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Research Article

Sensorless Master-slave Direct Torque Control of Permanent Magnet Synchronous Motors Based on Speed MRAS Observer in Electric Vehicle

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Abstract: In this study, a new sensorless master slave direct torque control of permanent magnet synchronous motors based on speed MRAS observer is proposed for a multi-machine system in electric vehicle. The speeds of both motors are estimated by using Model Reference Adaptive System (MRAS) scheme. A classical system with multi-inverter and multi-machine comprises a three-phase inverter for each machine to be controlled. Another approach consists in using only one three-phase inverter to supply several permanent magnet synchronous machines. A new DTC algorithm is used for the control of bi-machine traction system. Simulation results in MATLAB/SIMULINK indicated that the new DTC algorithm is well adapted for the synchronism of this system over a wide range of operations.

Keywords: DTC, in-wheel motor, MRAS, multi-machine control, multi-machine system, traction application

INTRODUCTION

Multi-machine multi-converter systems can be considered as extensions of classical drives. In many applications, one motor is controlled by one converter. These systems are called single-machine single-converter systems. However, in high power applications such as traction systems, conveyer lines and steel processing, two or more machines are fed by one converter. This topology results in a light, more compact and less costly system (Matsuse *et al*., 2004). These systems are called multi-machine single-converter systems. Control of multi-machine single-converter systems is the subject of this study. A three-leg inverter supplies two in-wheel PMS machines in a traction system. However, several methods have been proposed for the control of multi-machine single-converter systems. In this case, a master slave based on DTC strategy has been developed.

Recently, Permanent Magnet Synchronous Motors (PMSM) have been extensively analyzed as feasible candidates for variable speed Electric Vehicle (EV) traction application (Rahman and Qin, 1997).

In order to improve dynamic performance of the permanent magnet synchronous in-wheel motor, Direct Torque Control (DTC) has been proposed here. Because the DTC has many potential advantages (Lixin and Limin, 2003; Sun and He, 2005; Hartani *et al*., 2010), for example, it is different from the conventional vector control method, where torque is controlled in the rotor reference frame via current control loops and its structure is simple, however it has high dynamic performance and has strong robustness to the parameter variety of the PMSM. In addition, the field-weakening control becomes easier because stator flux linkage can be controlled directly in the DTC system of a PMSM (Hu *et al*., 2002) and the method does not need accurate rotor position information.

A new DTC algorithm is used for the control of a multi-machine system. Similar to a conventional DTC, the proposed method has two separate control loops. In the torque control loop, before selection of optimum voltage from the DTC look-up table, the system overall requirement is determined based on requirements of motors torque. Also, switchable master-slave control is used in the flux control loop. The method which is simulated for a two-parallel PMS machine system can be extended to a multi-machine system.

Sensorless control is an attractive feature in DTC for PMSM without the speed control loop, in which no position or speed signal is needed for motor and only an initial position is needed for PMSM. But in high performance applications, usually the speed control is required. In this case, it is essential to detect the rotor speed for feedback. As discussed earlier, the use of speed sensors would cancel out the advantages of the DTC systems. Many researchers have paid great attentions to the sensorless method of DTC for PMSM not only to eliminate the cost of the speed sensor, but also to improve the reliability of the drive system.

Sensorless control of permanent magnet synchronous motor drives is now receiving wide attention (Young *et al*., 2003; Ruzhong *et al*., 2008; Xiaodong and Yikang, 2007; Hao *et al*., 2009). The main reason is that the speed sensors spoils the ruggedness and simplicity of PMSM. In a hostile

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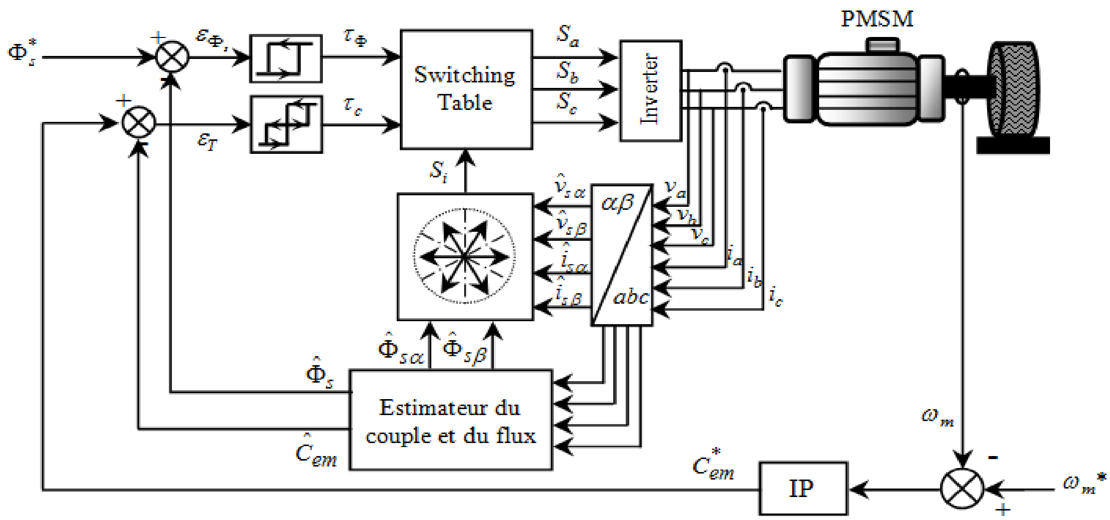


Fig. 1: Block diagram of DTC control strategy in PMSM

environment, speed sensors cannot even mounted. The sliding mode observer based techniques are simple and robust against variation of machine parameters but it suffers from chattering problem. The Model Reference Adaptive System (MRAS) represents one of the most attractive and popular solutions for sensorless control of AC drives. This project introduced the speed sensorless control of parallel connected dual PMSM by using MRAS technique.

METHODOLOGY

Direct torque control strategy: In order to obtain a high performance control, DTC strategy is employed in this system. The DTC, which was presented by I Takahashi in 1986 for an induction machine (Takahachi and Noguchi, 1986), is based on the direct control of the torque and flux and involves non linear hysteresis controllers. Direct control strategies do not require the previously mentioned reference transformation to achieve a decoupled control of flux and torque. The currents of the machine are indirectly controlled through torque and flux control. Figure 1 shows the general bloc diagram of the DTC control strategy.

Figure 2 shows the power converter voltage vectors in a stationary $\alpha\beta$ frame. By selecting the voltage vectors appropriately the flux trajectory and its speed can be controlled (Takahachi and Noguchi, 1986). Hysteresis comparators can have different levels, usually; the flux controller is a two-level comprator and the torque controller a three-level comparator (Draou and Hartani, 2012).

The stator flux linkage components $\Phi_{s\alpha}$ and $\Phi_{s\beta}$, the flux linkage amplitude $|\Phi_s|$, the torque T_{em} and the flux angle θ_s can be determined as follow:

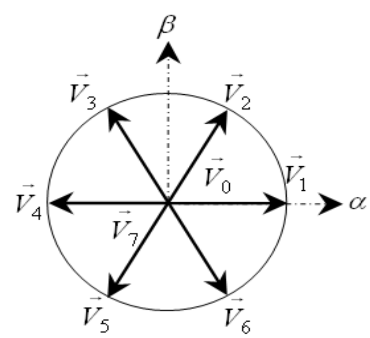


Fig. 2: Space vector diagram of inverter voltage vectors

Table 1: Switching table presented by Takahashi

		Secteur					
τ_Φ	τ_c	1	2	3	4	5	6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

$$\begin{cases} \Phi_{s\alpha} = \int_0^t (V_s - R_s i_{s\alpha})dt \\ \Phi_{s\beta} = \int_0^t (V_s - R_s i_{s\beta})dt \end{cases} \quad (1)$$

$$\Phi_s = \sqrt{\Phi_{s\alpha}^2 + \Phi_{s\beta}^2} \quad (2)$$

$$\theta_s = artg\left(\frac{\Phi_{s\beta}}{\Phi_{s\alpha}}\right) \quad (3)$$

$$T_{em} = \frac{3}{2} p\left(\Phi_{s\alpha} i_{s\beta} - \Phi_{s\beta} i_{s\alpha}\right) \quad (4)$$

The switching table presented by I Takahashi is in Table 1.

The speed MRAS observer: The Model Reference Adaptive System (MRAS) based estimators provide the desired state from two different models, one is reference model and another one is adjustable model (Wu and Xiao, 2009; Vaclavek and Blaha, 2008; Maogang *et al*., 2011; Kojabadi and Ghribi, 2006; Jinsong *et al*., 2009). The error between two models is used to estimate the unknown parameter (speed in this case). In MRAS only adjustable model should depend unknown parameter (Quntao and Li, 2008), the reference model is independent of speed. The error signal is fed into adaptation mechanism, which provides the estimated quantity which is used to tune the adjustable model. A sensorless control algorithm is employed here as shown in Fig. 3. PMSM is considered as reference model and the stator current equations are considered as adjustable model.

