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Single Inverter Fed Speed Sensorless Vector Control of Parallel Connected Two Motor Drive

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Original scientific paper

This paper describes a speed sensorless vector control method of the torque for cost-effective parallel-connected dual induction motor fed by a single inverter. A natural observer with load torque adaptation is employed to estimate the speeds of the same rating induction motors connected in parallel and fed by a single inverter. The speed difference between the two induction motors for unbalanced load conditions is less in natural observer than the conventional adaptive rotor flux observer. Direct field oriented control is used to calculate the rotor angle from the estimated rotor fluxes and the mean rotor flux is kept constant by rotor flux feedback control. The simulation and experimental results of studies are demonstrated for various running conditions to prove the effectiveness of the proposed method. The closed loop speed control operation with inner current control was performed by TMS320F2812 processor.

Key words: Field oriented control, Induction motor, Natural observer, Sensorless vector control

Vektorsko upravljanje momentom bez korištenja senzora brzine za paralelno spojeni pogon s dva motora. U ovom radu opisano je vektorsko upravljanje momentom bez korištenja senzora brzine za paralelno spojeni dualni asinkroni motor napajan jednim inverterom. Prirodni observer s adaptacijom momenta tereta koristi se za estimaciju brzina jednakih asinkronih motora spojenih u paralelu i napajanih jednim inverterom. Razlika u brzinama između dva asinkrona motora pri asimetričnim teretima je manja kod prirodnog observera, nego kod konvencionalnog adaptivnog observera toka u rotoru. Izravno vektorsko upravljanje koristi se za računanje kuta rotora iz estimiranih tokova rotora, a srednja vrijednost toka rotora održava se konstantnom korištenjem upravljanja u povratnoj vezi. Simulacijski i eksperimentalmni rezultati prikazani su za različite pogonske uvjete kako bi se pokazala učinkovitost predložene metode. Upravljanje brzinom u zatvorenoj petlji s unutanjim krugom za upravljanje strujom izvodi se u TMS320F2812 procesoru.

Ključne riječi: vektorsko upravljanje, asinkroni motor, prirodni observer, vektorsko upravljanje bez senzora

1 INTRODUCTION

Induction motors dominate ac industrial drive applications around the world because of their simple structure, ruggedness, reliability, inexpensive and less maintenance. Encoders or tacho-generators are required for the purpose of control of speed and position of the induction motor drive. The installation of an encoder is not always feasible or affordable: hollow shaft motors, high environment temperature, high speed range and adverse environmental conditions are some of the reasons that make a sensorless scheme desirable [1]. The term “sensorless” refers to the fact that no conventional speed or position sensors are used in these drives [2].

Speed sensorless vector control is used to drive the induction motor accurately with one inverter driving one induction motor. In electric traction and steel processing industries, one inverter drives multiple induction motors connected in parallel to save cost, to reduce space and weight. The speed sensor used in traction drive had ultra low resolution rotary encoder, such as 60 pulses/rev and the detection time was around 25ms [3]. It is difficult for a drive system of electric motor coach to realize a fine anti-slip and re-adhesion control by using speed sensor. So, the implementation of sensorless vector control to electric motor coach is necessary. The ratings and parameters of the induction motors connected in parallel are identical in traction drives. If the motors have matched speed-torque characteristics and their speeds are equal, their torque sharing will be equal at all operating conditions. In practice, there will be some amount of mismatch in motor characteristics, and speeds may not be identical because of mismatch in the wheel diameters.

Various works have been carried out in speed sensorless vector control of multi motor, single inverter drive system. Parallel connected induction motor drive with different speed controllers and speed observers were discussed in literatures. In most of the multiple induction motor drive systems 'single motor' vector control scheme was applied, which treats the parallel connected motors as one large induction motor and speed sensor was attached to only one motor properly chosen among many motors [4]. However, in these methods unbalances of torque and current make the system unstable. It is overcome by considering the average and differential parameters and also employing different speed controllers.

Speed sensorless vector control of parallel connected dual induction motor drive based on the dynamic model was presented in [5]. The speeds of both induction motors were estimated using discrete Luenberger observer. The unexpected speed and torque transients were the limitations due to parameter variations. A control technique in which the d-axis was aligned with the mean flux vector of both motors was presented in [6]. The tests were carried out only for constant torque load and also the mean value was considered. Parallel connected dual induction motor drive fed by a single inverter with adaptive rotor flux observer was discussed in [7]-[10] where the proposed method was not verified under different load conditions..

In addition, to control the speed of parallel connected induction motor drive and to make the drive stable for unbalanced load conditions, nonlinear programming method [11]-[12], rotor flux oriented control scheme with parameter averaging and space vector averaging [13], motors with different ratings [14]-[15], adjustable PI controllers [16], rotor flux feedback control [17], matrix converter with slip frequency vector control [18], one degree of freedom control (1DOF) and two degree of freedom control (2DOF) [19], weighted voltage vector [20], new hybrid control method (speed and torque controller) [21], speed-irrelevant motors using weighted flux linkage vector control [22], smart switching technique [23], mean and master slave field oriented control [24] and PI speed and current controllers [25] were employed.

In most of the research papers, adaptive rotor flux observer was employed to estimate the speed and rotor fluxes of both the motors. The selection of gain matrix constant (k) is a tedious task in adaptive rotor flux observers where the typical value is taken as 0.5. It is mandatory to have correction factors to track the speed variations that results the estimation lags the actual command signal. To overcome the above difficulties, natural observer [26] is proposed in this paper to calculate the rotor speed, stator current, rotor fluxes and the load torques of both the motors. Direct field oriented vector control scheme is employed to calculate the flux angle and the average rotor flux derived from both induction motors is kept constant by rotor flux feedback control. Average and differential currents flowing through the stator and rotor fluxes are used to calculate the reference currents. In most of the research papers dealt with parallel connected induction motor drive, the hardware results were presented for step change in speed under no load conditions. In this work, experimental results are proposed for increase and decrease in speed, multi-step change in speed, balanced and unbalanced load conditions to prove the effectiveness of the proposed method.

