EXPERIMENTAL INVESTIGATION ON FLUX ESTIMATION AND CONTROL IN A DIRECT TORQUE CONTROL DRIVE

Bhoopendra singh[1], ShailendraJain[2], Sanjeeet Dwivedi[3]
[1]Department of Electrical Engineering, RGTU University, Bhopal, India
[2]Department of Electrical Engineering, Manit, Bhopal, India
[3]Danfos Power Electronics, Denmark

ABSTRACT

A Direct torque control algorithm involves a decoupled control of torque and flux with the help of two independent control loops. Estimation of stator flux requires an integration of motor back emf which is achieved by a pure integrator.Accurate Flux estimation algorithm, choice of flux hysteresis controller bandwidth in the flux control loopand the value of reference flux are the determining factors in Direct Torque control induction motor drive.An enhancement in steady state performance can be achieved byan efficient flux estimation algorithm. For sensorless drives voltage model based integration algorithm are most suitable owing to their less dependency on machine parameters. In this paper a comparison of voltage model basedlow pass filter flux estimation algorithm in terms of steady state flux ripples and stator current harmonics is carried out.Furthermore the influence of flux hysteresis comparator band magnitude on drive performance is also investigated. The proposed study is investigated through simulation and experimentally validated on a test drive.

KEYWORDS: *Direct torque control, Induction motor, modified low pass filter.*

I. INTRODUCTION

In a direct torque control induction motor drive, the basic concept is to control both stator flux and electromagnetic torque of the machine simultaneously by the application of one of the six active full voltage vectors and two zero voltage vectors generated by an inverter. The stator flux and torque track their reference values within the limits of two hysteresis bands with two hysteresis comparators and a heuristic switching table to obtain quick dynamic response [1]-[5]. The steady state as well as the dynamic performance of the drive is closely related to the efficient implementation of flux and speed control algorithm. There are few well-known methods to estimate the stator flux. Most of them are voltage model based [3], where the flux and torque are estimated by sensing stator voltage and current. The methods based on voltage models are most preferable for sensor less drives since these methods are less sensitive to the parameter variations and does not require motor speed or rotor position signals. However, the estimation of stator voltage when the machine is operating at low speed introduces error in flux estimation which also affects the estimation of torque and speed in case of sensor less drive [6]-[12].

In a conventional DTC drive the basic voltage model based flux estimation is carried out by integrating the back emf of the machine [13]. A pure integrator has the following limitations.

1. Any transduction error in measured stator current due to offset introduces DC component and hence results in integrator saturation.
2. Integration error due to incorrect initial values.

A commonly employed solution is to replace a pure integrator with a low pass filter [13] [14], however it is achieved at the expense of deteriorated low speed operation of the drive, when the operating frequency of the drive is lower than the cut off frequency of the low pass filter.

Flux estimation based on the current model is most suitable for low speed operation [15], however it is a parameter dependent method, which require rotor speed or position. Thus parameter independent operation, which makes a DTC drive more robust and reliable compared to a FOC drive, gets affected when current model based flux estimation is implemented .

This paper investigates the performance of a DTC drive in terms of stator current harmonics and root mean square flux ripples under the influence of a voltage model based low pass filter digital integration algorithm [13].Furthermore the effect of flux hysteresis controller bandwidth on the operation of the DTC drive is investigated. The proposed control strategy is illustrated by simulation and validated through experimental results. In detail this paper is organized as follows. Section 2 reviews DTC operation. In Section 3 the comparison of the voltage model based flux estimation algorithm carried out.

II. DTC OPERATION

According to the DTC principle, an independent control of torque and flux can be achieved by the application of appropriate voltage vectors in such a way that the error between the estimated torque and flux with their respective reference values remains within the limits of hysteresis comparators. The desired voltage vectors to compensate the errors are selected based on the output of the torque and flux hysteresis comparator as well as the locus of stator flux vector.

