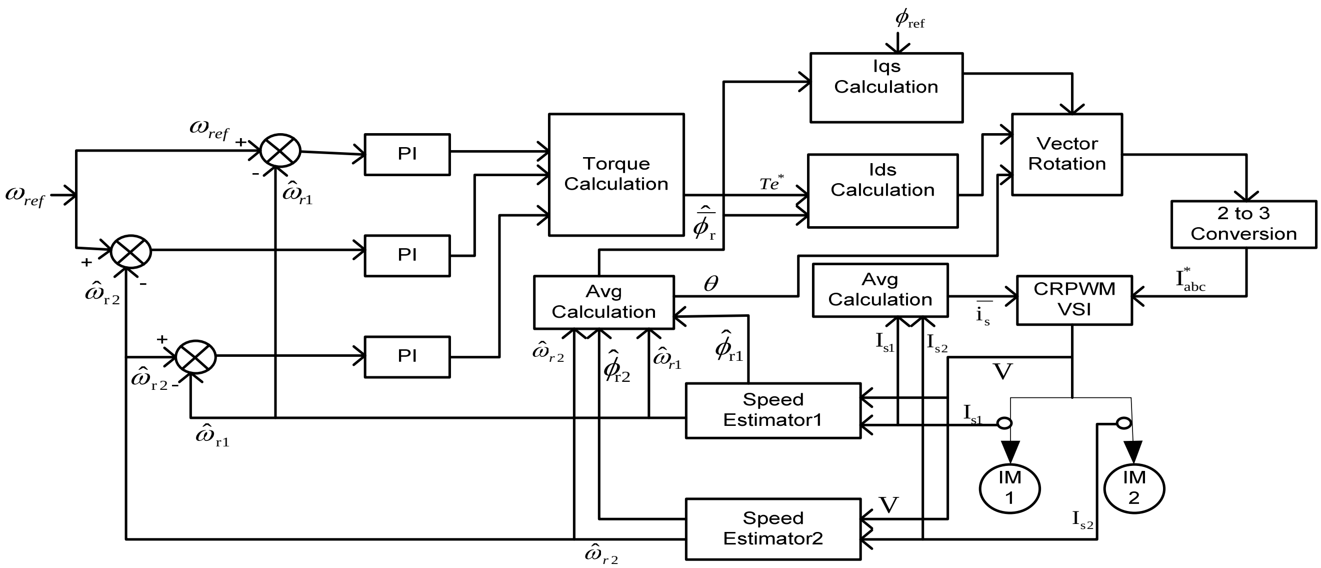

Fig. 3 Proposed System Configuration of parallel connected induction motor drive system

D. Calculation of Reference Torque for parallel Connected Induction Motor Drive

The average torque of dual induction motors is represented by the following equation:

$$\overline{T}_e^* = \frac{T_{e1}^* + T_{e2}^*}{2}$$

T_{e1}^* and T_{e2}^* are derived from the controller and are reference torque for motor 1 and motor 2.

TABLE I: RATING AND PARAMETERS OF INDUCTIOMOTOR

MOTOR RATING	
OUTPUT	0.746 KW
POLES	4
SPEED	1415 RPM
VOLTAGE	415 V
CURRENT	1.8 A
Rs	19.355 Ω
Rr	8.43 Ω
Ls	0.715 H
Lr	0.715 H
Lm	0.689 H

3. SYSTEM CONFIGURATION

Fig. 3 shows the proposed system configuration. The main components are Speed Estimator for both motor, a vector rotation block, the calculation block of reference currents and Current Regulated PWM voltage source inverter. The estimated speed is calculated from the measured Stator currents and voltage [3]. Calculation of torque reference of both motor is from the difference between speed reference and the estimated speed by using Proportional-integral controllers [5]. Fig. 4 shows the block diagram representation of speed estimator. The average torque reference is calculated from the combined output of PI controllers.