2 SPEED ESTIMATION USING NATURAL OBSERVER

The structure and features of the natural observer are identical to the induction motor for the given supply voltage and load torque. The major difference between natural and adaptive rotor flux observer is that there is no external feedback. So, the convergence rate of the natural observer is faster than that of the motor in reaching the steady state and as a result, the speed estimation follows the speed changes simultaneously. Load torque adaptation is used to estimate the load torque from the active power error. Fourth order state space induction motor model in stator flux oriented reference frame is used to estimate the speed, whereas fifth order state space induction motor model in synchronous reference frame is used in the literature [26]. The state variables are dq-axes stator currents and rotor fluxes and the induction motor is represented in the stationary reference frame by the following state equations [26]:

$$\frac{\mathrm{dX}}{\mathrm{dt}} = \mathrm{AX} + \mathrm{BV_s} \qquad (1)$$

$$\mathrm{Y} = \mathrm{CX} \qquad (2)$$

where,

$$A = \begin{bmatrix} \frac{-1}{\mathrm{T_s}} & 0 & \frac{\mathrm{L_m}}{\mathrm{L_s'L_r}\tau_\mathrm{r}} & \frac{\omega_\mathrm{r}\mathrm{L_m}}{\mathrm{L_s'L_r}} \\ 0 & \frac{-1}{\mathrm{T_s}} & \frac{-\omega_\mathrm{r}\mathrm{L_m}}{\mathrm{L_s'L_r}} & \frac{\mathrm{L_m}}{\mathrm{L_s'L_r}\tau_\mathrm{r}} \\ \frac{\mathrm{L_m}}{\tau_\mathrm{r}} & 0 & \frac{-1}{\tau_\mathrm{r}} & -\omega_\mathrm{r} \\ 0 & \frac{\mathrm{L_m}}{\tau_\mathrm{r}} & \omega_\mathrm{r} & \frac{-1}{\tau_\mathrm{r}} \end{bmatrix}$$

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

$$\frac{1}{T_s} = \frac{\mathrm{R_s}+\mathrm{R_r}\left(\frac{\mathrm{L_m}}{\mathrm{L_r}}\right)\left(\frac{\mathrm{L_m}}{\mathrm{L_r}}\right)^2}{\mathrm{L_s'}}; \mathrm{L_s'}=\sigma\mathrm{L_s}.$$

$\sigma = 1-\frac{\mathrm{L_m^2}}{\mathrm{L_sL_r}}$ - Leakage coefficient.

$$X=\left[\begin{array}{cccc} i_{ds}^{s} & i_{qs}^{s} & \varphi_{dr}^{s} & \varphi_{qr}^{s} \end{array}\right]^{T};$$

$$Y=\left[\begin{array}{cc} i_{ds}^{s} & i_{qs}^{s} \end{array}\right]=i_s;\, V_s=\left[\begin{array}{cc} V_{ds}^{s} & V_{qs}^{s} \end{array}\right]^{T}.$$

The observer equation for speed estimation is given below:

$$\frac{d\widehat{X}}{dt}=\widehat{A}\widehat{X}+BV_s \tag{3}$$

$$\widehat{Y}=C\widehat{X} \tag{4}$$

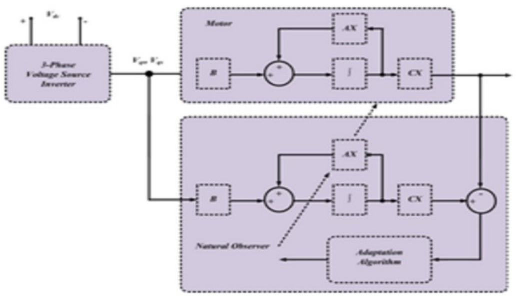


Fig. 1. Block diagram of a natural observer

Fig. 1 shows the block diagram representation of the Natural observer and the system described by (3) and (4) are exactly the same form as the induction motor model without any external feedback [26]. Load torque is estimated by the active power error as the correction term and is given by [26]:

$$\widehat{T_L}=K_P e_P+K_I\int e_P dt \tag{5}$$

where $e_P=V_{ds}^{s}\left(\widehat{i}_{ds}^{e}-i_{ds}^{e}\right)+V_{qs}^{s}\left(\widehat{i}_{qs}^{e}-i_{qs}^{e}\right)$

Rotor speed is estimated from the dq-axes stator currents, rotor fluxes and the rotor speed from the following equation [27]:

$$\dot{\hat{\omega}}_r=\left(\frac{3}{2}\right)\left(\frac{n_p}{J}\right)\left(\frac{L_m}{L_r}\right)\left[\widehat{\varphi}_{dr}^{s}\widehat{i}_{qs}^{s}-\widehat{\varphi}_{qr}^{s}\widehat{i}_{ds}^{s}\right]-\frac{\widehat{T_L}}{J} \tag{6}$$

3 PARALLEL CONNECTED INDUCTION MOTOR DRIVE

Fig. 2 shows the current flow in the parallel connected induction motor drive fed by a single inverter [10]. The inverter current is divided into two parts i_{s1} and i_{s2}. If the currents flowing through the stator windings are equal, the circulating current will be zero and the parallel connected

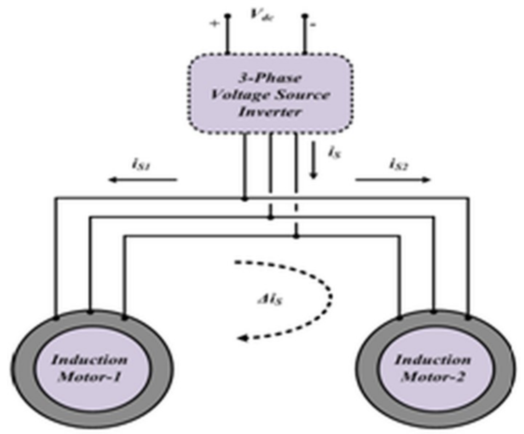


Fig. 2. Current flow for parallel connected induction motor drives

motors can be treated as a single motor. Current flow in each motor will not be equal if there is a difference in the wheel diameters or the motor parameters. In this situation, the average current and torque can be expressed as follows [10]:

$\bar{i}_s=\frac{i_{s1}+i_{s2}}{2}$ $\bar{i}_s$- Average of $i_{s1}$and i_{s2}

$$\overline{T}_e=\frac{T_1+T_2}{2}=T^* \tag{7}$$

where T_1 and T_2 are derived from the speed controllers.