From the basic equation governing induction motor operation stator flux λ_s is given by (1) and (2).

$$\lambda_s = \int (V_s - R_s I_s) dt \tag{1}$$

Neglecting the drop in stator resistance,

$$\Delta\lambda_s = \overline{V_s}\Delta t \tag{2}$$

Where Δt is the time interval of application of the applied voltage vector. Electromagnetic torque in an Induction motor is given by (3)

$$T_e = P\,\frac{L_m}{\sigma L_{s}\,L_r}|\lambda_s||\lambda_r|\sin(\delta) \tag{3}$$

Where

$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r} \tag{4}$$

It can be concluded from (3) that an increment in torque can be achieved by increasing the angle between stator and rotor flux vector. Splitting the vector $\Delta\lambda_s$ into horizontal and orthogonal components it can be concluded that orthogonal component of $\Delta\lambda_s$ is responsible for torque control and the horizontal component controls the flux as shown in Fig. 1.

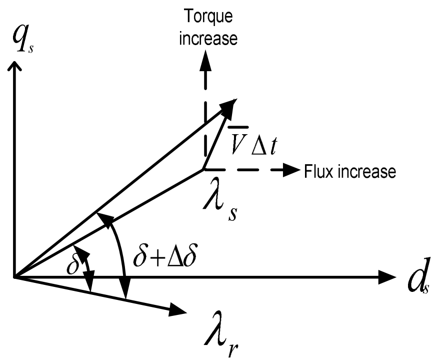


Fig. 1 Flux and torque control by the applied voltage vector in a DTC drive.

III. FLUX ESTIMATION AND CONTROL

The expression for the modified low pass filter with feedback compensation [13] integration algorithm for flux estimation is given by (5).The method can be implemented as shown in Fig.2.

$$\lambda_s = E_s \frac{1}{s+\omega_c} + \lambda_s^{lim} \frac{\omega_c}{s+\omega_c} \tag{5}$$

The first part of the equation represents a low pass filter while the second part realizes a compensating feedback signal which is used to compensate the error in the output. The parameter λ_s^{lim} in the second term of new integration algorithm is the output of a saturation block, which stops the integration when the output signal exceeds the reference stator flux amplitude.

The value of λ_s^{lim} can be obtained from the sine and cosine value of the angle obtained by integrating the stator angular frequency w_e given by (6) and (7).

$$\theta = \int w_e \mathrm{dt}. \tag{6}$$

Where stator frequency can be given by

$$w_e = \frac{E_{s\beta}\lambda_{s\alpha} - E_{s\alpha}\lambda_{s\beta}}{|\lambda_s|^2} \tag{7}$$

The accuracy of the modified flux estimation algorithm thus is strongly dependent on the value of angle (θ) which can either be obtained from the stator frequency or from the flux components ($\lambda_{s\alpha}$, $\lambda_{s\beta}$) . At low speeds (low frequencies), accuracy of calculation is jeopardized by the large percentage of ripple in w_e . Hence, using the ratio of sin and cosine of angle (θ) based on the estimated flux components at low speeds leads to better results than the calculation based on electrical frequency.

The final expression of the Mod LPF for implementation on a discrete controller can be developed with the help of equations (8)-(12)

$$\lambda_s^{com} = \lambda_s^{lim} \frac{\omega_c}{s+\omega_c} \tag{8}$$

$$\lambda_{s\alpha}^{com}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\lambda_{s\alpha}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\alpha}^{lim}(k)\right) \tag{9}$$

$$\lambda_{s\beta}^{com}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\lambda_{s\beta}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\beta}^{lim}(k)\right) \tag{10}$$

$$\lambda_{s\alpha}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\Delta t_s E_{s\alpha}(k) + \lambda_{s\alpha}(k-1) + \lambda_{s\alpha}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\alpha}^{lim}(k)\right) \tag{11}$$

$$\lambda_{s\beta}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\Delta t_s E_{s\beta}(k) + \lambda_{s\beta}(k-1) + \lambda_{s\beta}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\beta}^{lim}(k)\right) \tag{12}$$