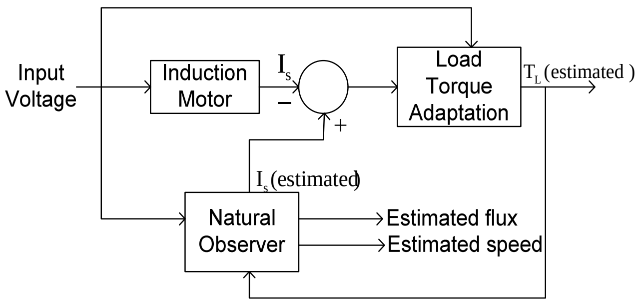

Fig. 4 Block diagram representation

4. SIMULATION RESULTS AND DISCUSSIONS

Fig. 5-10 shows the simulation results under balanced and unbalanced load condition. Direct vector control Induction motor drive is tested for the step changes in speed for the Balanced and Unbalanced load condition. Simulations are carried out under MATLAB Simulink environment. Table II and III shows the simulation conditions under step changes in speed. The reference and actual speed of Induction motor for the successive speed command for the balanced load as shown in Table II. The reference speed is set at 1100 rpm. Initially, both motor has no load. At t = 0.5 s, a load of 2 Nm is applied to both Motor throughout the operation. The estimated and actual speed responses of both the motors are shown in Fig. 5. We see that the actual speed follows the reference speed.

In unbalanced load condition, i.e. a load of 1 Nm is applied to IM1 for 2 s as shown in Table III. The estimated and actual speed responses of both the motors are shown in Fig. 6. Actual speed is obtained from the induction motor model constructed in Simulink environment using state space equations. Speed estimation is done by the measured terminal voltages and currents by a natural observer. Estimated speed of motor 1 decreases by 2 rpm and speed of motor 2 decreases by 100 rpm but still the system is stable; this is because of additional PI controllers used in the speed control loop. The speed deviation of motor 1 and motor 2 with respect to the reference speed is shown in Fig. 9-10. At t = 5 s, load torque of motor 1 increases from 1 Nm to 2 Nm and the load torque of motor 2 remains same. The torque of both motors is estimated by load torque adaptation. Estimation of torque is done the power equation and load torque adaptation technique. And calculation of actual torque is done by the motor-load dynamic equation. By changing the width of the hysteresis band, Ripple in actual torque is compensated. The estimated torque and actual torque responses are shown in Fig. 7-8. It shows that the estimated torque of both induction motors follows the actual load torque with very less ripple.

5. CONCLUSION

In this paper, new observer design technique and adaptation has been used to estimate the speed and rotor fluxes of induction motors. Simulation results under step change in speed shows that the stability of the proposed technique for both balanced and unbalanced load conditions.

TABLE II: Balanced Load Condition

TIME(s)		0	0.5	1	2	3	4	5
REFERENCE SPEED(rpm)	IM1	0	0	1100	700	700	1100	0
	IM2	0	0	1100	700	700	1100	0
TORQUE (Nm)	IM1	0	2	2	2	2	2	2
	IM2	0	2	2	2	2	2	2

TABLE III: Unbalanced Load Condition

TIME(s)		0	0.5	1	2	3	4	5
REFERENCE SPEED(rpm)	IM1	1100	1100	1100	1100	1100	1100	1100
	IM2	1100	1100	1100	1100	1100	1100	1100
TORQUE (Nm)	IM1	0	2	2	2	1	1	2
	IM2	0	2	2	2	2	2	2