Average current $\bar{i}_s$ is compared with the reference current i_s^* to generate the control voltage for the inverter. Fig. 3 shows the configuration of the parallel connected induction motor drive fed by a single inverter. The main components are: speed estimator with adaptation algorithm, calculation block for reference currents and Current Regulated Pulse Width Modulated (CRPWM) voltage source inverter. With the measured line voltages and currents, the speeds of both motors are estimated and the torque reference of each motor is obtained from the speed error using PI controllers. The reference currents for average flux and average torque are derived by considering the average and differential parameters of the motors, stator currents and rotor fluxes to make the system stable. Correspondingly, the reference currents are represented by the following equations [10]:

$$\overline{i_{ds}^{e*}}=\frac{\overline{S_r}\;\overline{\varphi_{dr}^{e*}}+\Delta\widehat{\overline{\omega_r}}\;\Delta\widehat{\overline{\varphi_{qr}^{e}}}+\Delta\overline{S_r}\Delta\widehat{\overline{\varphi_{dr}^{e}}}\;-\Delta\overline{U}\;\Delta\widehat{\overline{i_{ds}^{e}}}}{\overline{U}} \tag{8}$$

$$\bar{i}_{qs}^{e*}=\frac{\frac{\overline{T'}}{\overline{pM'}}-\Delta\widehat{\bar{i}}_{ds}^{e}\times\Delta\widehat{\bar{\varphi}}_{dr}^{e}+\Delta\widehat{\bar{i}}_{qs}^{e}\times\Delta\widehat{\bar{\varphi}}_{qr}^{e}}{\widehat{\bar{\varphi}}_{dr}^{e*}} \tag{9}$$

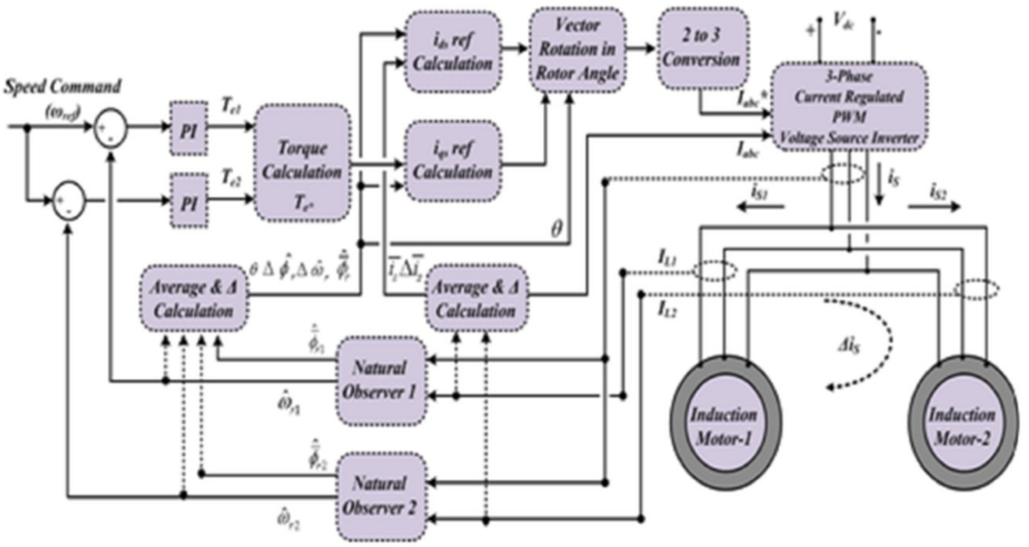


Fig. 3. Control system of the parallel connected induction motor drive

$$\overline{\mathrm{T}'}=\frac{\overline{\mathrm{T_e}}-\left(\frac{\overline{\triangle\mathrm{M}'}}{\overline{\mathrm{M}'}}\right)\Delta\overline{\mathrm{T_e}}}{1-\left(\frac{\overline{\triangle\mathrm{M}'}}{\overline{\mathrm{M}'}}\right)^2} \tag{10}$$

where,

$$U=S_rL_m \quad \overline{\mathrm{U}}=\frac{\mathrm{U_1+U_2}}{2} \quad \triangle\overline{\mathrm{U}}=\frac{\mathrm{U_2-U_1}}{2}$$

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

$$\overline{i_s^e}=\frac{i_{s1}^e+i_{s2}^e}{2}\overline{\Delta i_s^e}=\frac{i_{s2}^e-i_{s1}^e}{2}$$

$$\overline{\widehat{\omega}_\mathrm{r}}=\frac{\widehat{\omega}_\mathrm{r1}+\widehat{\omega}_\mathrm{r2}}{2}\overline{\widehat{\Delta\omega_\mathrm{r}}}=\frac{\widehat{\omega}_\mathrm{r2}-\widehat{\omega}_\mathrm{r1}}{2}$$

$$\overline{\mathrm{S_r}}=\frac{\mathrm{S_{r1}}+\mathrm{S_{r2}}}{2}\overline{\Delta\mathrm{S_r}}=\frac{\mathrm{S_{r2}}-\mathrm{S_{r1}}}{2}$$

4 SIMULATION RESULTS AND DISCUSSIONS

Two identical three-phase squirrel cage induction motors of 0.746 kW (1HP) are used for parallel configuration. Table 1 shows the rating and parameters of the induction motors used for simulation and experimental set up. Direct field oriented sensorless vector control scheme is used to calculate the rotor angle from the estimated rotor fluxes.