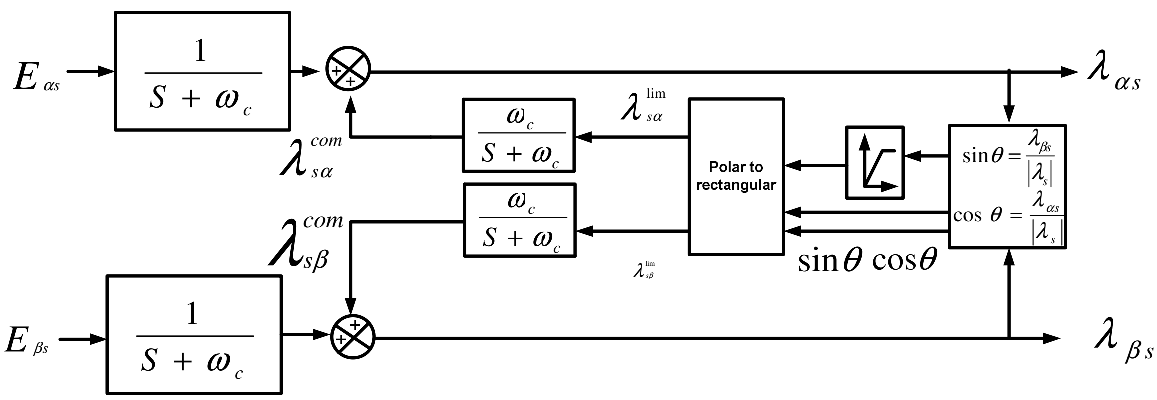


Fig.2 Modified low pass filter with feed back compensation.

The switching losses and stator current harmonics strongly depends flux hysteresis controller bandwidth($H_{\emptyset}$). Small hysteresis controller band of flux results in a very high switching frequency, resulting in higher switching losses. On the other hand, a higher value of the flux hysteresis band amplitude causes degeneration of stator flux vector locus resulting in higher harmonic losses. The flux hysteresis band has no influence on torque pulsation and the torque hysteresis band has slight effect on the harmonic copper losses.

IV. RESULTS AND DISCUSSION

The performance of the proposed drive is investigated through simulations using Matlab/Simulink and is further validated experimentally.

A test drive set up developed in the laboratory is shown in Fig.3.The experimental test drive setup consists of the following elements:

1) Machine unit; a 0.75 kW, 410 V, 50-Hz squirrel-cage induction motor with a shaft mounted tachogenerator for speed sensing coupled with dc generator for loading.

2) A power module with MOSFET based voltage source inverter with Hall Effect sensors and gate drive circuitry.

3) dSpace DS1104 control board.

The parameters of the motor for experimentation are as follows.R_s=10.75 Ω,$R_r = 9.28\ \Omega$, $L_s = L_r = 51.9$ mH , P=4 and $L_m = 479.9$ mH . The sampling time of the DTC experiments is taken as 100 µs while the dead time for the switches is 10 µs. The value of torque and flux hysteresis comparator bandwidth is takes as 0.5 Nm and 0.005 wb. All experimental results are recorded using the Control Desk platform of dSpace DS1104 by saving the target variable as mat files.

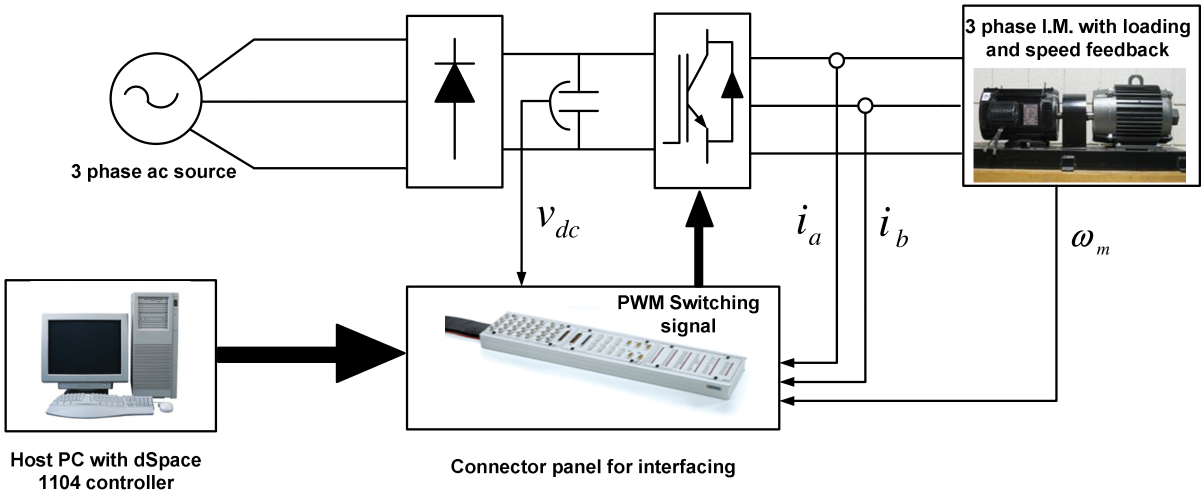


Fig.3 Experimental test drive set up.