In the adaptation mechanism the PI controller is used to tune the adjustable model. The estimated rotor speed is used for tuning of adjustable model based on current equations of motor. Speed error is continuously monitored to ensure negative feedback and hence stability of overall system. The current equations of PMSM are given as:

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R_s}{L_s} i_d + \dfrac{L_q}{L_d} i_q \omega_r + \dfrac{1}{L_s} v_d \\ \dfrac{di_q}{dt} = -\dfrac{R_s}{L_s} i_q - i_d \omega_r - \dfrac{\Phi_f}{L_s} \omega_r + \dfrac{1}{L_s} v_d \end{cases} \tag{5}$$

The above current equations can be written:

$$\frac{d}{dt}\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_s} & \dfrac{\omega_r L_q}{L_s} \\ -\dfrac{\omega_r L_d}{L_s} & -\dfrac{\hat{R}_s}{L_s} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} v'_d \\ v'_q \end{bmatrix} \tag{6}$$

where,

$$\begin{cases} i'_d = i_d + \dfrac{\Phi_f}{L_d} \\ i'_q = i_q \\ v'_d = v_d + \dfrac{R_s \Phi_f}{L_d} \\ v'_q = v_q \end{cases} \tag{7}$$

The Eq. (7) is having speed as variable and will be used for adjustable model. PMSM is used as reference model and provides i_d and i_q. In this algorithm estimated value of rotor speed is calculated as:

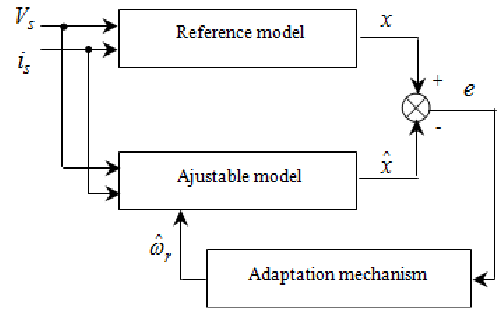


Fig. 3: Structure of model reference adaptive system

$$\hat{\omega}_r = k_p + \frac{k_i}{s}\left[-(i'_q - \hat{i}'_q) + (i'_d - \hat{i}'_d) + \hat{\omega}_r(0)\right] \tag{8}$$

The block diagram of sensorless DTC-PMSM employing MRAS as speed estimator is shown in Fig. 4. The MRAS based speed estimated is implemented for PMSM drive in MATLAB. MRAS used in this system designed based on the current model of PMSM and uses PI controller.

The performance of MRAS observer is based on controller used in adaptation mechanism. Here in this case a PI controller is used to tune the adaptive model based on reference model. The controller forces the error to be zero. The better performance of the proposed observer is tested at law and high speed. In order to test the performance of the observer at law and high speed, a simulation is carried out with the reference speed from zero to 5 rad/sec and after 0, 2 sec to 100 rad/sec. Figure 5a shows the waveforms of the estimated and actual motor speeds from startup to 100 rad/ses. It is clear from Fig. 5a that speed of motor is following the reference speed. Figure 5b shows the waveforms of the speed error between the estimated speed and the actual speed. It can be concluded from the waveforms that the observer performances as well other observers. The simulation result of the proposed observer indicates that the observer performs almost as well as the ordinary shaft encoder.

Figure 5c shows the electromagnetic torque generated by PMSM as step-chang (10 Nm at 0 sec, 15 Nm at 1, 2 sec and 10 Nm at 1, 6 sec) in load torque applied to motor (Fig. 5d). Figure 5e shows three-phase stator currents of PMSM when the load torque applied to motor are changed from 10-15-10 Nm. As the load on motor is changing, the stator current is changing accordingly. Figure 5f shows the zoomed view of stator currents which are sinusoidal.

NEW MASTER SLAVE DIRECT TORQUE CONTROL

The proposed method is based on the conventional DTC technique of permanent magnet synchronous

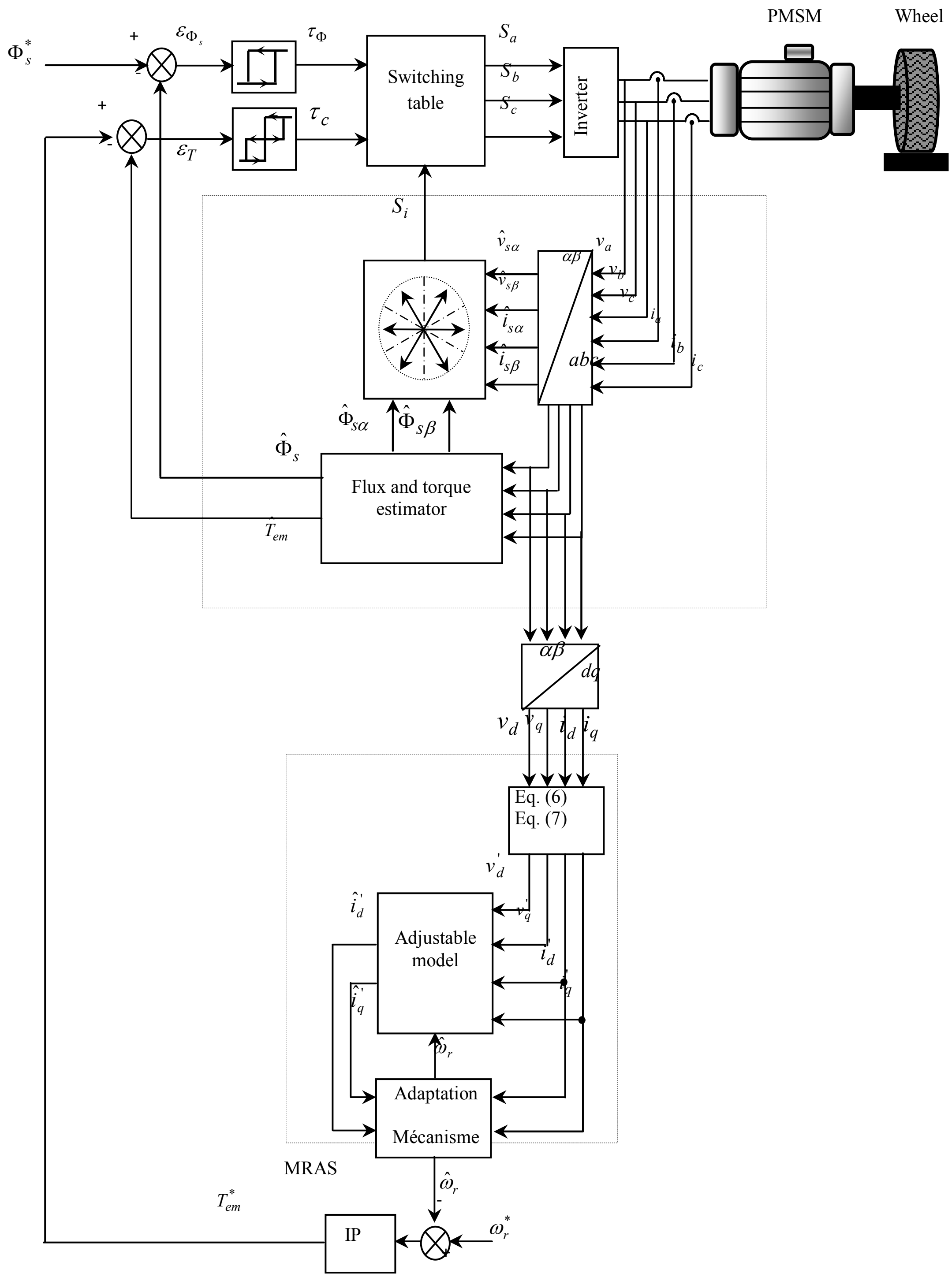
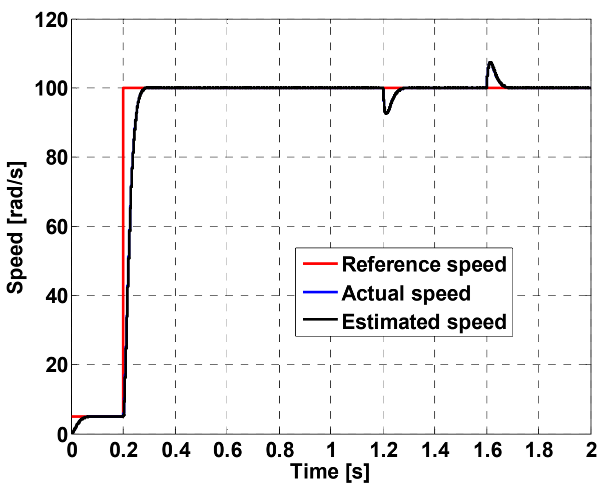
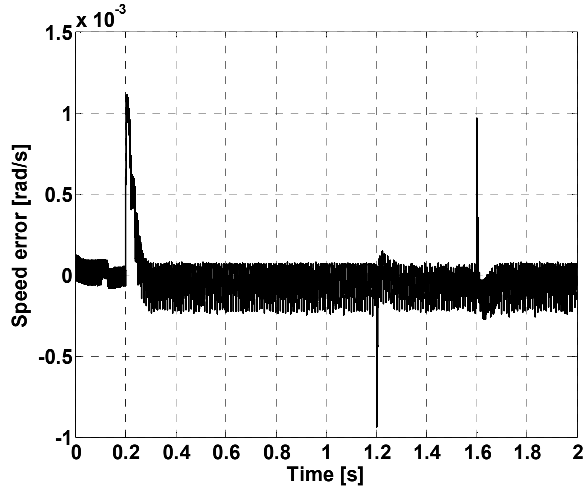