Table 1. Ratings and parameters of induction motor

Motor ratings			
Output	0.746 kW	R_s	19.355 Ω
Poles	4	R_r	8.43 Ω
Speed	1415 rpm	L_s	0.715 H
Frequency	50 Hz	L_r	0.715 H
Voltage	415 V	L_m	0.689 H
Current	1.8 A		

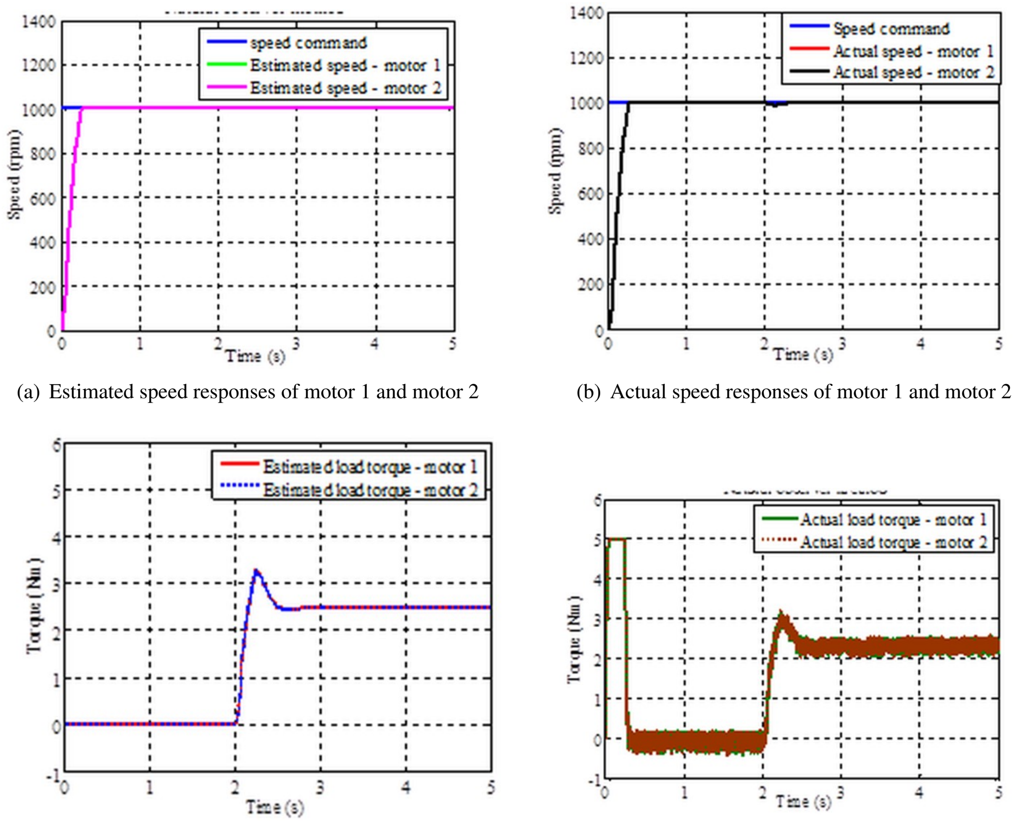
Simulations are carried out in MATLAB simulink environment.

Case (i) Balanced Load

The reference speed command is set at 1000 rpm initially. Neither motor has load. A balanced load of 2.5 Nm is applied to both induction motors at t = 2s. The estimated and actual speed and torque responses of induction motor 1 and motor 2 are shown in Fig. 4. The estimated and actual speeds of motor 1 and motor 2 are depicted in Fig. 4 (a) and Fig. 4 (b) respectively. At steady state, the difference between the estimated and actual speed is zero and the estimated speed follows the actual speed. With respect to the command speed, the estimated and actual speeds of the induction motors follow the command speed without any steady state error.

The actual and estimated load torque responses of the induction motor 1and motor 2 are illustrated in Fig. 4 (c) and Fig. 4 (d) in that order. These results demonstrate that when the load is balanced, the speeds of both motors follow the speed command.

Case (ii) Unbalanced Load Conditions



(a) Estimated speed responses of motor 1 and motor 2

(b) Actual speed responses of motor 1 and motor 2

(c) Estimated load torque responses of motor 1 and motor 2

(d) Actual load torque responses of motor 1 and motor 2

Fig. 4. Simulation results for balanced load conditions

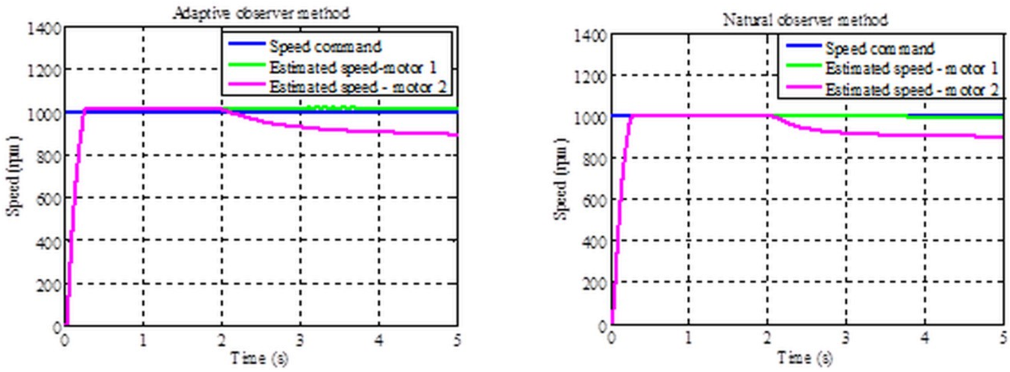
Unbalanced load test is carried out for the proposed natural observer and it is compared with the well known conventional adaptive observer [9]. Both induction motors run at a constant speed of 1000 rpm. A load of 2.5 Nm is applied to motor 2 at t = 2s and motor 1 is at no load condition. Fig. 5 (a) and Fig. 5 (b) show the estimated and actual speed responses of motor 1 and motor 2 respectively for unbalanced load conditions. The speed difference between the induction motor 1 and motor 2 are depicted in Fig. 5 (c).

