International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 17 (2015) pp 37751-37757

MRAS Speed Observer for Low Speed Estimation in Sensorless DTC-SVM Induction Motor Drives

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Abstract
Sensorless Direct Torque Controlled (DTC) Induction Motor Drives (IMD) has a major role in industrial application because of its instantaneous and direct control of electromagnetic torque and flux linkages. Stator resistance variation due to temperature changes, DC offset in electronic components and drift due to pure integrator are the low speed issues which deteriorate the performance of DTC IMD at low speeds. Model Reference Adaptive System (MRAS) is a closed loop observer used to estimate the rotor speed for improving the performance of the drive. In different MRAS schemes, rotor flux MRAS and reactive power MRAS with PI controller as adaptation mechanism are observed for low speed operation. Reactive power MRAS independent of stator resistance and pure integrator with PI controller is analyzed in low speed and a detailed investigation is carried out to evaluate the performance of reactive power MRAS and the results are compared with most commonly used rotor flux MRAS. The comparative study shows that reactive power MRAS reduced the speed estimation error and actual speed error at steady state operating condition. Simulation is performed in MATLAB Simulink platform to validate the performance of the drive at low speeds with rated and variable load condition.

Keywords: Induction motor, DTC, MRAS, Adaptive controllers, IMD, PI controller, rotor flux.

Introduction

Recently most of the high performance industrial application uses DTC as the control technique to get instantaneous and direct control of electromagnetic torque and flux linkages in IMD [1-3]. In DTC, direct control of electromagnetic torque and flux linkages are obtained by the selection of optimum inverter switching vectors [4]. Selection of inverter voltage vectors using Space Vector Modulation (SVM) has the advantage of reduced torque and flux ripples when compared to conventional DTC IMD [5].

The presence of mechanical sensors to extract actual rotor speed will increase hardware cost, system inertia, maintance and complexity and decreases reliability of the drive. Sensorless DTC IMD overcomes these disadvantages and estimates the rotor speed from stator voltages and stator currents using suitable estimators [4]. Different basic estimators and observers are available for rotor speed estimation. The accuracy of estimation in basic estimator depends on machine parameter. The issue of parameter dependency is eliminated in the observer by the insertion of error correction term to improve the accuracy of estimation.

MRAS is a simple and stable observer and require minimum computational and implementation effort for low speed operation of IMD [6], [7]. MRAS consist of a reference model, adaptive model and an adaptation mechanism. Adaptation mechanism tries to reduce the error between reference and adaptive model by adjusting the estimated rotor speed used in the adaptive model. When this error is reduced to zero, the estimated rotor speed by the adaptation mechanism corresponds to the actual speed of the motor. MRAS is broadly classified as rotor flux method, back emf method and reactive power method based on the formulation of speed tuning signal [4], [8-10]. Rotor flux scheme is the simple and the most popular MRAS method [9], but the presence of stator resistance and pure integrator in the reference model deteriorates the low speed performance of the drive [4], [8]. Back emf method avoids pure integrator from reference model but the inclusion of stator resistance adversely affects the low speed operation. Reactive power method independent of stator resistance and pure integrator is the most efficient estimation technique for optimum low speed performance compared to other two methods [4].

PI controller as the adaptation mechanism in MRAS has the advantage of giving satisfactory performance at low speed ranges of IMD [11]. A detailed analysis is carried out for low speed estimation of sensorless DTC induction motor drive with rotor flux MRAS and reactive power MRAS using PI as adaptive controller in MATLAB-Simulink platform. The results are compared to prove the effectiveness of reactive power MRAS with PI as adaptive controller for low speed estimation.

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Sensorless DTC-SVM IMD

Direct control of electromagnetic torque and stator flux linkage are obtained in DTC-SVM IMD by the selection of exact stator voltage vector. This selection is based on the outputs of torque and flux PI controller of the DTC drive to meet the requirement of desired torque and flux. This method offers reduced torque ripples and maintains constant switching frequency compared to conventional hysteresis band DTC controllers [12]. Among the different techniques available for speed estimation in sensorless drives, MRAS is considered here for rotor speed estimation. The estimated rotor speed from the MRAS using stator voltages and stator currents are compared with the reference speed and the error is fed to the speed controller for producing reference values of torque and flux. The values of torque and flux produced by the corresponding estimators from stator voltages and stator currents are compared with the corresponding reference values from speed controller as shown in Fig.1.