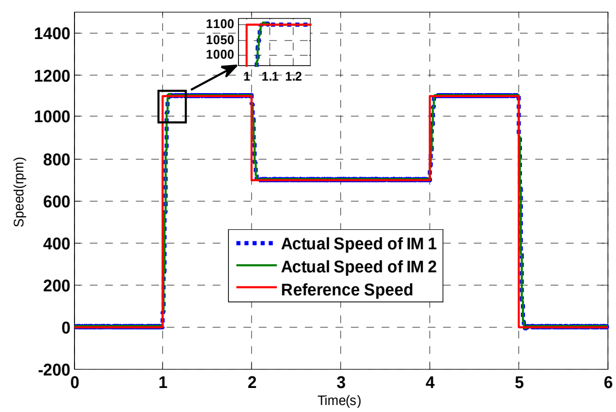

Fig. 5(a) Actual Speed Response under balanced load

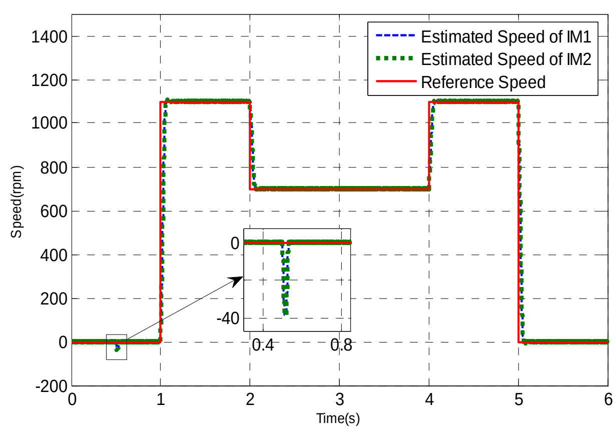

Fig. 5(b) Estimated Speed Response under balanced load

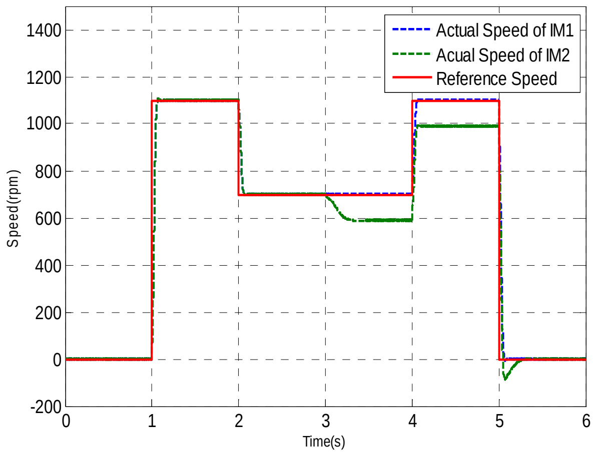

Fig. 6(a) Actual Speed Response under unbalanced load

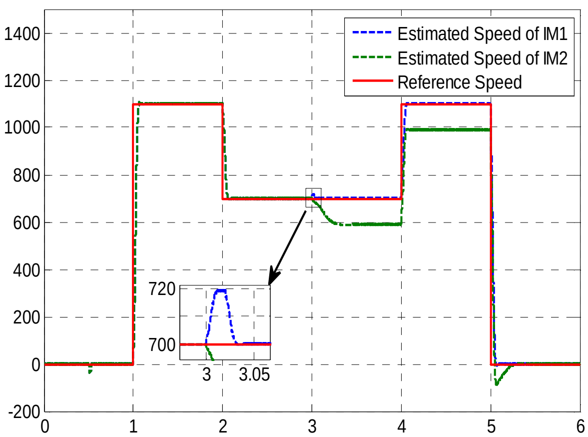

Fig. 6(b) Estimated Speed Response under unbalanced load

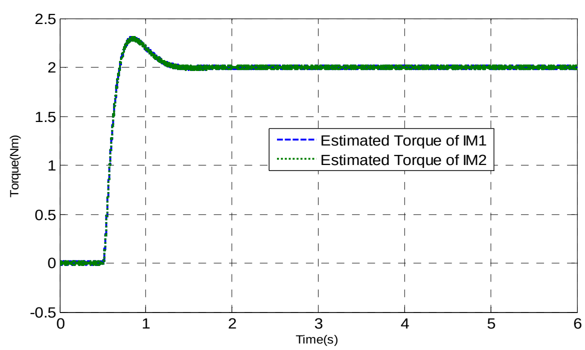

Fig. 7(a) Estimated Torque Response under balanced load

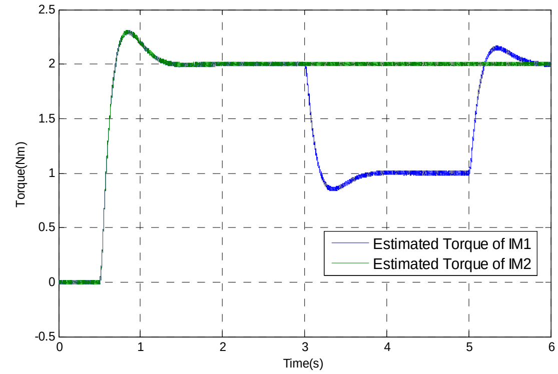

Fig. 7(b) Estimated Torque Response under unbalanced load

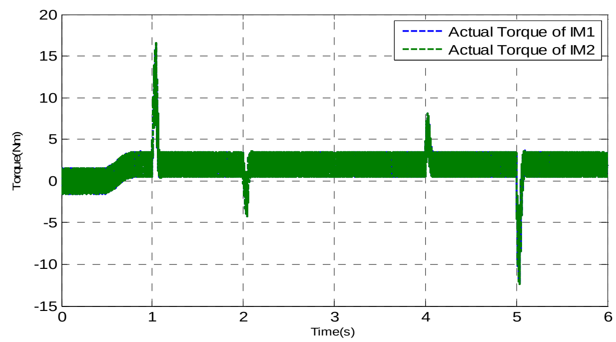