In adaptive observer method, the estimated speed of motor 2 decreases to 890 rpm and the speed of motor 1 increases to 1020 rpm. The speed difference among the motors under steady state is 130 rpm. The speed difference between the estimated speed of motor 1 and speed command is 20 rpm (2%) and the speed difference between the estimated speed of motor 2 and speed command is 110 rpm (11%). In natural observer method, the estimated speed of motor 2 decreases to 906 rpm and the speed of motor 1 remains the same as 1000 rpm. The speed difference of the motors under steady state is 94 rpm. There is no difference between the estimated and speed command in motor 1 and a difference of 94 rpm (9.4%) exists between the estimated speed and speed command in motor 2.

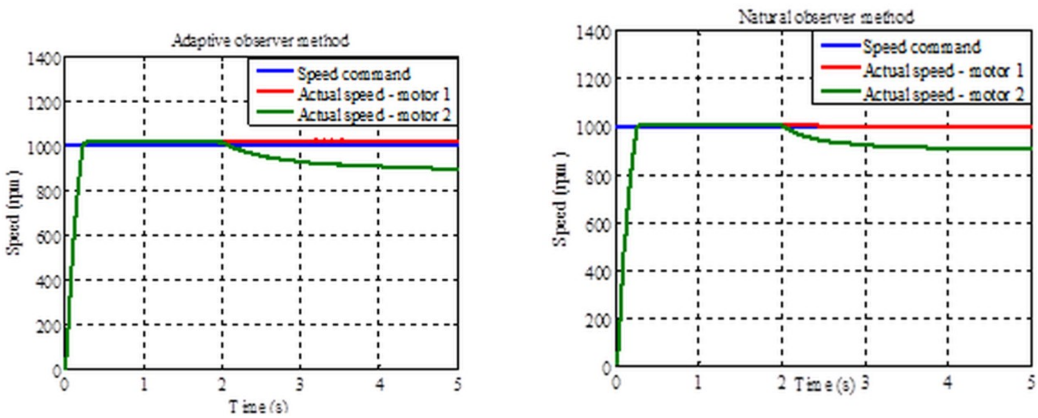
The actual torque responses of induction motor 1 and motor 2 by both observers are illustrated in Fig. 5 (d). The torque ripple is less in natural observer than in adaptive observer. The estimated torque response of the motor 1 and motor 2 by natural observer method is illustrated in Fig. 6 and it is inferred that it follows the actual load torque.

It is concluded that a natural observer can be used instead of an adaptive rotor flux observer because of its simple structure and the absence of feedback gain. It also estimates the load torque. The speed difference among the induction motors for unbalanced load conditions is less in natural observer. The difference between the estimated and reference speed is nearly zero for balanced load conditions in both the observers. The speed deviation occurs during unbalanced load conditions with respect to the reference speed in both the observers. The estimated and actual speed of motor 1 and motor 2 is not equal to the command speed under unbalanced load conditions. However, both motors run at a constant steady speed and are stable.

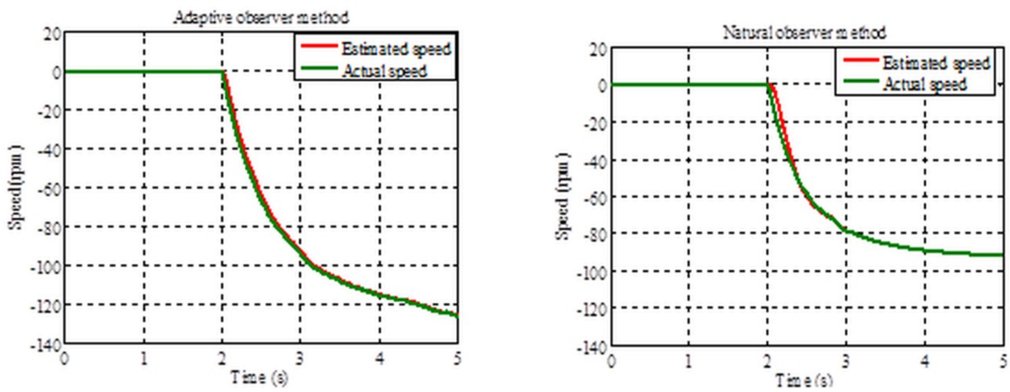
Case (iii) Multi -step change in speed



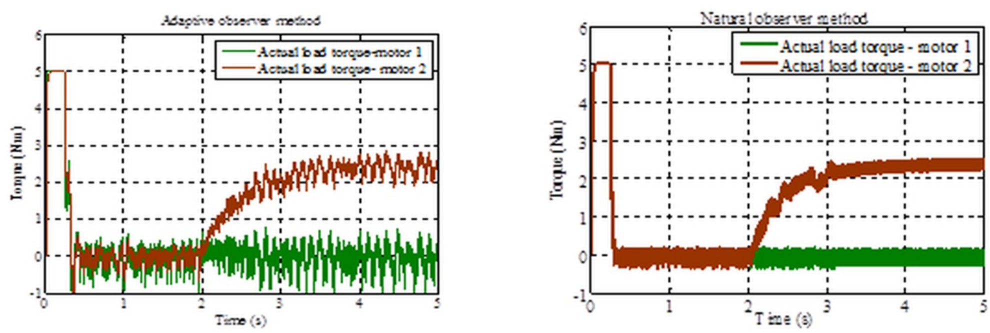
(a) Estimated speed responses of motor 1 and motor 2