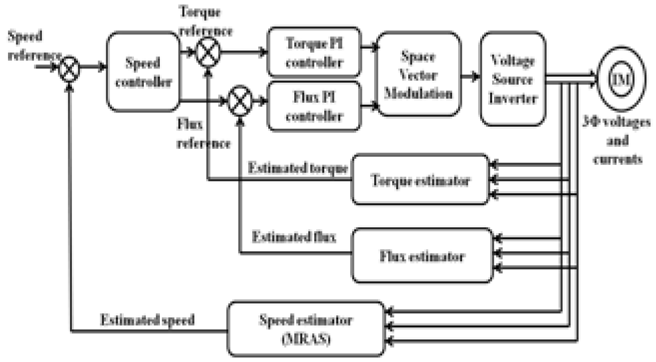


Fig.1. Block diagram of sensorless SVM-DTC with speed estimator

The error signal obtained during comaprison of estimated and reference values are giving to the correspoding torque and flux PI controller. The tuned values from these controllers are used to select the exact voltage vector for SVM for reducing the torque and flux errors.

Model Reference Adaptive System

MRAS is simple and stable closed loop observer used in sensorless DTC IMD to estimate the rotor speed for improving the drive performance at low speed [13]. MRAS constitutes reference model, adaptive model and adaptation mechanism for speed estimation. Reference model uses stator voltage and stator current as inputs where as adaptive model uses stator current and estimated rotor speed from adaptation mechanism as inputs. The system parameters estimated by reference and adaptive model is compared and the error is fed as speed tuning signal to the adaptation mechanism. The rotor speed obtained from adaptation mechanism which is used in the adaptive model for estimation is adjusted to reduce the error between reference and adaptive models. The estimated rotor speed will be equal to the actual rotor speed of IMD when the speed tuning signal becomes zero. The adaptation mechanism should always satisfy the Popov's criterion of hyper stability. MRAS can be classified as rotor flux method, back emf method and reactive power method based on the speed tuning signal used in adaptation mechanism.

In rotor flux method the reference and adaptive model independently estimates the rotor flux in stationary reference frame and the difference between these two are giving to the adaptation mechanism to estimate the rotor speed [11] as shown in Fig.2. The reference model will calculate the direct and quadrature axis of rotor flux components using stator voltage and stator current in stationary reference frame. The expressions for the rotor flux components are given in equations (1) and (2).

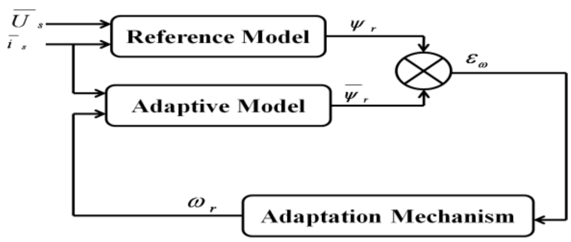


Fig.2. Block diagram of rotor flux based MRAS

$$\varphi_{rd} = \frac{L_r}{L_m}\left[\int (U_{sD} - R_s i_{sD})dt - L'_s\, i_{sD}\right] \quad (1)$$

$$\varphi_{rq} = \frac{L_r}{L_m}\left[\int \left(U_{sQ} - R_s i_{sQ}\right)dt - L'_s\, i_{sQ}\right] \quad (2)$$

φ_{rd}& φ_{rq} are the rotor fluxes from reference model in direct and quadrature axis respectively, U_{sD}&U_{sQ} are the stator voltages in direct and quadrature axis, i_{sD}& i_{sQ} are the stator currents in direct and quadrature axis, R_s is stator resistance, L_r is rotor self inductance, L_m is mutual inductance and $L_s^{'}$ is stator transient inductance.

The adaptive model will also calculate the same rotor flux components using stator current and estimated rotor speed and the expressions are given in equations (3) and (4).

$$\hat{\varphi}_{rd} = \frac{1}{T_r}\int \left(L_m i_{sD} - \hat{\varphi}_{rd} - \omega_r T_r \hat{\varphi}_{rq}\right)dt \quad (3)$$

$$\hat{\varphi}_{rd} = \frac{1}{T_r}\int \left(L_m i_{sQ} - \hat{\varphi}_{rq} + \omega_r T_r \hat{\varphi}_{rd}\right)dt \quad (4)$$

where $\hat{\varphi}_{rd}$& $\hat{\varphi}_{rd}$the rotor fluxes from adaptive model in direct and quadrature axis, T_r is rotor time constant and ω_r is estimated rotor speed.