Fig. 4: Block diagram of sensorless DTC-PMSM drive with MRAS based speed estimator

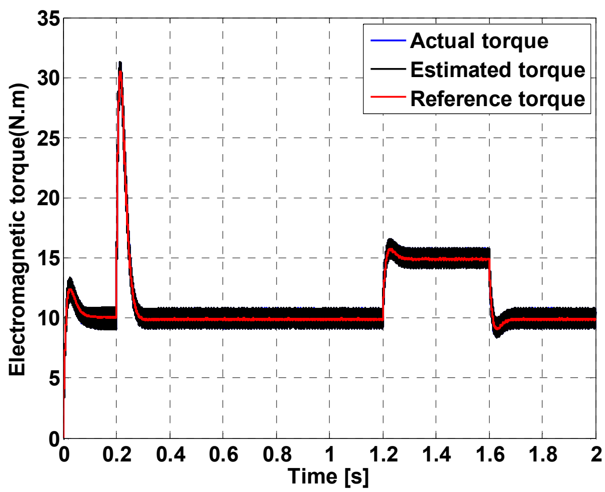
motors (Kelecy and Lorenz, 1994; Chiasson *et al*., 2002; Bidart *et al*., 2008, 2011). In the DTC method, the flux and electromagnetic torque are controlled by adjusting the magnitude and position of the stator flux respectively. This principle is used in the proposed method. The method is explained for a two-machine system and can be extended to a multi-machine system (Shibata and Hoshi, 2007). In the proposed method, a conventional single-machine DTC strategy is independently applied to each motor and the same principle is extended to make it applicable to a multi-machine DTC method. In this proposed control strategy, there are two control loops; one for the stator flux control and one for the electromagnetic torque as



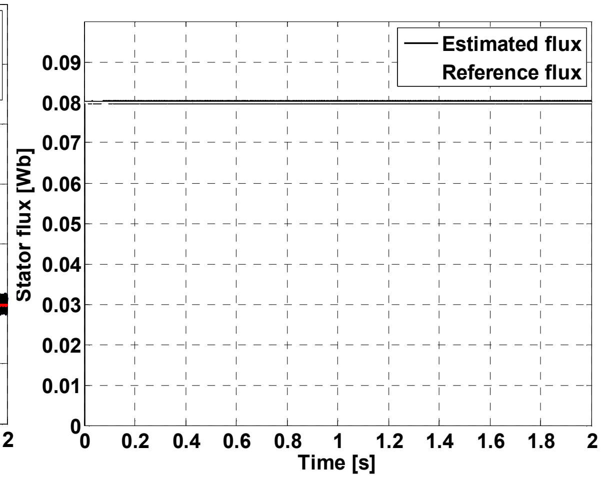
(a) Estimated and actual speed



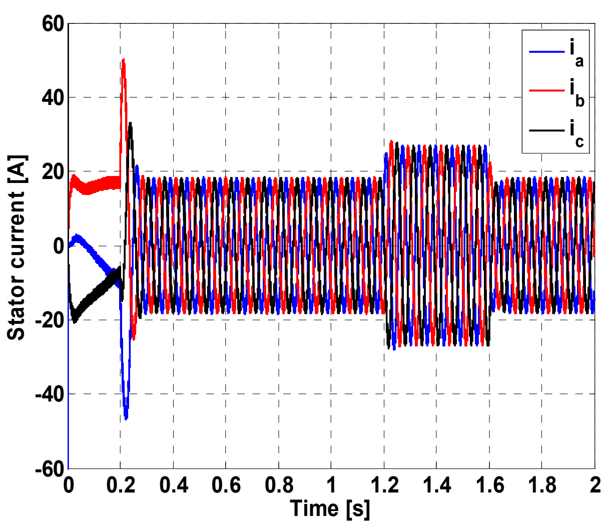
(b) The error between estimated and actual speed



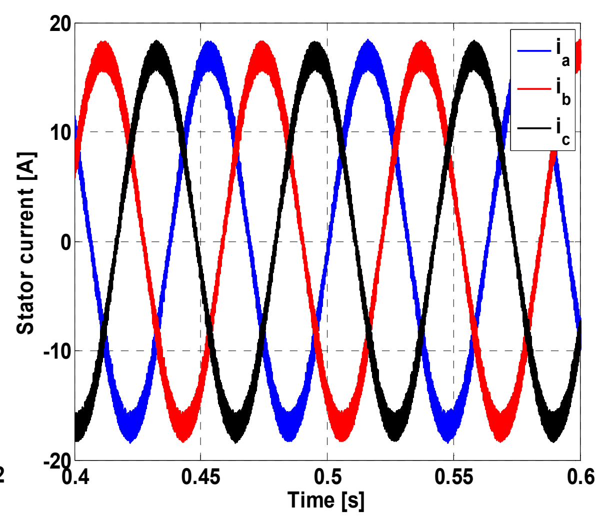
(c) Electromagnetic torque



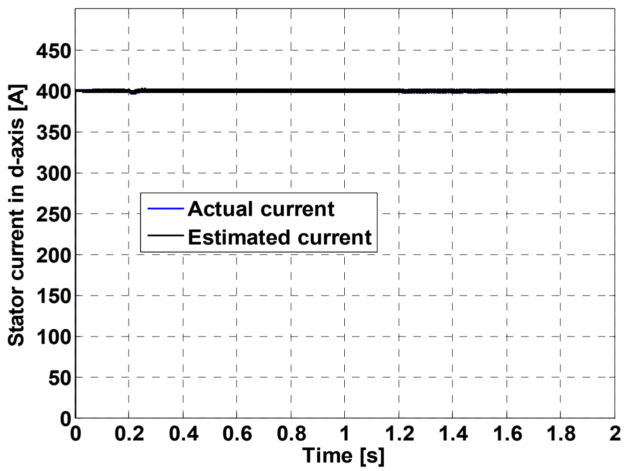
(d) Stator flux



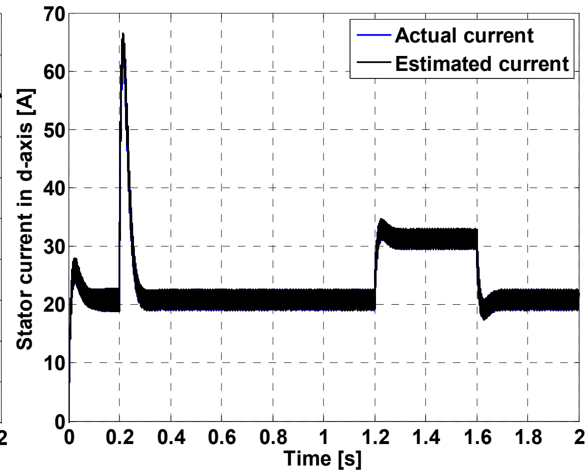
(e) Three-phase stator current



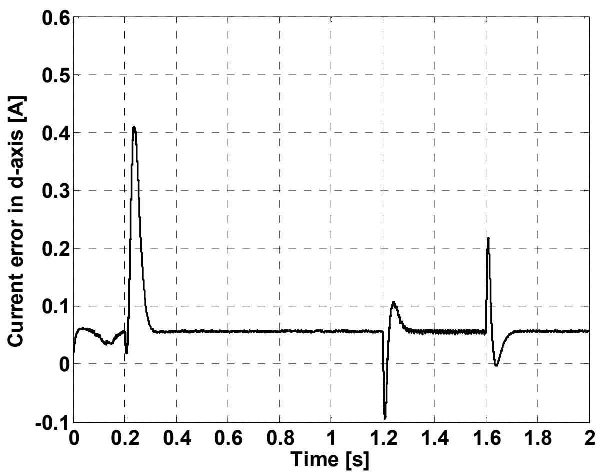
(f) Zoomed view of currents



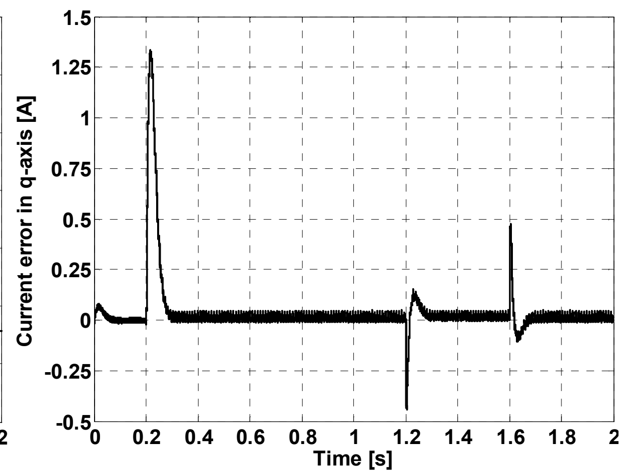
(g) Estimated and actual current in d-axis



(h) Estimated and actual current in q-axis



(i) Current error in d-axis



(j) Current error in q-axis

Fig. 5: Simulation results of sensorless DTC-PMSM drive with MRAS based speed estimator

can be seen in Fig. 6 but with different procedure for each loop. The procedure of each control loop will be explained thoroughly in the following section of the study.