(b) Actual speed responses of motor 1 and motor 2

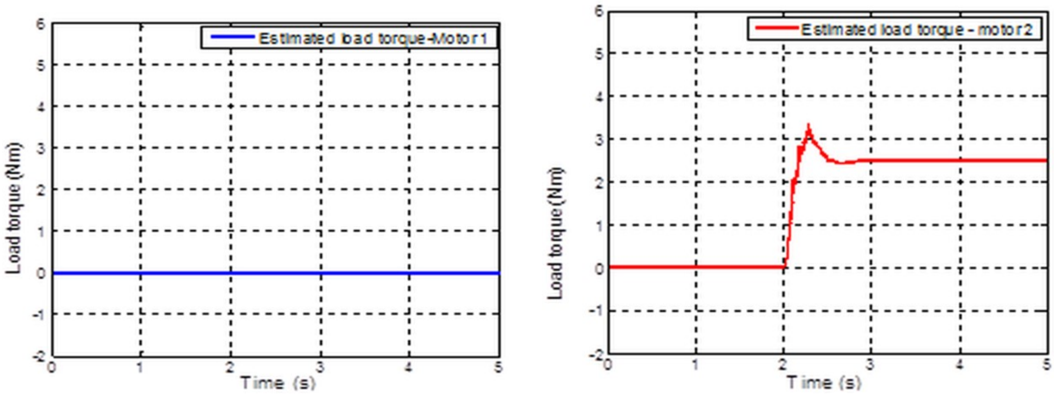


(c) Speed difference between motor 1 and motor 2



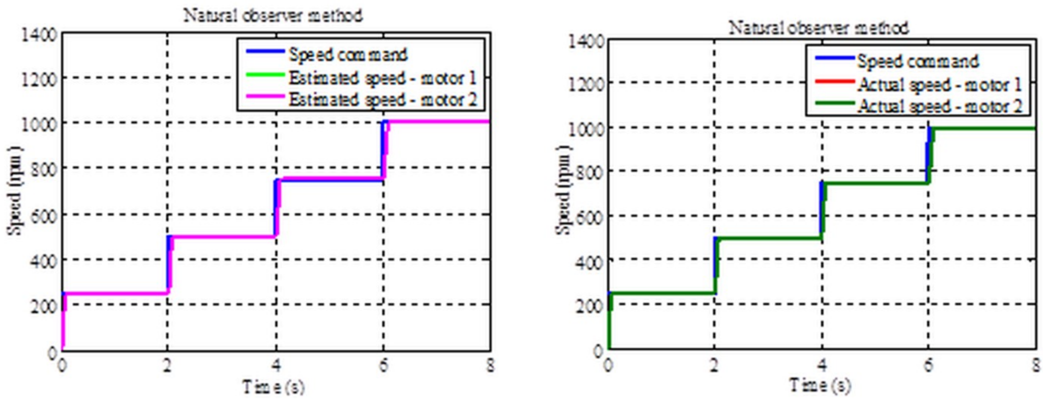
(d) Actual load torque responses of motor 1 and motor 2

Fig. 5. Simulation waveforms of motor 1 and motor 2 for a speed of 1000 rpm and an unbalanced load of 2.5 Nm



(a) Estimated load torque response of motor 1 (b) Estimated load torque response of motor 2

Fig. 6. Estimated load torque responses of motor 1 and motor 2 by natural observer for a speed of 1000 rpm and an unbalanced load of 2.5 Nm



(a) Estimated speed response (b) Actual speed response

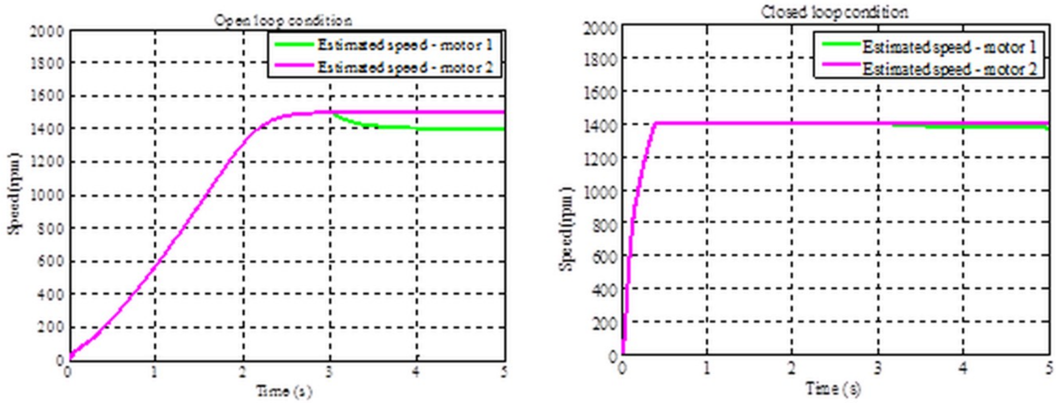
Fig. 7. Simulation results for multi-step change in speed

Speed command is increased step by step to test the speed tracking capability of the natural observer and speed controller. The simulation results for a multi-step change in speed command for motor 1 and motor 2 are shown in Fig. 7. Both motors are at no load condition and the speed command is set at 250 rpm initially. Every 2s, the speed command is increased with a step increment of 250 rpm and the final set speed is 1000 rpm. It is observed that the actual and estimated speeds of both induction motors follow the speed command quickly and the steady state error is zero.

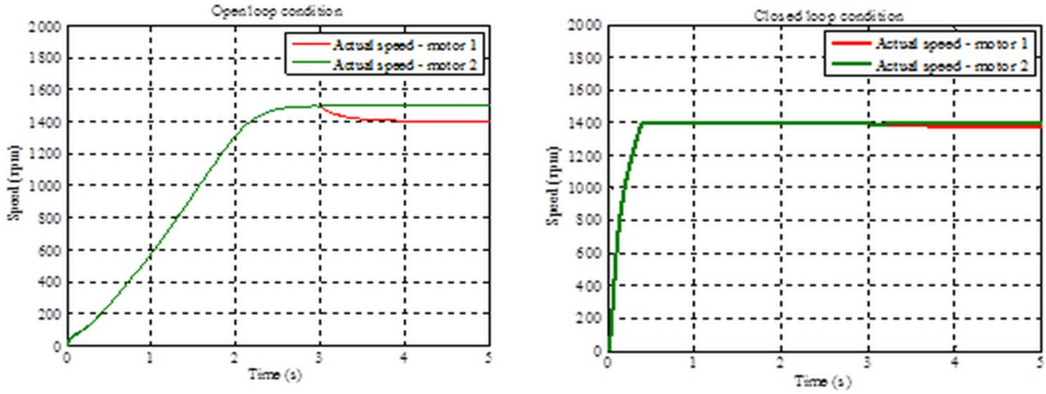
Case (iv) Open loop conditions

Simulation results are presented in open loop without any control and the results are compared with the closed loop results under unbalanced load conditions. The simulation is performed at rated load and very nearer to rated speed. In open loop operation, the speed of both motors is around 1500 rpm at no load because of no control action. At the time of applying the load, the speed of motor 1 decreases to 1400 rpm and the speed of motor 2 remains same. The speed and torque responses of both motors at open and closed loop conditions are illustrated in Fig. 8. The actual torques of both the motors at no load has maximum overshoot and are limited by a torque limiter. The performance of the motors are improved by closed loop speed control.