The speed tuning signal (ε_ω) is the difference in rotor flux from reference and adaptive model and the expression is given in equation (5).

$$\varepsilon_\omega = \varphi_{rq}\hat{\varphi}_{rd} - \varphi_{rd}\hat{\varphi}_{rq} \quad (5)$$

The stator resistance and pure integrator in the reference model of this method affect the drive performance at low speeds due to temperature changes. Derivative of rotor flux avoids pure integrator which multiplies with $\frac{L_m}{L_r}$ gives back emf and used as back emf method [6]. In back emf MRAS, reference and adaptive model independently estimates the back emf and equations (6) and (7) represents the direct and quadrature axis of back emf in stationary reference frame by reference model.

$$e_d = \frac{L_m}{L_r}\frac{d\varphi_{rd}}{dt} = u_{sD} - R_s i_{sD} - L_s^{'}\frac{di_{sD}}{dt} \quad (6)$$

$$e_q = \frac{L_m}{L_r}\frac{d\varphi_{rq}}{dt} = u_{sQ} - R_s i_{sQ} - L_s^{'}\frac{di_{sQ}}{dt} \quad (7)$$

Equations (8) and (9) represent the direct and quadrature axis of back emf in stationary reference frame by adaptive model.

$$\hat{e}_d = \frac{L_m}{L_r}\frac{d\hat{\varphi}_{rd}}{dt} = \frac{L_m}{L_r}\frac{(L_m i_{sD} - \hat{\varphi}_{rd} - \omega_r T_r \hat{\varphi}_{rq})}{T_r} \quad (8)$$

$$\hat{e}_q = \frac{L_m}{L_r}\frac{d\hat{\varphi}_{rq}}{dt} = \frac{L_m}{L_r}\frac{(L_m i_{sQ} - \hat{\varphi}_{rq} + \omega_r T_r \hat{\varphi}_{rd})}{T_r} \quad (9)$$

Where e_d & e_q are the direct and quadrature axis of back emf from reference model and $\hat{e}_d$ & $\hat{e}_q$ are the direct and quadrature axis of back emf from adaptive model. The speed tuning signal is the difference in back emf from reference and adaptive model and is given in equation (10)

$$\varepsilon_\omega = e_q\hat{e}_d - e_d\hat{e}_q \quad (10)$$

The reference model of this method avoids pure integrator but presence stator resistance deteriorates the performance of the drive at low speeds due to change in temperature. The cross product of back emf with stator currents avoids the stator resistance and gives reactive power. The reference and adaptive model uses this reactive power for making speed tuning signal known as reactive power method. Equation (11) and (12) represents the mathematical expression for reactive power from reference and adaptive model respectively.

$$y = \bar{\iota}_s \times \bar{e}$$

$$= U_{sQ} i_{sD} - U_{sD} i_{sQ} - L_s^{'}\left(i_{sD}\frac{di_{sQ}}{dt} - i_{sQ}\frac{di_{sD}}{dt}\right) \quad (11)$$

$$\hat{y} = \bar{\iota}_s \times \hat{e}$$

$$= \frac{L_m}{L_r}\begin{bmatrix} \frac{1}{T_r}(\hat{\varphi}_{rd} i_{sQ} - \hat{\varphi}_{rq} i_{sD}) \\ +\omega_r(\hat{\varphi}_{rd} i_{sD} + \hat{\varphi}_{rq} i_{sQ}) \end{bmatrix} \quad (12)$$

Where y & $\hat{y}$ are the reactive power from reference and adaptive model respectively. The speed tuning signal is the difference in reactive power from reference and adaptive model is given equation (13).

$$\varepsilon_\omega = y - \hat{y} \quad (13)$$

PI Adaptive Controller

PI controllers are having simple structure and can give satisfactory performance for all speed ranges including low speeds. Sensorless IMD uses MRAS speed estimator which uses PI controllers as adaptation mechanism to estimate the actual rotor speed. The estimated rotor speed from PI controller can be expressed as

$$\omega_r = K_p\varepsilon_\omega + K_i\int \varepsilon_\omega\, dt \quad (14)$$

Where K_p & K_i are the proportionality and integral constant of PI controller and these values are are selected arbitrarily to obtain satisfactory performance.

Simulation Results And Analysis

A 20 hp sensorless DTC-SVM IMD with MRAS as speed observer is considered and simulated for rotor flux MRAS and reactive power MRAS in MATLAB-Simulink platform. The motor parameters of 20 hp motor are given in Table I.

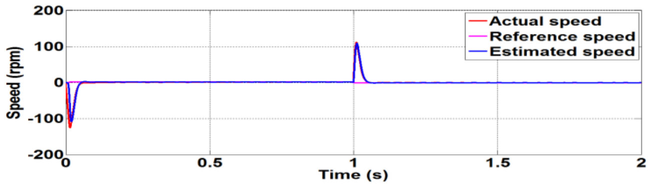
TABLE.1. Machine Parameters

Parameters	Value
R_s	0.2147 Ω
R_r	0.2205 Ω
L_s	0.065181 H
L_r	0.065181 H
L_m	0.06419 H
Rated speed	1460 rpm
Rated torque	98 Nm
No of poles	4
Voltage	400 V (line to line)
Frequency	50 Hz
Inertia	0.102 $Kg.m^2$

A detailed simulation is carried out to validate the performance of rotor flux MRAS and reactive power MRAS with PI as adaptive controller for low speed ranges. An exhaustive analysis is performed for reactive power MRAS independent of stator resistance and pure integrator with PI controller as adaptation mechanism and the results are compared with rotor flux MRAS with same adaptive controller to find the effectiveness of reactive power MRAS method. The detailed simulation analysis of rotor flux MRAS and reactive power MRAS and comparison of both MRAS scheme are given in this paper.