Electromagnetic torque control loop: The new idea in the suggested control loop is to consider the motors torque requirements and system overall needs before selecting a voltage vector. This is done by designing a new look-up table in which a three level comparator is used in the torque control loop. The procedure is explained below and shown in Table 1 where, -1, 0, 1 are the outputs of torque error comparator:

- If both motors require a reduction in torque, a vector is applied to decrease torque.
- If no motor requires a torque change, then a vector is applied such that the torque is kept constant.
- If both motors require an increase in torque, then a vector is applied to increase the torque.
- If one motor requires a decrease in torque but the other does not, then a vector is applied to decrease the torque.
- If one motor requires a increase in torque but the other does not, then a vector is applied to increase the torque.
- If one motor requires a decrease in torque but the other one requires an increase, then a vector is applied such that the torque is kept constant.

Figure 7 shows the implementation of the method. In this figure, different possible kinds of torque errors in torque control loop are presented. The black points are the typical position for the electromagnetic torque of the two motors. For the conditions depicted in Fig. 7a, a voltage vector is applied such that the torque

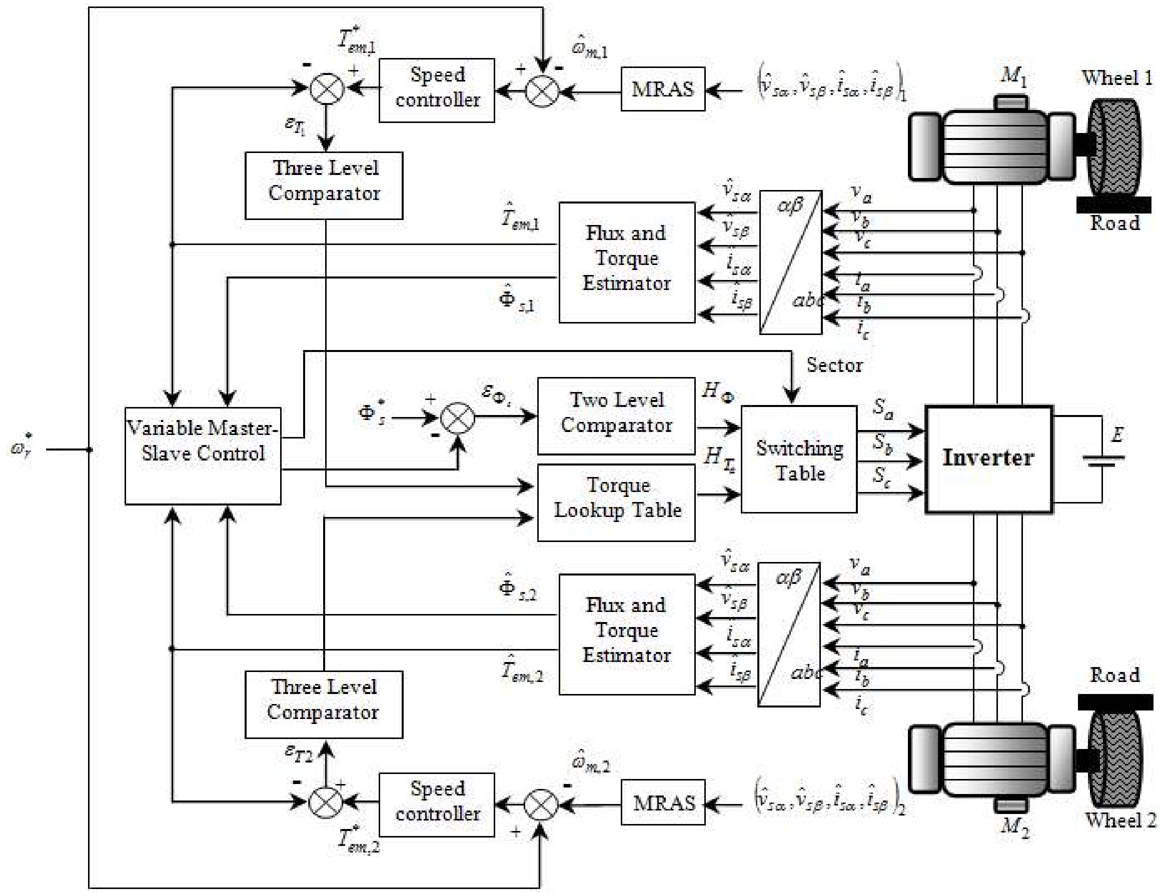


Fig. 6: Block diagram of the new sensorless master slave DTC

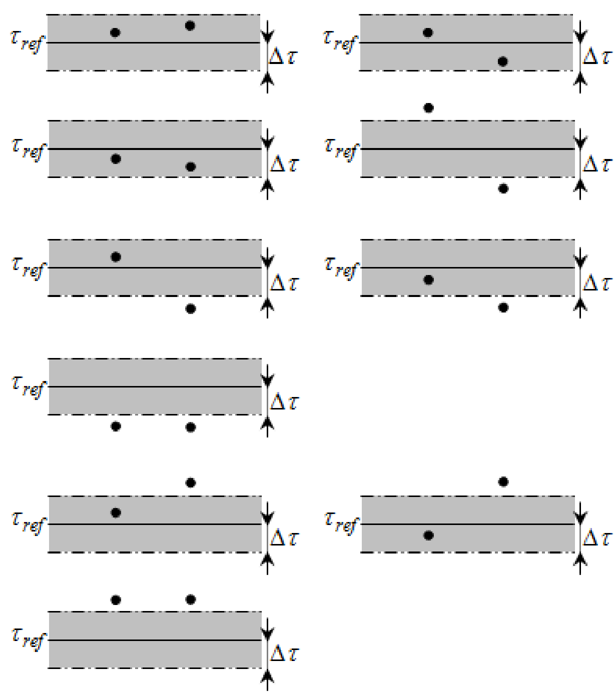


Fig. 7: Different possible cases of torque errors, (a) the torque should be kept constant, (b) the torque should be increased, (c) the torque should be decreased

Table 2: Proposed table in torque control loop

		Motor 2		
	H_{τ_e}	-1	0	1
Motor 1	-1	-1	-1	0
	0	-1	0	1
	1	0	1	1

does not vary. For the conditions shown in Fig. 7b, a voltage vector is applied to increase the torque. Also, for the conditions presented in Fig. 7c, a voltage vector is applied to decrease torque.

Finally, using the output of this table and the output of the stator flux control loop, the appropriate voltage vector is selected based on the conventional DTC switching look-up Table 2.

Stator flux control loop: Before introducing the proposed idea, some issue must be explained regarding parallel PMS motors. As a result of applying one voltage vector, stator flux vector of all the parallel PMS motors will vary instantaneously in the same direction. Therefore:

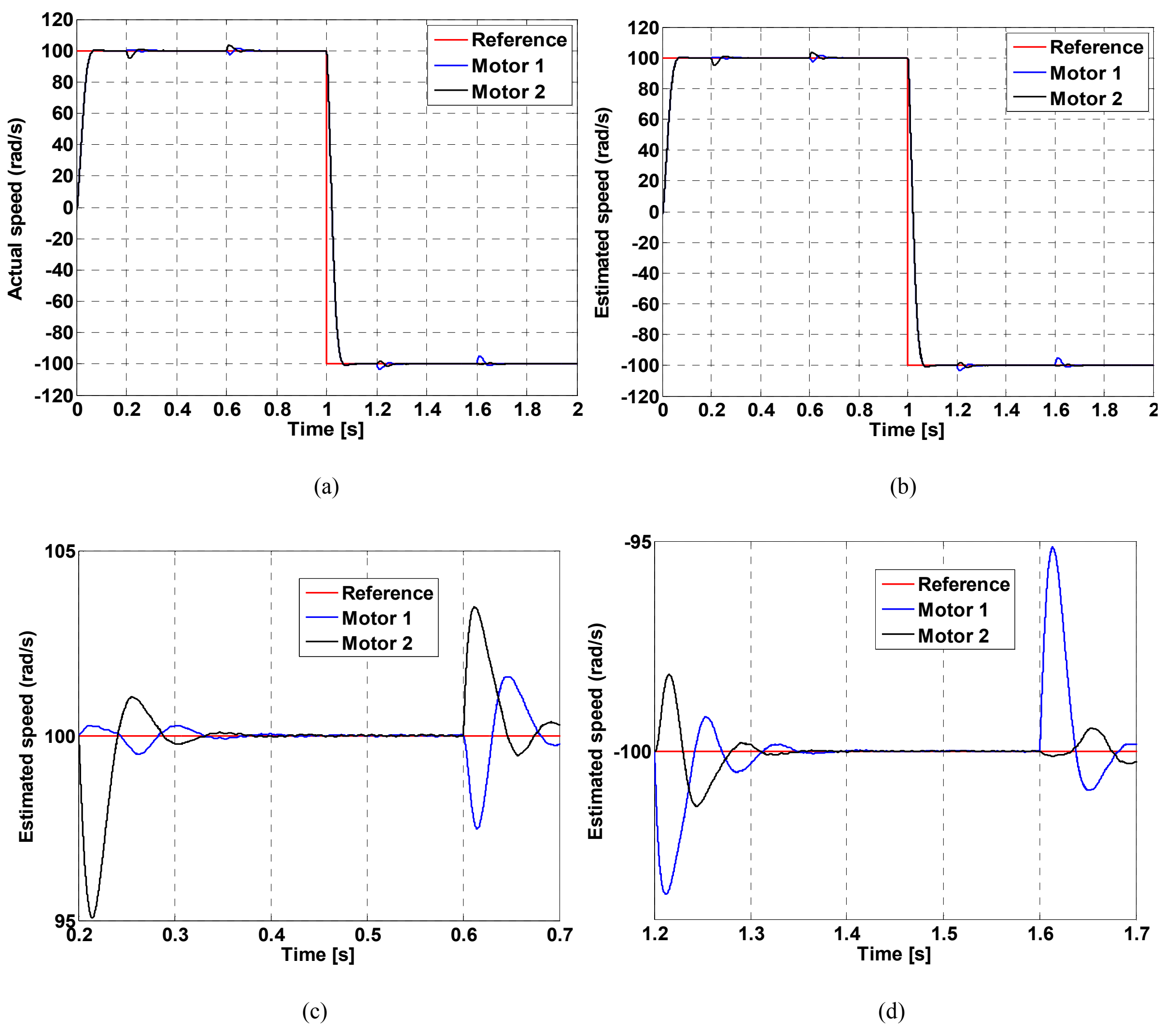
$$\frac{d\bar{\Phi}_s}{dt} = \bar{V}_s - R_s \bar{I}_s \qquad (9)$$