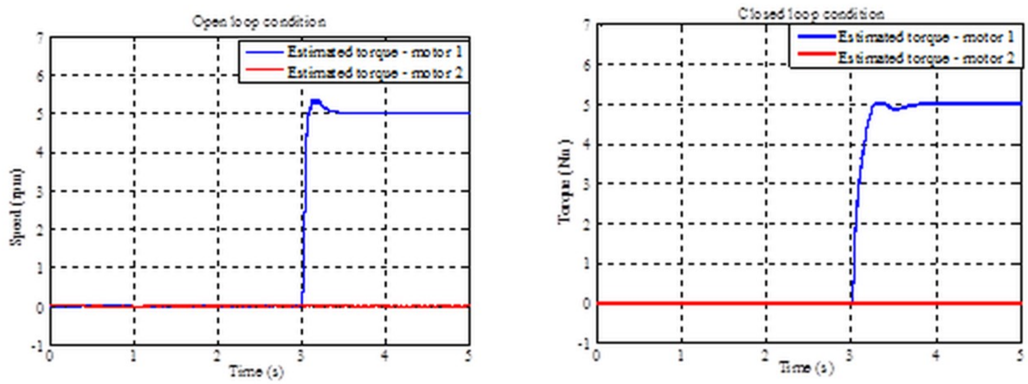
In closed loop operation, both motors run at a speed of 1400 rpm at no load. At t=3s, a load of 5 Nm is applied to motor 1 and motor 2 is still at no load conditions. The speed of motor 2 follows the speed command and the speed of motor 1 decreases to 1370 rpm. The starting torque of the actual load torque is high and is limited by employing torque limiter. The estimated load torque follows the applied load and is free from ripple because natural observer estimates the torque during high distortion of load current.



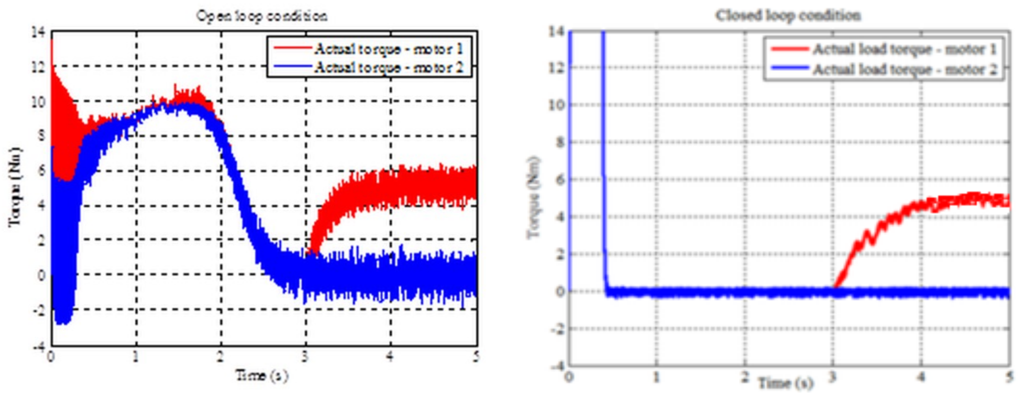
(a) Estimated speed responses of motor 1 and motor 2



(b) Actual speed responses of motor 1 and motor 2



(c) Estimated load torque responses of motor 1 and motor 2



(d) Actual load torque responses of motor 1 and motor 2

Fig. 8. Simulation waveforms under open and closed loop conditios for a speed of 1400 rpm and an unbalanced load of 5 Nm

5 EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental set up for the speed sensorless vector control of parallel connected induction motor drive fed by a single inverter for real time implementation is shown in Fig.9. The major components are: same rating induction motors, three phase IGBT based PWM inverter module with built-in Hall Effect current and voltage sensors, TMS320F2812 DSP, Personal Computer (PC) for control and digital storage oscilloscope for display and measurement.

For parallel connected induction motor drive, two identical 0.746 kW (1HP) three-phase squirrel cage induction motors are used. Various simulink blocks like estimator and PI controllers are constructed in VISSIM environment. TMS320F2812 DSP processor supporting blocks are available in VISSIM and the simulink blocks are converted into C- codes using the target support for TMS320F2812. It is compiled using code composer studio internally and the output file is downloaded into the DSP processor through J-tag emulator. Six numbers of Hall Effect current sensors and voltage sensors are used to measure the phase currents of induction motors and terminal voltages respectively. The measured analog currents and voltages are converted into digital by on chip ADC with 12 bit resolution. The feedback signals are linked to DSP processor using 26 pin header and the processor estimates the stator current, rotor flux, load torque and speed. The processor also generates the required PWM pulses to enable the three phase IGBT inverter switches in the Intelligent Power Module (IPM). The PWM pulses are connected to the IPM through 34 pin PWM header. IPMs are advanced hybrid power devices that combine high speed, low loss IGBTs with optimized gate drive and protection circuitry. Highly effective over-current and short-circuit protection is realized through the use of advanced current sense IGBT chips that allow continuous monitoring of power device current. System reliability is further enhanced by the IPM's integrated over temperature and under voltage lock out protection.

The estimated speed waveform (500 rpm/div) obtained from the experimental set up for a balanced load is illustrated in Fig. 10 (a) and it is inferred that both motors follow the reference speed. The estimated torque waveform (1 Nm/div) is shown in Fig. 10 (b) and it follows the actual load torque. Both the speed and torque follow the reference signal and the system is stable for balanced load conditions.