A. Performance analysis of the drive using rotor flux MRAS with PI controller as adaptation mechanism

Simulation is done with rotor flux MRAS as speed estimator in DTC SVM IMD and analyzed for wide range of speed from rated to low speed ranges under rated and variable torque conditions. The results show that the estimated rotor speed and electromagnetic torque are following the actual rotor speed and electromagnetic torque of the IMD. The plot of speed and torque curve for positive speed with positive rated torque in 0 to 1s and negative speed with negative rated torque in 1 to 2s for 1 rpm as shown in Fig.3.



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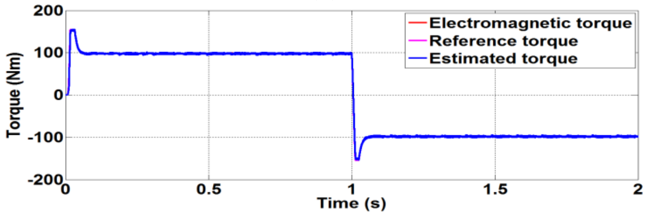


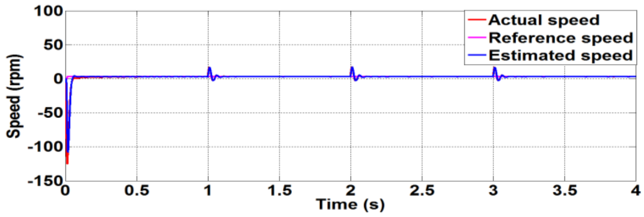
(b)

Fig.3. Curves of speed at 1 rpm and torque of 98 Nm with rotor flux MRAS with PI adaptive controller showing reference, estimated and actual values speed along Y-axis and time in seconds along X-axis. a) speed curve b) torque curve

To find the effectiveness of drive for varrying load condition, the drive is subjected to 1/4th, 1/2nd and 3/4th of rated torque condtition for constant speed. The different load codition are anlyzed for different constant speeds and Fig. 4 shows the speed and torque curve for 3 rpm for the torque condition given in Table. 2.

TABLE.2. Profile of the Reference Torque Applied

Torque (Nm)	98	73.5	49	24.5
Time (s)	0-1	1-2	2-3	3-4



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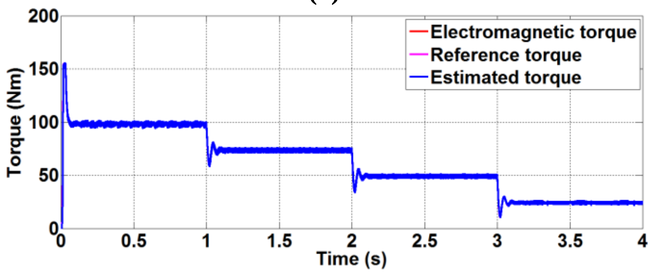


(b)

Fig.4. Speed and and Torque curves of rotor flux MRAS with PI controller showing reference, estimated and actual values along Y-axis and time in seconds along X-axis for 3rpm at rated, 3/4th, 1/2nd and 1/4th load condition a) speed curve b) torque curve

During the steady state operating condition of the drive different performace parameter like percentage speed estimation error and actual speed error, Ripple in actual and estimated speed and ripple in electromagnatic torque and estimated torque are analyzed for speed ranges from rated speed to 1 rpm are given in Table. 3.

Speed estimation error in percentage is the percentage difference between actual and estimated speed and actual speed error in pecentage is the percentage error between reference speed and actual speed.The speed estimation error is less than 14% for speeds from 2rpm to rated speed and it is 33.07% for 1rpm. The actual speed error is less than 32% for speeds from 2rpm to rated speed and it is 53.47% for 1rpm. The stator flux trajectory is drawn for 3rpm by plotting the direct and quadrature stator flux components are shown in Fig.5.