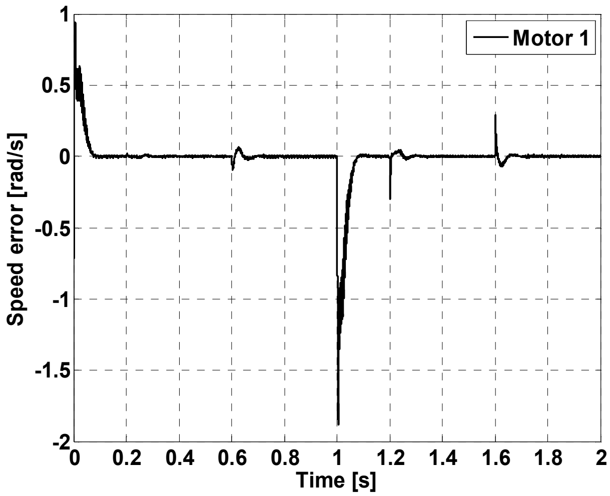
where,

$\bar{V}_s$, $\bar{I}_s$ and $\bar{\Phi}_s$ = Stator voltage vector, stator current vector and stator flux vector respectively

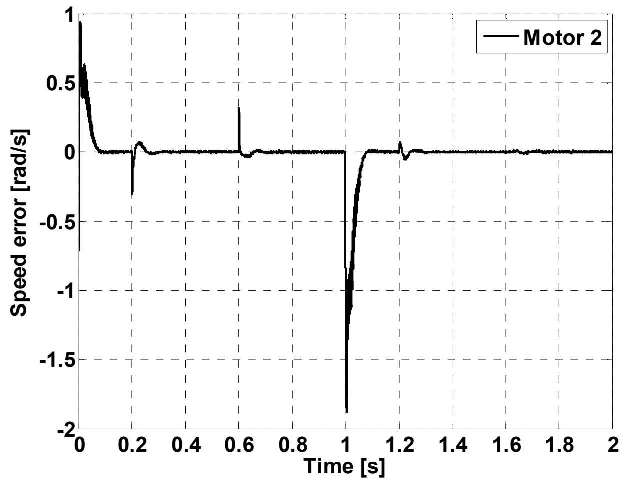
R_s = The stator resistance

In the stator flux control loop, one should know that the flux of any machine can go beyond its rated value. According to (25) the stator flux of each permanent magnet synchronous motor surely depends on the applied voltage. In cases where parameters of the motors are different, or motors load are not the same, stator fluxes will be different, or motors load are not the same, stator fluxes will be different. From (9) it can be seen that the stator flux vector only depends on stator resistance among all other parameters. Therefore, when stator resistance are the same, one expects to see the same flux for both machines. This is valid only at

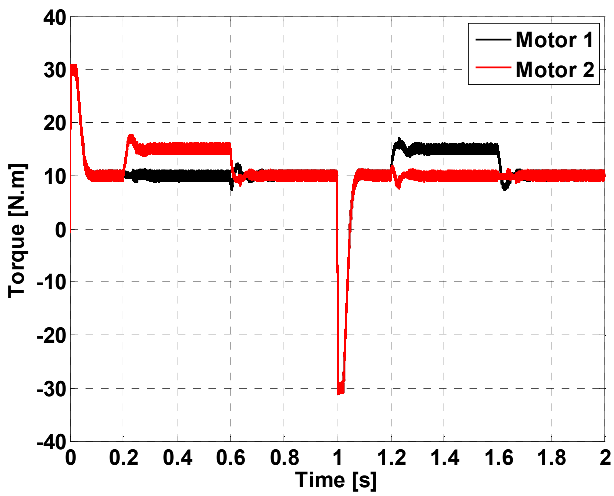



Motor 1
Speed error [rad/s]
Time [s]

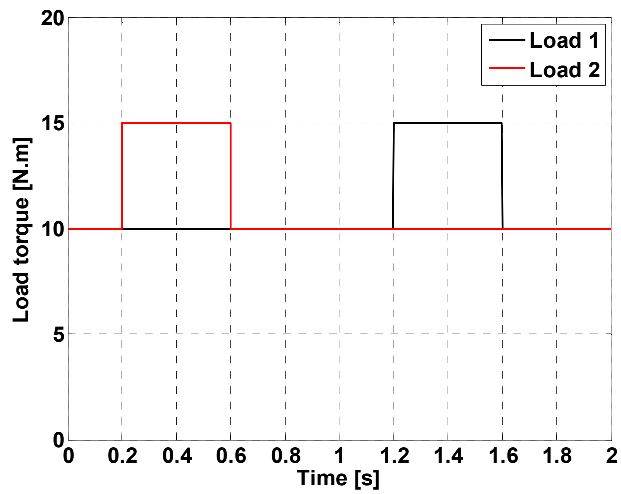
(e)


Motor 2
Speed error [rad/s]
Time [s]

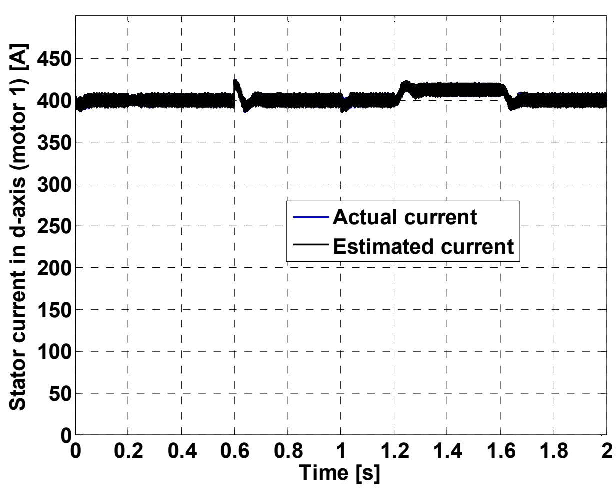
(f)


Motor 1
Motor 2
Torque [N.m]
Time [s]

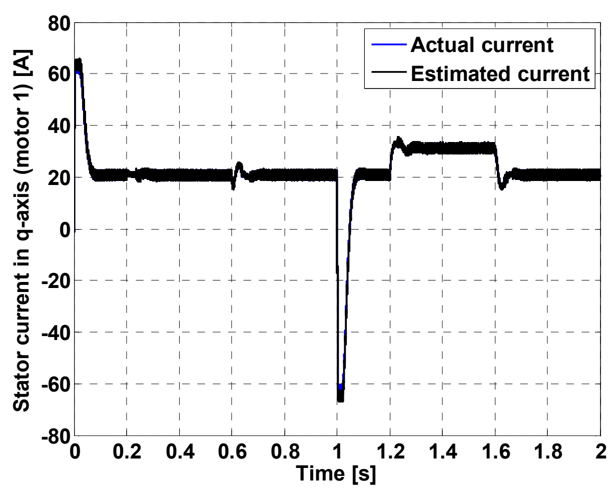
(g)


Load 1
Load 2
Load torque [N.m]
Time [s]

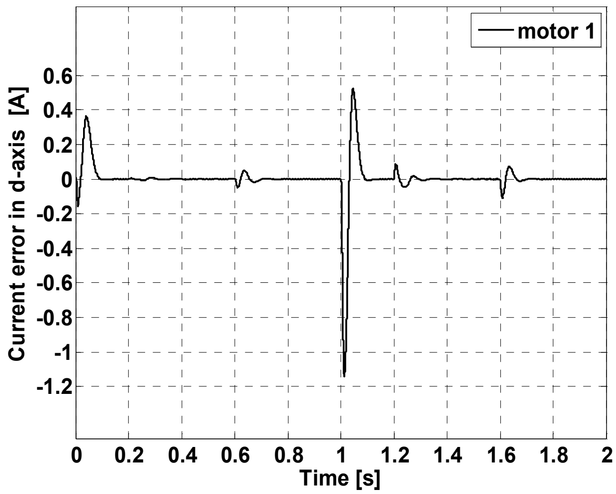
(h)