The estimated speed response obtained by the experimental set up for unbalanced load condition is shown in Fig.11 (a). A load of 2.5 Nm is applied to motor 2 and motor 1 is at no load condition. It is indicated that the estimated speed of motor 1 follows the speed command and

Fig. 9. Experimental set up of parallel connected induction motor drive controlled by TMS320F2812 DSP controller

the speed of motor 2 deviates from the reference speed by 100 rpm. In simulation, the speed difference among the induction motors is 94 rpm. The estimated and actual torque responses of motor 1 and motor 2 are shown in Fig. 11 (b). It is observed that the speed of motor 2 deviates from the speed command at the time of applying the load and reaches the steady state short while. This implies that the system is stable. The experiments are also conducted for a load of 5 Nm at 1400 rpm and are depicted in Fig. 12. The experimental result for multi-step change in speed command is illustrated in Fig. 13 for a step increment of 250 rpm and it is indicated that motor 1 and motor 2 follow the speed command.

6 CONCLUSION

In this paper, natural observer with load torque adaption is employed to estimate the speeds of same rating induction motors connected in parallel and fed by a single inverter. Simulation are demonstrated for various running conditions to prove the effectiveness of the proposed method and compared with conventional adaptive observer method. The speed deviations are reduced in this proposed method compared with the conventional adaptive observer method. The validity of the proposed method is confirmed through simulation and experimental results. It is known that the system is found to be stable under unbalanced load conditions. It is concluded that the performance of torque tracking and speed control by natural observer are apparently better than conventional method.

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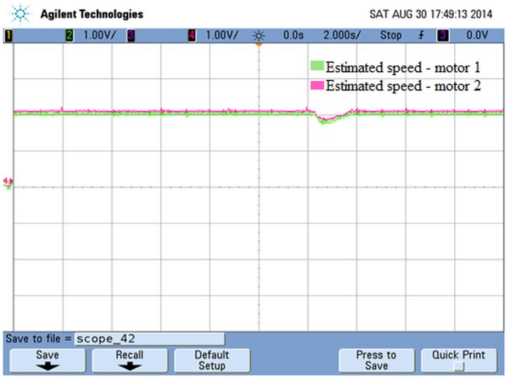
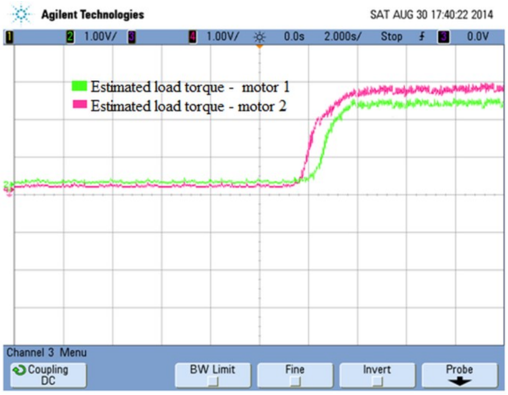
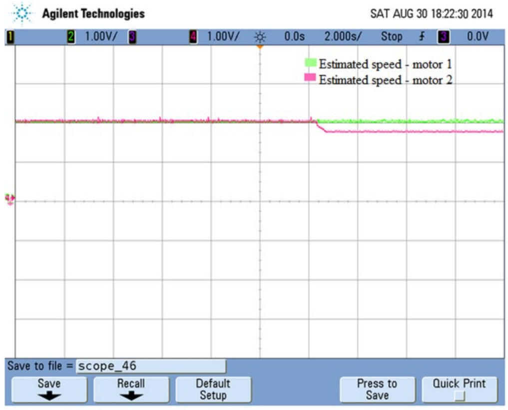


(a) Estimated speed response (500 rpm/div)

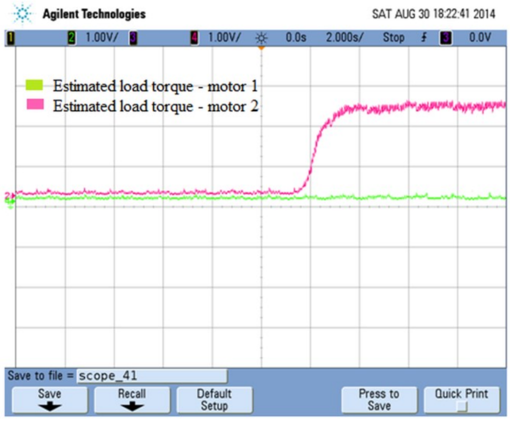


(b) Estimated load torque response (1Nm/div)

Fig. 10. Experimental results for balanced load conditions



(a) Estimated speed response (500 rpm/div)



(b) Estimated load torque response (1Nm/div)

Fig. 11. Experimental results for unbalanced load conditions when motor 2 is loaded

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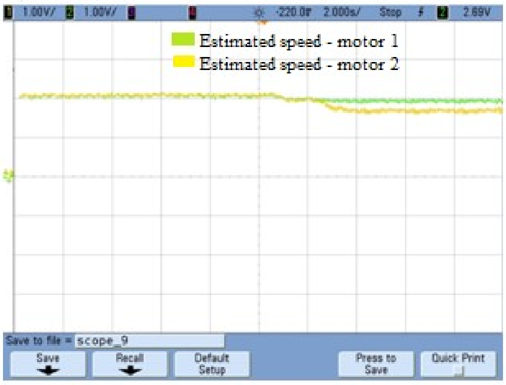
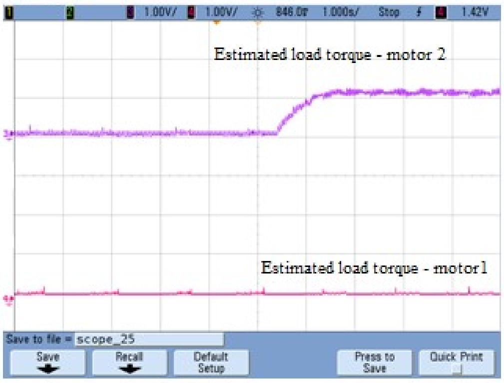


(a) Estimated speed response (700 rpm/div)



(b) Estimated load torque response (5Nm/div)

Fig. 12. Experimental results for unbalanced load conditions with a load of 5 Nm and 1400 rpm

Fig. 13. Experimental results for multi-step change in speed (500 rpm/div)

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