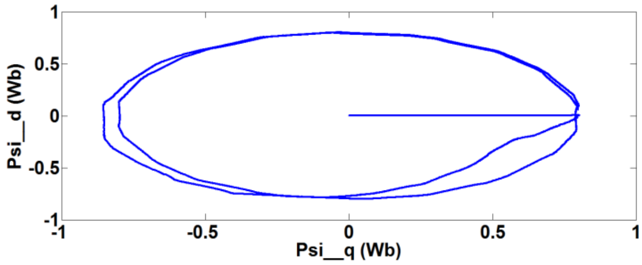


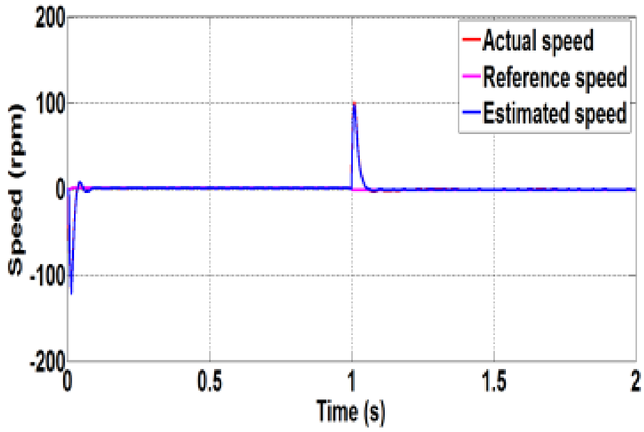
Fig.5. Stator flux trajectory of rotor flux MRAS with PI adaptive controller for 3 rpm

TABLE.3. Performance of the Parameter at Steady State for Rotor Flux MRAS with PI Controller

Speed (rpm)	Speed Estimation error (%)	Actual speed error(%)	Ripple in actual speed(rpm)	Ripple in estimated speed(rpm)	Ripple in electromagnetic torque (Nm)	Ripple in estimated torque (Nm)
1	33.07	53.47	1.0154	0.9031	6.98	7.02
2	13.79	31.77	1.173	1.101	7.24	7.24
3	10.72	22.32	1.021	1.086	6.89	6.89
5	8.912	17.95	1.082	1.026	6.56	6.56
10	8.137	11.56	0.786	0.645	6.78	6.78
30	7.457	8.5	0.61	0.5	6.37	6.37
50	7.702	8.418	0.52	0.32	6.79	6.79
100	6.977	7.947	0.66	0.53	6.84	6.84
300	6.19	7.12	0.72	0.63	13.12	13.12
500	5.62	6.22	0.75	0.69	15.37	15.37
1000	4.12	5.87	0.98	0.79	19.23	19.23
1460	3.93	4.92	1.184	1.102	17.14	17.14

B. *Performance analysis of the drive using reactive power MRAS with PI controller as adaptation mechanism*

Simulation is carried out with reactive power MRAS using PI adaptive controller for the speed ranges from rated to low speeds under rated and variable load condition. The speed and torque curve of the drive for positive rated torque and speed in 0 to 1s and negative rated torque and speed in 1 to 2s for 1rpm are given in Fig. 6.



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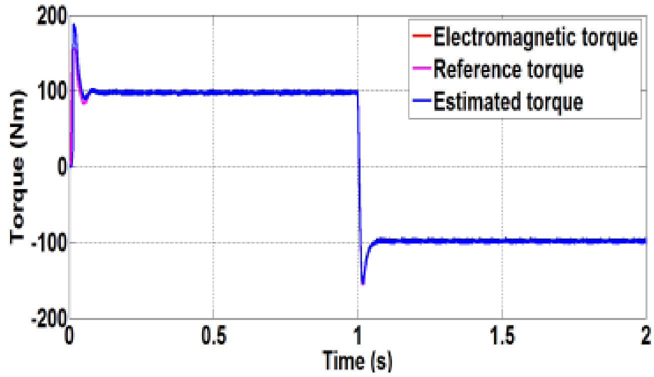
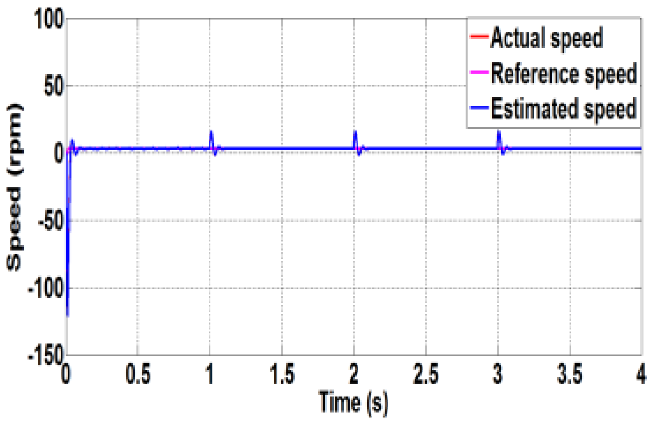


(b)

Fig.6. Curves of speed at 1 rpm and torque of 98 Nm with reactive power MRAS with PI adaptive controller showing reference, estimated and actual values speed along Y-axis and time in seconds along X-axis. a) speed curve b) torque curve

The different load conditon like 3/4th, 1/2nd and 1/4th rated torque given in Table. 2. are analyzed for reactive power MRAS with constant speed of 3rpm as shown in Fig.7.