The performance parameters to evaluate the effectiveness of the flux estimation algorithm are steady state flux response and stator current harmonics.Fig.4(a) shows that the two stator flux components are orthogonal and are sinusoidally varying with time. A circular flux trajectory shown in Fig.4(c) further validates the effectiveness of the flux estimation method .The dynamic response for a step change in ref. flux is shown in Fig.4 (b), and it can be verified from the figure that the actual flux traces the ref. flux. The harmonic spectrum of full load stator current at rated speed is shown in Fig.4 (d) and a THD of 3.3% confirms the effectiveness of the flux estimation method.

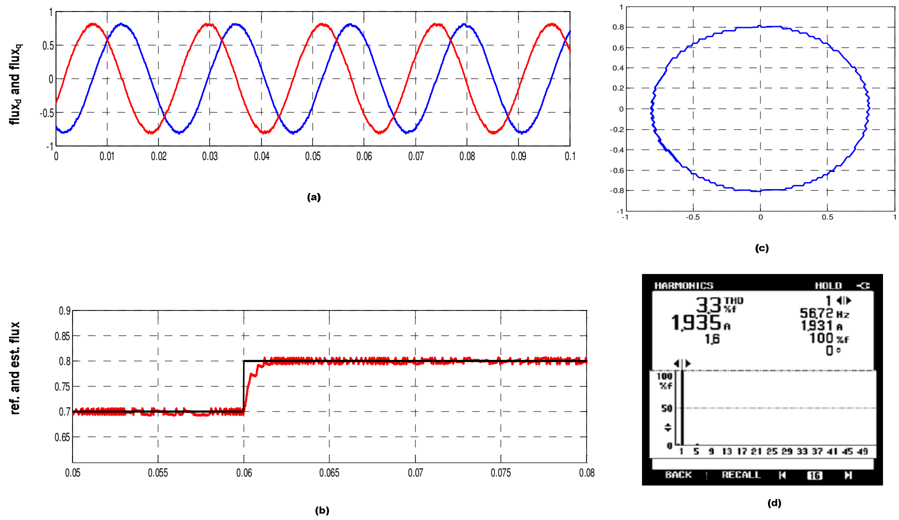
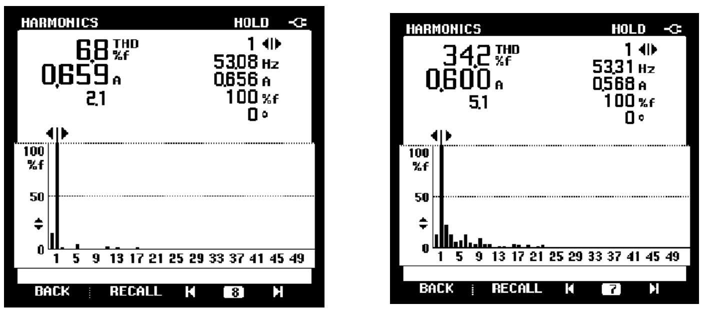


Fig.4 Experimental steady state flux response and current harmonics. (a) Stator flux components ($\lambda_{s\alpha}$, $\lambda_{s\beta}$) (b) flux response for step change in ref. flux (c) flux trajectory (d) stator current harmonics at full load.

To study the effect of flux hysteresis controller band ($H_\varnothing$), the experimental drive was operated at different values of band magnitude($H_\varnothing$ =.005 wb and .05 wb) at 50% loading. From Fig.5 – Fig.8, it can be verified that a reduction in flux hysteresis controller band by 10% results in decrement in flux ripples, stator current harmonics and improvement in stator flus trajectory .The Root men square flux error and THD for $H_\varnothing$ =0.05 wb is 0.0384 wb and 34.2 % respectively, while it get reduced to 0.0143 wb and 6.8% for $H_\varnothing$ =0.005wb when the drive is operated at rated speed and nominal flux.