Actual current
Estimated current
Stator current in d-axis (motor 1) [A]
Time [s]

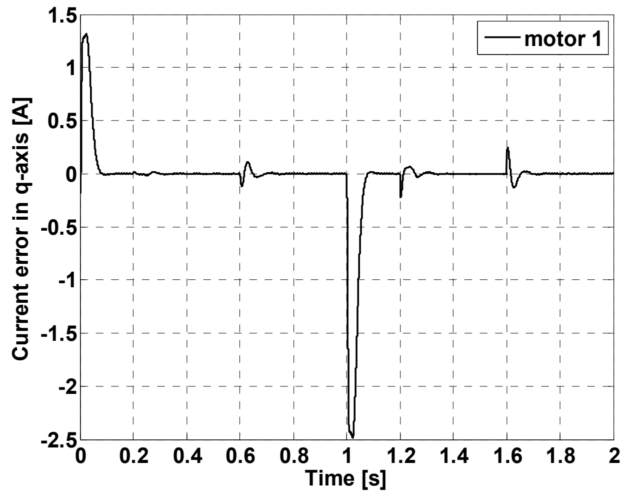
(i)


Actual current
Estimated current
Stator current in q-axis (motor 1) [A]
Time [s]

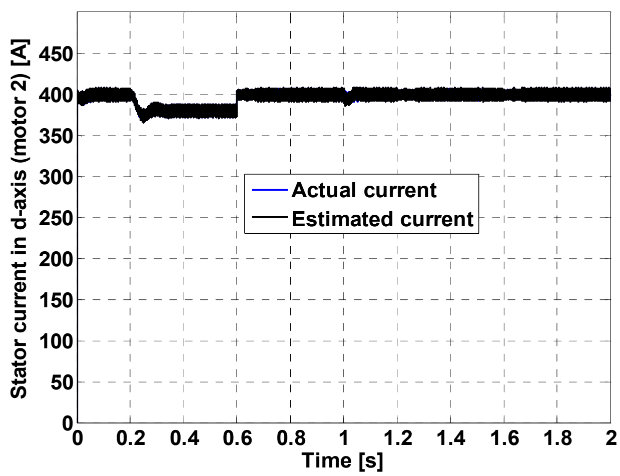
(j)


motor 1
Current error in d-axis [A]
Time [s]

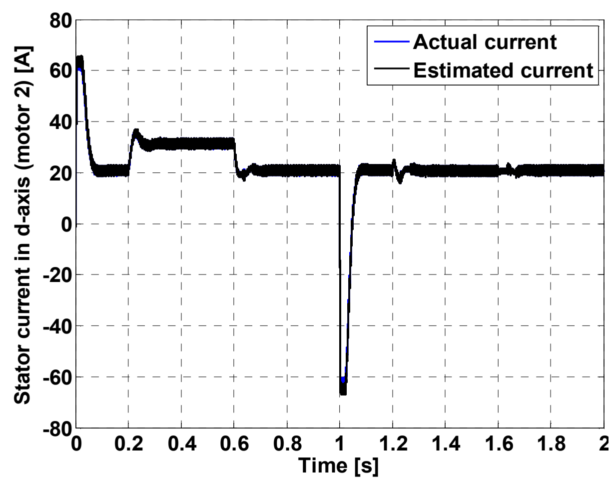
(k)


motor 1
Current error in q-axis [A]
Time [s]

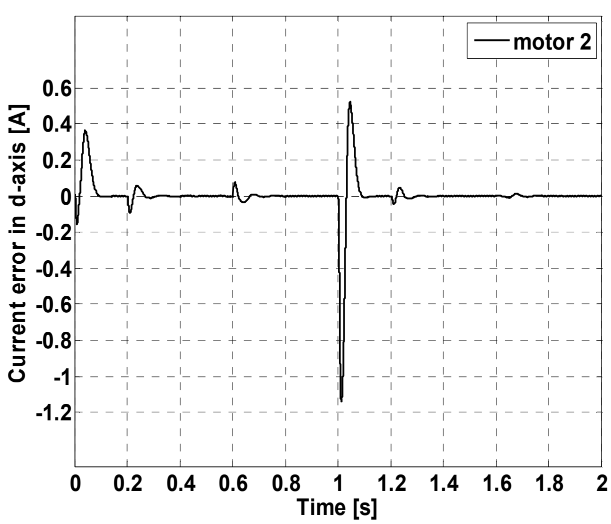
(l)


Actual current
Estimated current
Stator current in d-axis (motor 2) [A]
Time [s]

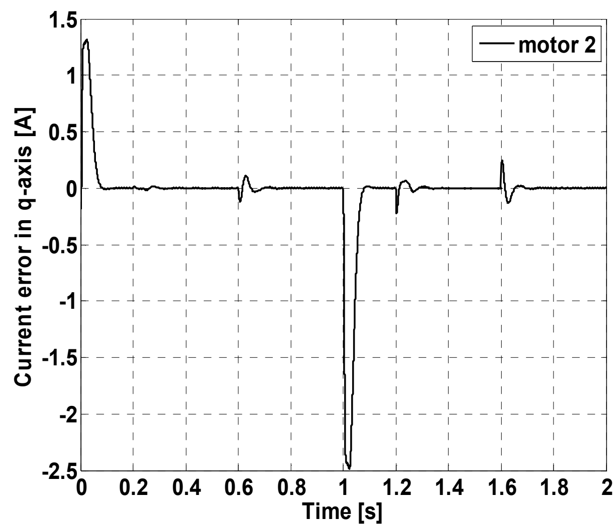
(m)


Actual current
Estimated current
Stator current in d-axis (motor 2) [A]
Time [s]

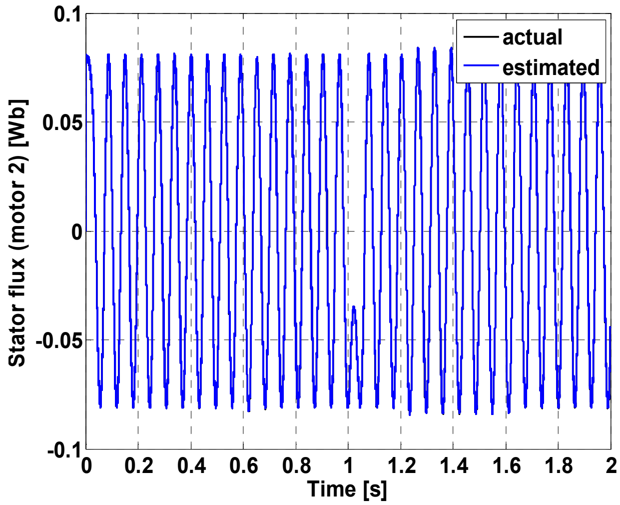
(n)


motor 2
Current error in d-axis [A]
Time [s]

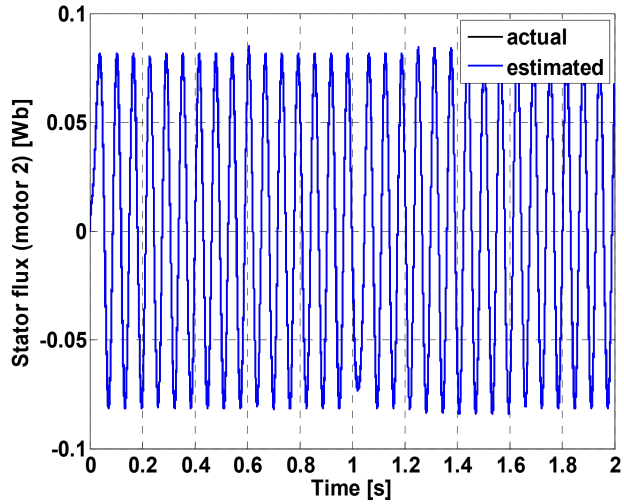
(o)


motor 2
Current error in q-axis [A]
Time [s]

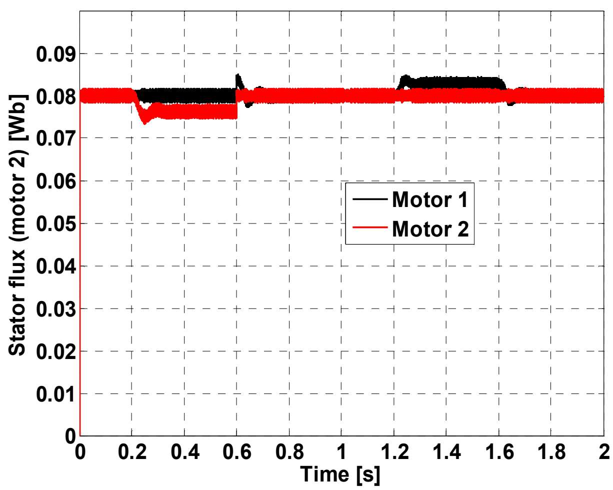
(p)


actual
estimated
Stator flux (motor 2) [Wb]
Time [s]