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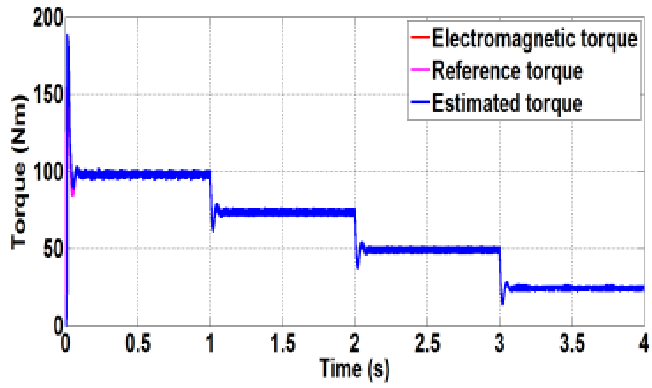

(b)

Fig.7. Speed and and Torque curves of reactive power MRAS with PI controller showing reference, estimated and actual values along Y-axis and time in seconds along X-axis for 3rpm at rated, 3/4th, 1/2nd and 1/4th load condition a) speed curve b) torque curve

Different performace parameter at steady state like percentage speed estimation error and actual speed error, Ripple in actual and estimated speed and ripple in electromagnatic torque and estimated torque are analyzed for speed ranges from rated speed to 1 rpm are given in Table.4. The speed estimation error is less 5% for speeds from 2rpm to rated speed and it is 13.8% for 1rpm. The actual speed error is less than 26% for speeds from 2rpm to rated speed and it is 50% for 1rpm. The stator flux trajectory is drawn by plotting the direct stator flux and quadrature stator flux components foor 3rpm is shown in Fig.8.

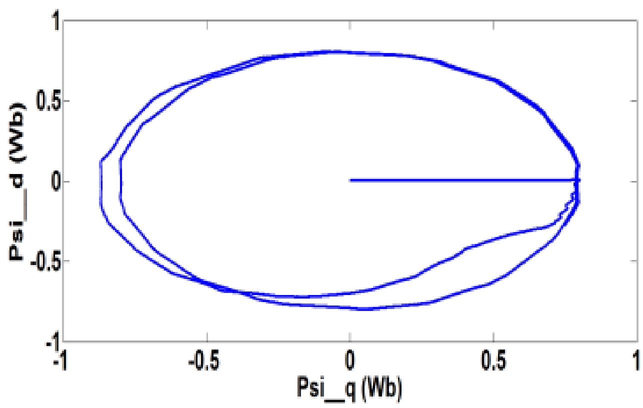

Fig.8. Stator flux trajectory of reactive power MRAS with PI adaptive controller for 3 rpm

*C. **Comparative performance analysis of the drive using rotor flux MRAS with PI controller and reactive power MRAS with PI controller***

Comparative analysis are done for performance parameter at steady state by using rotor flux MRAS with PI controller and reactive power MRAS with PI controller to find the effectiveness of reactive power MRAS with PI controller at low speed ranges. The analysis is carried out for different

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 17 (2015) pp 37751-37757

speeds from rated speed to 1rpm. The speed estimation error is less than 5% from rated speed to 2rpm and less than 14% for 1rpm for reactive power MRAS with PI controller. Similarly the actual speed error is less than 9% for from rated speed to 5rpm and less than 26% for 5rpm to 1rpm and 50% for 1rpm for reactive power MRAS with PI controller. A comparative analysis of speed estimation error and actual speed error are shown in Fig.9 and Fig.10.

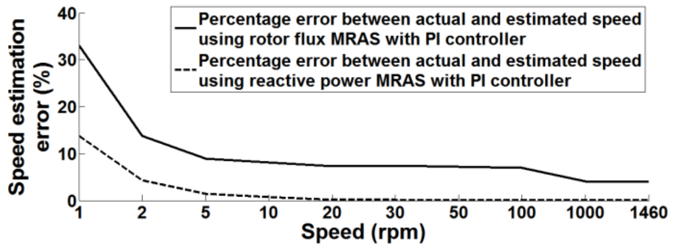

Fig.9. Speed estimation error profile for different speeds for rotor flux MRAS with PI controller and reactive power MRAS with PI adaptive controller

TABLE.4. Performance of the Parameter at Steady State for Reactive Power MRAS with PI Controller