(a) **(b)**

Fig.5 Stator current harmonics for flux controller bandwidth at 50% load ,(a) $H_\varnothing$ =0.005 wb (b) $H_\varnothing$ =0.05 wb

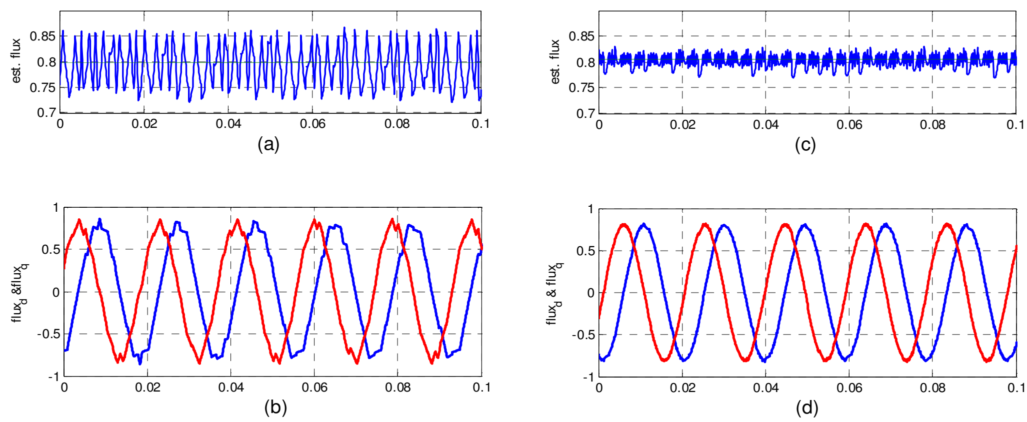


Fig.6 Exprimental results of steady state flux response comparison with different flux hysteris controller bandwidth ($H_\varnothing$)(a) flux for $H_\varnothing$=0.05 wb (b)quadrature flux componens $H_\varnothing$=0.05 wb (c)flux($H_\varnothing$=0.005) wb (d)quadrature flux componens ($H_\varnothing$=0.005 wb)

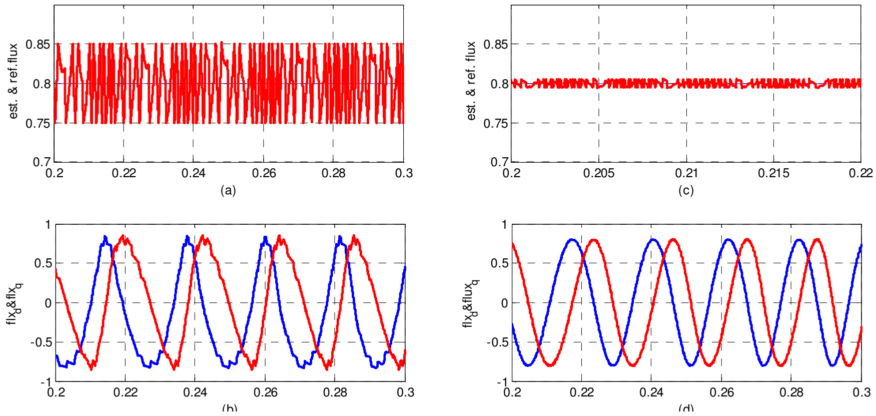


Fig.7 simulation results of steady state response comparison with different flux hysterisis controller bandwidth (H$_\varnothing$) (a) flux for H$_\varnothing$=0.05 wb (b)quadrature flux componens (H$_\varnothing$=0.05 wb) (c) flux (H$_\varnothing$=0.005 wb) (d)quadrature flux componens(H$_\varnothing$=0.005 wb)

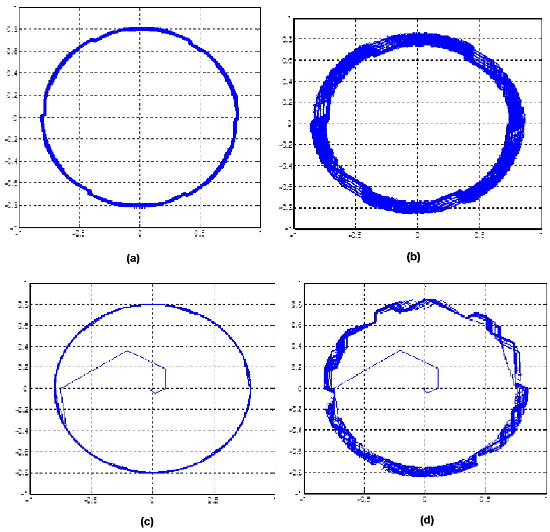


Fig .8 Stator flux locus for flux controller bandwidth,(a) H$_\varnothing$=0.005 wb(experimental)(b) H$_\varnothing$=0.05 wb(experimental) (c) H$_\varnothing$=0.005 wb(simulation)(d) H$_\varnothing$=0.05 wb,(simulation)