Fig. 8(a) Actual Torque Response under balanced load

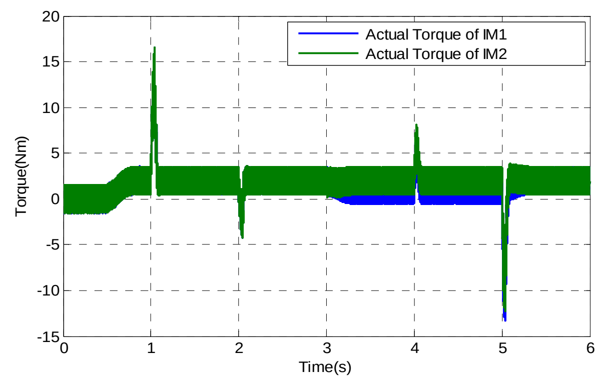

Fig. 8(b) Actual Torque Response under unbalanced load

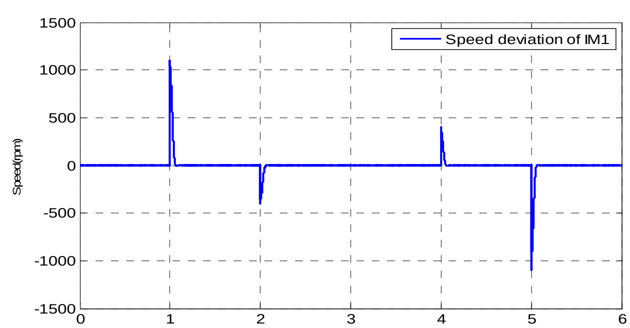

Fig. 9(a) Speed deviation of IM1 under balanced load

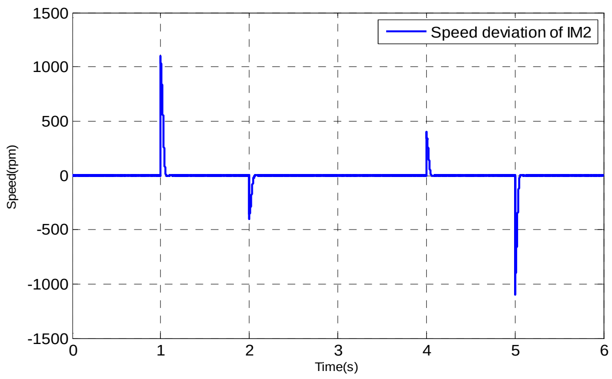

Fig. 9(b) Speed deviation of IM2 under balanced load

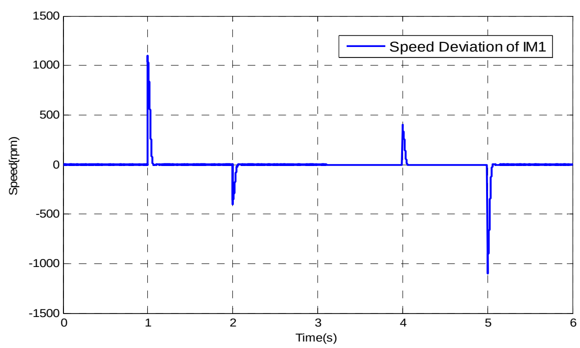

Fig. 10(a) Speed deviation of IM1 under unbalanced load

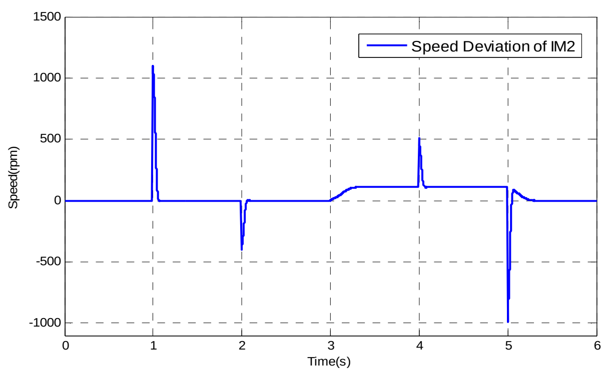

Fig. 10(b) Speed deviation of IM2 under unbalanced load

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