Speed (rpm)	Speed Estimation error (%)	Actual speed error (%)	Ripple in actual speed (rpm)	Ripple in estimated speed (rpm)	Ripple in electromagnetic torque (Nm)	Ripple in estimated torque (Nm)
1	13.8	50	0.915	0.8767	6.73	6.73
2	4.337	26.02	0.912	0.885	7.01	7.01
3	2.694	17.04	0.908	0.868	6.92	6.92
5	1.405	8.76	0.861	0.837	6.69	6.69
10	0.7343	3.424	0.65	0.6	6.81	6.81
30	0.1412	0.7688	0.43	0.41	6.3	6.3
50	0.07548	0.3726	0.33	0.33	6.89	6.89
100	0.05443	0.1659	0.37	0.36	7.8	7.8
300	0.01915	0.06447	0.37	0.378	9.46	9.46
500	0.015	0.0522	0.51	0.5	13.6	13.6
1000	0.0114	0.03317	0.65	0.67	17.21	17.21
1460	0.0088	0.02303	0.65	0.71	14.55	14.55

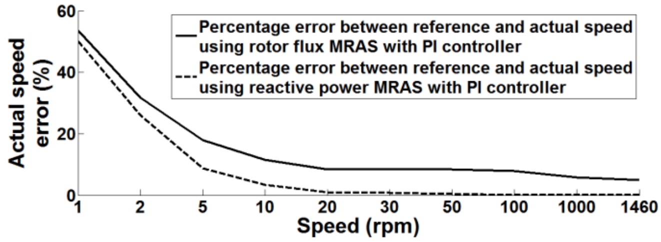

Fig.10. Actual speed error profile for different speeds for rotor flux MRAS with PI controller and reactive power MRAS with PI adaptive controller

The ripple in actual speed and estimated speed are reduced in reactive power MRAS with PI controller. The actual speed ripple are in between 0.52rpm to 1.184rpm for rated speed to 1rpm for rotor flux MRAS with PI controller and in between 0.33rpm to 0.915rpm for rated speed to 1rpm for reactive power MRAS with PI controller. The estimated speed ripples are in between 0.32 rpm to 1.102rpm for rated speed to 1rpm for rotor flux MRAS with PI controller and in between 0.33 rpm to 0.885rpm for rated speed to 1rpm for reactive power MRAS with PI controller. The Fig. 11 and Fig. 12 shows the comparison of rotor flux MRAS and reactive power MRAS with PI as adaptive controller for ripple in actual speed and estimated speed for various speeds.

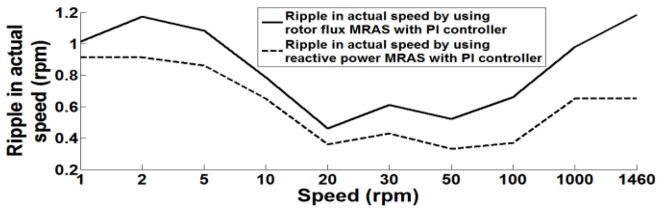

Fig.11. Ripple in actual speed profile for different speeds for rotor flux MRAS with PI controller and reactive power MRAS with PI controller

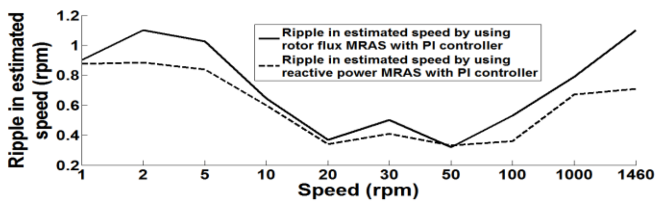

Fig.12. Ripple in estimated speed profile for different speeds for rotor flux MRAS with PI controller and reactive power MRAS with PI controller

The ripple in electromagnetic torque and estimated torque are reduced in reactive power MRAS with PI as adaptive controller. The Fig. 13 and Fig. 14 shows the comparison of rotor flux MRAS and reactive power MRAS with PI as adaptive controller for ripple in electromagnetic torque and estimated torque for various speeds.

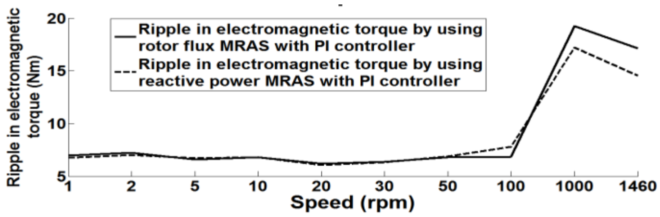

Fig.13. Ripple in electromagnetic torque profile for different speeds for rotor flux MRAS with PI controller and reactive power MRAS with PI controller

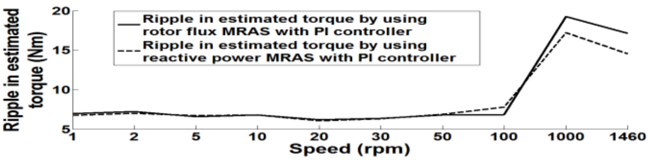

Fig.14. Ripple in estimated torque profile for different speeds for rotor flux MRAS with PI controller and reactive power MRAS with PI controller

The exhaustive analysis proves the effectiveness of recative power MRAS with PI adaptive controller for low speed estimation of DTC-SVM induction motor drive using MRAS as speed estimator.