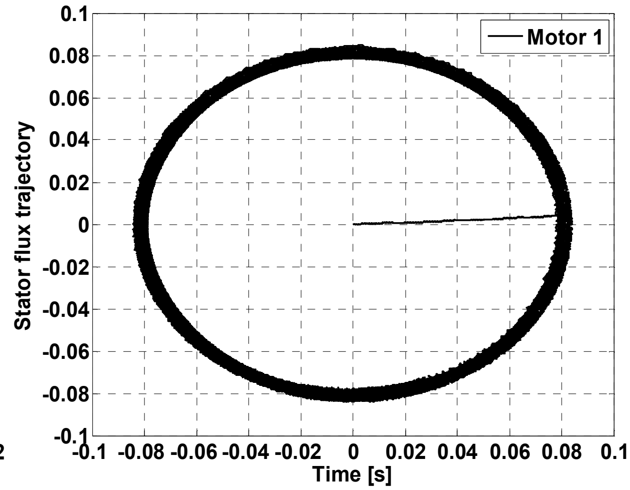
(q)


actual
estimated
Stator flux (motor 2) [Wb]
Time [s]

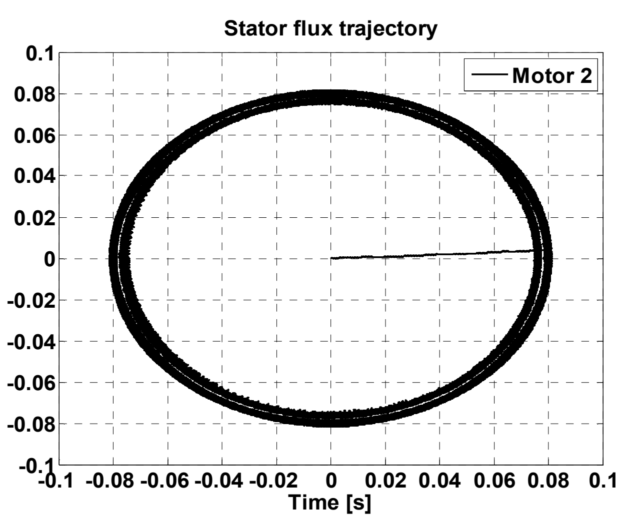
(r)


Motor 1
Motor 2
Stator flux (motor 2) [Wb]
Time [s]

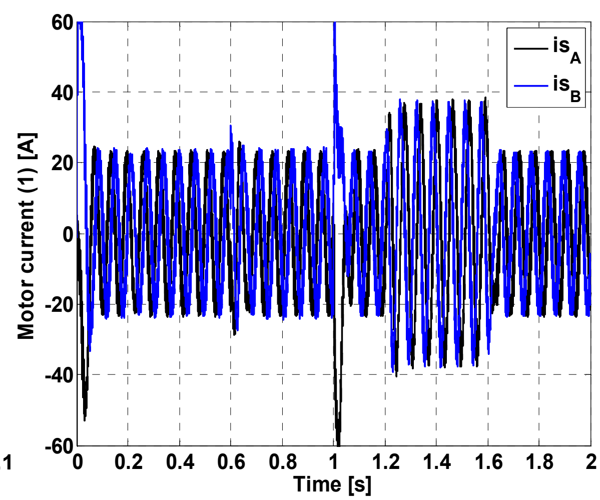
(s)


Motor 1
Stator flux trajectory
Time [s]

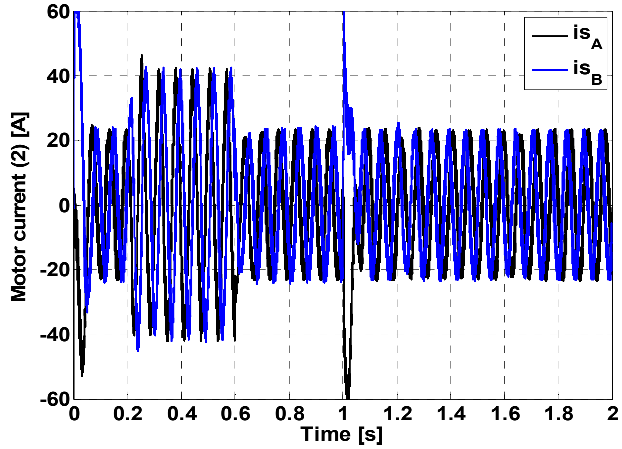
(t)


Stator flux trajectory
Motor 2
Time [s]

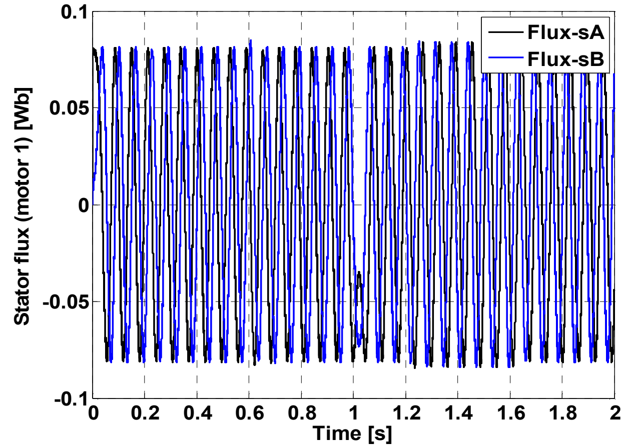
(u)


is_A
is_B
Motor current (1) [A]
Time [s]

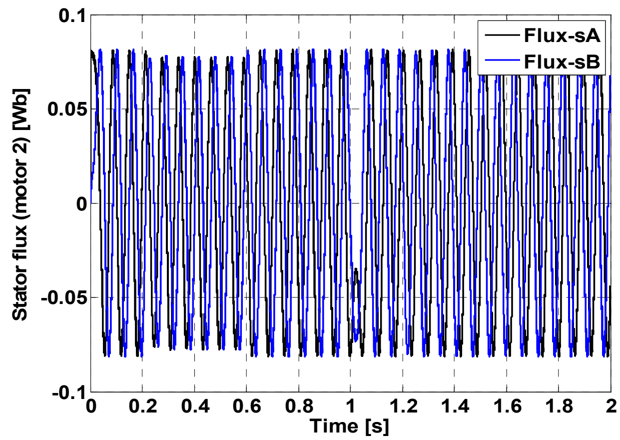
(v)


Motor current (2) [A]
Time [s]
60
40
20
0
-20
-40
-60
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
is_A
is_B

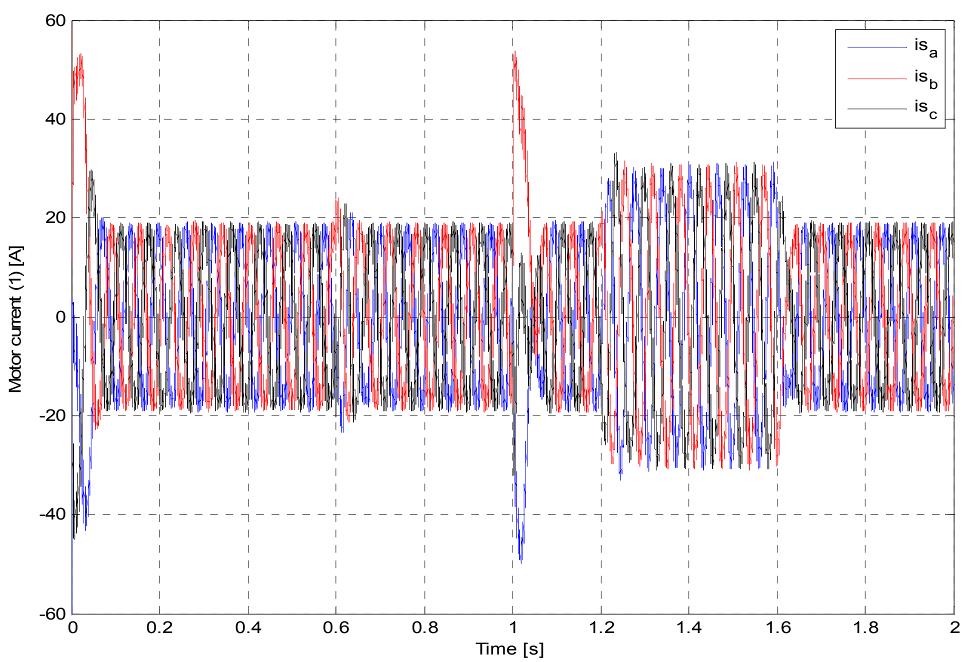
(w)


Stator flux (motor 1) [Wb]
Time [s]
0.1
0.05
0
-0.05
-0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Flux-sA
Flux-sB

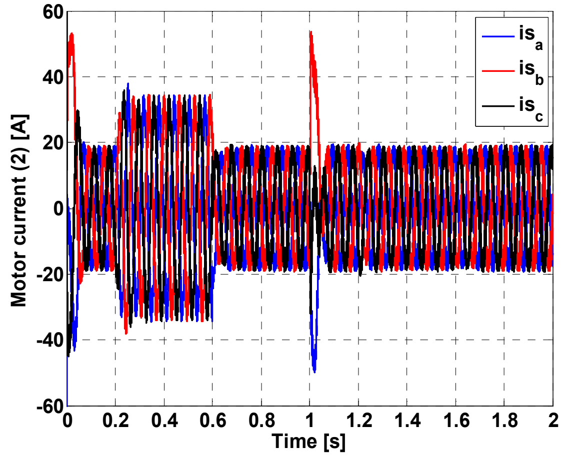
(x)


Stator flux (motor 2) [Wb]
Time [s]
0.1
0.05
0
-0.05
-0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Flux-sA
Flux-sB

(y)


Motor current (1) [A]
Time [s]
60
40
20
0
-20
-40
-60
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
is_a
is_b
is_c

(z)



(z1)

Fig. 8: Speed, torque, stator flux and motor current of two motors with proposed method using load change

steady state and during transients, the difference between the fluxes may be observed. This difference will also increase as motor speed decreases. For this reason, in cases where motor loads or stator resistances are different, speed reference cannot go below a certain value for speed control application. Thus, as the stator flux of one of the motors decreases, its torque generation capability will also decrease.