To judge the effectiveness of the proposed integration algorithm a comparison between the proposed integration algorithm and a pure integrator is carried in terms of flux ripples and Total Harmonic Distortion (THD) of the stator current. The flux ripples can be mathematically expressed by Root Mean Square Flux Error (RMSFE) given by (13).

$$\text{RMSFE} \quad = \frac{1}{N}\sqrt{\sum_{k=1}^{N}\left(\lambda_s{}^{ref} - \lambda_s(k)\right)^2} \tag{13}$$

Where $\lambda_s(k)$ and $\lambda_s{}^{ref}$ are the estimated stator Flux and reference flux at Kth and (K-1)th sampling instant and N is the number of data samples. The steady state flux ripples were studied for 100% and 30% loading of the machine at 100% rated speed. To judge the effectiveness of the flux estimation methods the test drive was operated with three different reference flux 0.6wb, 0.8wb and 1wb respectively. Furthermore to judge the low speed performance of the flux estimation algorithm the experimental DTC drive was operated at 20% of the rated speed. The RMSFE and THD for different loadings and ref. flux are summarized in Table 1.

Table 1. RMSFE comparison for different flux estimation algorithms.

INTEGRATION ALGORITHM	RMSFE (in percentage of ref Flux) at 80% rated speed						RMSFE at 20% speed	
	100% load			30% load			100% load	
	Refrence stator Flux			Refrence stator Flux			Refrence stator Flux	
	1 wb	0.8 wb	0.6wb	1wb	0.8wb	0.6wb	1 wb	0.8 wb
Mod. Low pass	1.02	1.24	1.77	1.03	1.2	1.62	.83	.9
Pure Integrator	2.07	2.46	3.43	2.06	2.41	3.4	1.52	1.62

Table 2 THD of stator current at different loadings.

INTEGRATION ALGORITHM	TOTAL HARMONIC DISTORTION (In percentage)					
	100% load			30% load		
	Refrence stator Flux			Refrence stator Flux		
	1 wb	0.8 wb	0.6wb	1wb	0.8wb	0.6wb
Mod. Low pass	8.3	5.8	3.3	8.9	9.5	7.3
Pure Integrator	13.8	12.4	8.2	14.5	14.7	12.2

V. CONCLUSION

This paper presents an investigation on flux estimation and its control in a DTC drive .The two voltage model based flux estimation integration algorithm are compared experimentally on a test drive. The performance of the Drive in terms of flux ripples and stator current harmonics is carried out at different loadings. The low pass filter with feedback compensation flux estimation method prove to be superior in terms of flux ripples and input current harmonics when the drive is operated at rated as well as low speeds. An improved flux response during low speed operation with a circular flux trajectory has also been achieved by the proposed technique. Furthermore the influence of flux hysteresis comparator bandwidth on the performance of the drive is investigated.It has been verified that a reduction in flux hysteresis controller band by 10% results in decrement in flux ripples, stator current harmonics and improvement in stator flus trajectory.

ACKNOWLEDGEMENTS

This work was funded and supported by the All India Council of Technical Education, research promotion scheme (AICTE-RPS).