Conclusion

In this paper MRAS is used as speed observer in DTC-SVM IMD to improve the drive performance at low speed ranges. A comparative analysis is carried out between rotor flux MRAS and reactive power MRAS methods for speed estimation with PI as the adaptive controller. The condition of speed and torque reversal and varying load torque is also tested for both the methods to validate the performance of the drive in steady state and transient conditions in low speed ranges.

Various performance parameters like speed estimation error, actual speed error and ripples in estimated and actual values of speed and torque are evaluated for both the speed estimation methods from rated speed to low ranges. The statistics shows that the rotor flux MRAS method gives a speed estimation error less than 9% for all speeds starting from 5 rpm up to the rated speed and for speeds upto 2rpm it is less than 14%, where as reactive power method limits it within 2% and 5% respectively for the same speed ranges. Similarly the rotor flux MRAS method gives actual speed error less than 18% for all speeds starting from 5 rpm up to the rated speed and it is less than 9% with reactive power method for the same speed range. Significant reduction in actual and estimated speed ripple is also achieved using reactive power method of speed estimation. The study reveals that reactive power method exhibits superior performance comapred to rotor flux method for low speed estimation in MRAS on the basis of reduction in error and ripple.

References

[1] I. Takahashi and T. Noguchi, "A new quick-response and high-efficiency control strategy of an induction motor," IEEE Trans. Ind. Applicat., vol. 22, pp. 820–827, Sept./Oct. 1986.

[2] T. G. Habetler and F. Profumo, "Direct torque control of induction machines using space vector modulation," IEEE Trans. Ind. Applicat., vol. 28, pp. 1045–1052, Sept./Oct. 1992.

[3] C. Lascu, I. Boldea and F. Blaabjerg, "A modified direct torque control (DTC) for induction motor sensorless drive," Industry application confererence, vol. 1, pp. 415-422, Oct. 1998.

[4] P. Vas,— Sensorless vector and direct torque control ‖ Oxford Newyork Tokyo, Oxford university press,1998.

[5] Y. S. Lai and J. H. Chen, "A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripple reduction," *IEEE Trans. Energy Conversion*, vol. 16, pp. 220–227, Sept. 2001.

[6] M. Rashed and A. F. Stronach, "A stable back-EMF MRAS-based sensorless low speed induction motor drive insensitive to stator resistance variation," Proc. Inst. Elect. Eng.—Electr. Power Appl., vol. 151, no. 6, pp. 685–693, Nov. 2004.

[7] V. Vasic and S. Vukosavic, "Robust MRAS-based algorithm for stator resistance and rotor speed identification," *IEEE Power Eng. Rev.*, vol. 21, no. 11, pp. 39–41, Nov. 2001.

[8] F. Peng and T. Fukao, "Robust speed identification for speed-sensorless vector control of induction motors," *IEEE Trans. Ind. Appl.*, vol. 30, no. 5, pp. 1234–1240, Sep./Oct. 1994.

[9] C. Schauder, "Adaptive speed identification for vector control of induction motors without rotational transducers," *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1054–1061, Sep./Oct. 1992.

[10] S. Maiti, C. Chakraborty, Y. Hori, and M. C. Ta, "Model reference adaptive controller-based rotor resistance and speed estimation techniques for vector controlled induction motor drive utilizing reactive power," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 594–601, Feb. 2008.

[11] S. M. Gadoue, D. Giaouris and J. W. Finch, "MRAS sensorless vector control of induction motor using new sliding-mode and fuzzy logic adaptation mechanisms," *IEEE Trans. On Energy Conversion*, vol. 25, pp. 394-402, June. 2010.

[12] Z. Zhang, R. Tang, B.Bai and D, Xie, "Novel direct torque control bades on space vector mpdulation with adaptive stator flux observer for induction motors,"*IEEE Trans. On magnetics*, vol. 46, pp. 3133-3136, Aug. 2010.

[13] J. Holtz and J. Quan, " Sensorless vector control of induction motors at very low speed using a nonlinear inverter model and parameter identification," *IEEE Trans. Ind. Applicat.*, vol. 38, pp. 1087-1095, July/Aug. 2002.