For these conditions, the mean control strategy cannot be used since the flux of the one machine can be saturated while its average value is equal to the reference value. Therefore, the master-slave control technique can be used for the stator flux control loop. In this way, only the stator flux of one motor is controlled. But the motor with the bigger stator flux magnitude has to be selected as the master and its stator flux is set to the reference value. To prevent flux saturation at different situations, the master motor may change. Therefore, in the proposed method, switchable master-slave technique is employed for stator flux control.

To accurately select the master motor and prevent flux saturation, an index is needed. The product of stator resistance and electromagnetic torque, i.e., R_sT_s is selected as the index. For each motor, this product is calculated. The motor with the smallest R_sT_s is chosen as the master motor. In cases where motor parameters are equal, the motor with the lower torque is selected as the master. The duration and amount of difference between indices are important in order to prevent frequent change variation of master motor during transients.

In the conventional DTC, the final step is the selection of voltage vector using a look-up table. The voltage is selected with respect to the section of the stator flux. The proposed method uses the stator flux of the master motor for flux sector selection.

RESULTS AND DISCUSSION

The block diagram of speed sensorless master-slave DTC of parallel-connected dual PMSM is shown in Fig. 6. The parameters for both motors are same as shown in Table 3.

In order to ensure the stability of the system composed of two PMSM connected in parallel on the same inverter which uses the sensorless DTC "master-slave" structure, different loads are applied to both machines as shown on Fig. 8c. We can readily notice that whatever values of the torque provided by the two machines, the system is always stable.

The master machine is the one that provides the highest torque and the difference in position between the two machines corresponds to the theoretical basis $\theta_1 < \theta_2$ when the highest torque is provided by PMSM1. For the speeds of the two machines (Fig. 8a), whether master or slave, there is a close follow up of the reference speed imposed by the control strategy whatever is the value of the load applied. We notice that the difference between the two speeds has very satisfactory rates, which indicates the good perfection in swapping the master and slave motors according to the control behavior when disturbances occur. We notice fast response of electromagnetic torques of the two motors (master and slave) when we apply different loads as shown in Fig. 8b, this confirms the fast and good management in master and slave under the conditions laid down in the algorithm of the control.

Table 3: Motor parameters

R_s	Resistance	0.03 Ω
L_d	d-axis inductance	0.2 mH
L_q	q-axis inductance	0.2 mH
Φ_f	Permanent magnet flux	0.08 Wb
p	Pole pairs	4

We remark the fast response of electromagnetic torque of the two motors (master and slave) when applying different loads, Fig. 8b, which confirms the speed and good alternation in master and slave under the conditions laid down in the algorithm control.

The phase currents of the two machines present good waveforms and confirm the responses of the motors as far as the changes in loads are concerned. Figure 8i, j, m and n which represent the trajectories of the stator magnetic flux show good magnetic stability of both machines which ensures a good behavior that was imposed by the DTC control "master-slave" to the two machines against all disturbances. The simulation results of this proposed method offers better steady state response (Fig. 8).

CONCLUSION

In this study, a new sensorless master-slave direct torque control is introduced for bi-machine single inverter system which can be easily extended to multi-machine traction system. The proposed method is based on conventional DTC with speed MRAS observer. Simulation results indicate that the performance of the proposed method in control of bi-machine is favourable and offers good response at steady state.

REFERENCES

Bidart, D., M. Pieterzak-David and M. Fadel, 2011. Mono inverter multi parallel PMSM- structure and control strategy. IET Electr. Power App., 5(3): 288-294.

Bidart, D., M. Pieterzak-David, M. Fadel and P. Maussion, 2008. Mono inverter dual parallel PMSM structure and control strategy. Proceeding of the 34th Annual Conference of IEEE Industrial Electronics (IECON, 2008), pp: 3073-3078.

Chiasson, J., D. Seto, F. Sun, A. Stankovic and S. Bortoff, 2002. Independent Control of PM motor using a single inverter: Application to elevator doors. Proceedings of the IEEE American Control Conference, pp: 093-3098.

Draou, A. and K. Hartani, 2012. A novel direct torque control scheme for PMSM for improving quality in torque and flux. Proceeding of the International Conference on Renewable Energy and Power Quality (ICREPQ'12). Galicia's Conference and Exhibition Centre, Santiago de Compostela, Spain.

Hao, W., Z. Deng and X. Wang, 2009. Enhanced adaptive observer for sensorless PMSM drive system. T. China Electrotech. Soc., 24(3): 41-46.

Hartani, K., Y. Miloud and A. Miloudi, 2010. Improved direct torque control of permanent magnet synchronous electrical vehicle motor with proportional-integral resistance estimator. J. Electr. Eng. Technol., 5(3): 451-461.

Hu, Y.W., C. Tian, Y.K. Gu, Z.Q. You, L.X. Tang and M.F. Rahman, 2002. In-depth research on direct torque control of permanent magnet synchronous motor. Proceedings 28th Annual Conference of the Industrial Electronics Society (IECON, 2002), 2: 1060-1065.

Jinsong, K., Z. Xiangyun, W. Ying and H. Dahing, 2009. Study of position sensorless control of PMSM based on MRAS. Proceeding of the IEEE International Conference on Industrial Technology (ICIT, 2009), pp: 1-4.

Kelecy, P.M. and R.D. Lorenz, 1994. Control methodology for single inverter, parallel connected dual induction motor drives for electric vehicles. Proceeding of the 25th Annual IEEE Power Electronics Specialists Conference (PESC'94), 2: 987-991.

Kojabadi, H.M. and M. Ghribi, 2006. MRAS-based adaptive speed estimator in PMSM drives. Proceeding of the 9th International Workshop on Advanced Motion Control, pp: 569-572.

Lixin, T. and Z. Limin, 2003. A novel direct torque control for interior permanent magnet synchronous machine drive with low ripple in torque and flux. IEEE T. Ind. Appl., 39(6): 1748-1756.

Maogang, W., Z. Rongxiang and W. Junwei, 2011. Sensorless estimation and convergence analysis based on MRAS for PMSM. Proceeding of the 8th World Congress on Intelligent Control and Automation (WCICA, 2011), pp: 1641-1644.

Matsuse, K., H. Kawai, Y. Kouno and J. Oikawa, 2004. Characteristics of speed sensorless vector controlled dual induction motor drive connected in parallel fed by a single inverter. IEEE T. Ind. Appl., 40(1).

Quntao, A. and S. Li, 2008. On-line parameter identification for vector controlled PMSM drives using adaptive algorithm. Proceeding of the IEEE Vehicle Power and e Propulsion Conference, pp: 1-6.

Rahman, M.A. and R. Qin, 1997. A permanent magnet hysteresis hybrid synchronous motor for electric vehicles. IEEE T. Ind. Electron., 44(1): 46-53.

Ruzhong, Y., L. Beizhi and F. Zhou, 2008. Sensorless control of PMSMs based on parameter optimized MRAS speed observer. Proceeding of the IEEE International Conference on Automation and Logistics. Qingdao, China, pp: 1573-1578.

Shibata, M. and N. Hoshi, 2007. Novel inverter topologies for two-wheel drive electric vehicles with two permanent magnet synchronous motors. Proceeding of the European Conference on Power Electronics and Applications, pp: 1-10.

Sun, D. and Y.K. He, 2005. Space vector modulation based constant switching frequency direct torque control for permanent magnet synchronous motor. Proc. CSEE, 25(12): 112-116.

Takahachi, I. and T. Noguchi, 1986. A new quick-response and high-efficiency control strategy of an induction motor. IEEE T. Ind. Appl., 22(5): 820-827.

Vaclavek, P. and P. Blaha, 2008. Synchronous machine drive observability analysis and sensorless control design. Proceeding of the IEEE 2nd International Power and Energy Conference (PECon, 2008), pp: 265-270.

Wu, G. and X. Xiao, 2009. Speed controller of several of servo system based on MRAS method. Proceeding of the IEEE International Conference on Industrial Technology (ICIT, 2009), pp: 1-5.

Xiaodong, X. and H. Yikang, 2007. Sensorless operation of PMSM based on Hybrid rotor position self-sensing scheme. Proceeding of the International Conference on Electrical Machines and Systems. Seoul, Korea, pp: 714-718.

Young, S.K., K.K. Kyoon and A.K. Young, 2003. MRAS based sensorless control of permanent magnet synchronous motor. Proceeding of the SICE Annual Conference. Fukui, Japan, August 4-6, pp: 1632-1637.