REFERENCES

[1] I.Takahashi and T.Noguchi, "A new quick-response and high efficiency control strategy of Induction Motor", IEEE Transactions on Industrial application, vol. 22, no 5, pp. 820-827, 1986.
[2]M. Depenbrok, "Direct self-control (DSC) of inverter-fed induction machine," IEEE Trans. Power Electron. vol. 3, no. 4, pp. 420–429, Oct. 1988.
[3] G. S. Buja and M. P. Kazmierkowski, "Direct Torque control of a PWM inverter-fed AC motors-A Survey," IEEE Trans. Ind. Electron., vol. IE-51, no. 4, pp. 744–757, Aug. 2004.
[4] C.L. Toh, N.R. N. Idris, A.H.M. Yatim, Constant and High SwitchingFrequency Torque Controller for DTC Drives, IEEE PowerElectronics Letters, vol. 3, n. 2, June 2005, pp. 76-80.
[5] N.R. Nik, C.L. Toh, M.E. Elbuluk, A New Torque and FluxController for Direct Torque Control of Induction Machines, IEEETransactions on Industry Applications, vol. 42, n. 6, December 2006,pp. 1358-1366.
[6] M. Shin, D.S. Hyun, S.B. Cho, and S.Y. Choe, "An improved stator Flux estimation for speed Sensorless stator Flux orientation control of induction motors", IEEE Trans. Power Electron.,vol. 15, pp.312 -318, 2000.
[7] E. D. Mitronikas, A. N. Safacas, "An Improved Sensorless Vector-Control Method for an Induction Motor," IEEE Trans. Ind. Electron., Vol. 52, No. 6, Dec. 2005.
[8] J. Holtz, "Sensor less position control of induction motors—An emerging technology," IEEE Trans. Ind. Electron., vol. 45, pp.840–852, Dec. 1998.

[9] J. Holtz, "Drift and Parameter Compensated Flux Estimator for Persistent Zero-Stator-Frequency Operation of Sensorless-Controlled Induction Motors," IEEE Trans. Ind. Electron., vol. 39, no. 4, pp. 1052–1060, Aug. 2003.
[10] K. D. Hurst, T. G. Habetler, G. Griva, and F. Profumo, "Zero-speed tacholess IM Torque control: Simply a matter of stator voltage integration", IEEE Trans. Ind. Application, vol. 34, pp.790 -795, 1998.
[11] B. K. Bose and N. R. Patel, "A programmable cascaded low-pass filter-based Flux synthesis for a stator Flux-oriented vector-controlled induction motor drive", IEEE Trans. Ind. Electron., vol. 44,pp.140-143,1997.
[12] J. Holtz and J. Quan, "Sensorless vector control of induction motors at very low speed using a Nonlinear inverter model and parameter identification", Conf. Rec. IEEE-IAS Annu. Meeting, vol. 4, pp.2614-2621,2001.
[13] J. Hu and B.Wu, "New integration algorithms for estimating motor Flux over a wide speed range," IEEE Trans. Power Electron., vol. 13, pp.969–977, Sept. 1998.
[14] M. Hinkkanen, J Luomi," Modified integrator for voltage model Flux estimation of induction motors," IEEE Trans. Ind. Electronics, Vol. 50, No. 4,Aug. 2003.
[15] Bertoluzzo, M.; Buja, G.; Menis, R, "A Direct Torque Control Scheme for Induction Motor Drives using the Current Model Flux Estimation," Conf. Rec. IEEE Int. symposium, pp. 185 - 190, Nov. 2006.

AUTHORS BIOGRAPHIES

Shailendra Jain (SM'12) received his B.E.(Elect.), M.E.(Power Elex) and Ph.D. degree in 1990, 1994 and 2003 respectively, and PDF from UWO London, ON, Canada in 2007. He is working as Professor at the Department of Electrical Engineering, NIT, Bhopal, India. Dr Jain is the recipient of "Career Award for Young Teachers" given byAICTE New Delhi, India for the year 2003-2004. His research interests include power electronics and electric drives, power quality improvement, active power filters, high-power factor converters, Multilevel Inverters and fuel cell based distributed generation.

Sanjeet Dwivedi received his M.E. degree (with Gold Medal) from the University of Roorkee, Roorkee, India in 1999 and Ph.D. degree in 2006 from IIT Delhi. He is currently working as R&D Engineer, Control Engineering R&D Design Centre Danfoss Power Electronics, Denmark. His research interests are in area of, digital control of Permanent Magnet Brushless Motors, sensor reduction techniques in ac drives and power quality improvement aspects of ac drives.

Bhoopendra Singh received his B.E. (Elect.) and M.E.(HEE) in 1995, and 2005 respectively from National institute of technology Bhopal. He is presently pursuing his Ph.D. Degree from National Institute of Technology, Bhopal. He is currently an asst. Professor in Electrical Engineering at R.G.T.U. State technical University, Bhopal. His research interests include power electronics and electric drives, power quality improvement, high-power factor converters.