Performance Comparison of PWM Inverter Fed IM Drive & BLDC Drive for Vehicular Applications

S.S.Bharatkar, Raju Yanamshetti
Research Scholars, Electrical Engg. Deptt.
Jadavpur University,
Kolkata-32, India
bharatkar_sachin@rediffmail.com

D.Chatterjee, A.K.Ganguli
Electrical Engg. Deptt
Jadavpur University
Kolkata –32, India
dchatterjee@ee.jdvu.ac.in

Abstract— **Two main types of motor can be used for vehicular application-BLDC and the Induction Motors. This paper compares the performance of a BLDC motor driver system using PWM with that of an induction motor drive also fed from a PWM Inverter. The induction motor is operated under efficiency optimization mode where as the BLDC motors are having inherent high efficiency property. The simulation and experimental results are presented to verify the stability of the driver system. Computer simulation results obtained, confirm that the proposed induction motor control approach also can be applied for electric vehicle when they are operated under efficiency optimization mode.**

Keywords- ***Brushless DC (BLDC) motor, induction motor, PWM, electric Vehicles (EVs), digital signal processors (DSP), speed controller.***

I. INTRODUCTION

Electric vehicles (EVs), because of its zero emission characteristics and different other advantages, are finding increasing applications day by day. Nowadays, the air pollution and economical issues are the major driving forces in developing electric vehicles (EVs). In recent years EVs are the only alternatives for a clean, efficient and environmental friendly urban transportation system. The only difficulty of the electric driven vehicles is that, for a large capacity drives, the battery requirement increases drastically. Therefore, the main application is for the lower capacity drives. As the input power is electrical, the motor required shall be utilizing the electrical input and driven by a suitable controller. That usual motor taken for this purpose is the BLDC motor because of the high torque/weight ratio, higher efficiencies, greater speed capabilities, better thermal efficiencies and low maintenance. Several works are executed to judge the performance of an electric vehicle run from the BLDC motors [1]. The BLDC motors though produce a good performance at higher speeds, can result in to a torque pulsation especially at lower speeds. Also the commutation torque ripple may become prominent if the switching of the devices are not taken care properly [2]. Also at higher sizes, the motor becomes costlier than other machines. The permanent magnet properties change after considerable usage. The other motor, that can be used for this purpose is the cage type induction motor as it is also very simple, robust & rugged construction wise. Also low cost, minimum maintenance, high performance, sufficient starting torque and good ability of acceleration. Squirrel cage induction motor is a good candidate for EVs. The difficulty with the induction motor is its poor efficiency at light loads. This can be overcome by operating the motor at optimized efficiency at all the loads. Different techniques are available for this purpose [3-4]. With the adopted techniques, the induction machine performance can be comparable to that of a BLDC machine and hence can be used as a drive motor for the electric Vehicles (EVs).

In BLDC motor torque ripple due to delayed phase current commutation exists at some intervals. Since, torque smoothness is an essential requirement for EV applications, a wide variety of techniques have been proposed by many researchers during the past two decades to minimize the torque ripple [5-10]. Lot of research has been carried out and various dynamic search techniques for efficiency optimization for variable speed induction motor have been proposed [11-20].

In this current paper a comparison is made between two choices namely, BLDC & caged induction motor. As the induction motors are inherently having less efficiency than the BLDC motors, they are normally not used for the battery powered electric vehicles because of obvious reasons. But, the induction motors, when operated under maximized efficiency operation by adjusting the field fluxes under light loading conditions, their efficiency can be comparable to that of an induction motor. Suitable experiments are executed and the results are presented to compare the performance of the two systems to validate the proposed concept.

II. MODELING OF BLDC MOTOR

The equivalent circuit of three-phase, 4-pole BLDC motor fed from a PWM inverter is modeled and shown in Fig. 1. The three phase current waveforms with ideal trapezoidal back EMF voltages of a BLDC motor is shown in Fig. 2.

The BLDC machine is operated under 120^0 conduction mode where the system efficiency can be optimum. For the current analysis, it is assumed that the motor is unsaturated, armature reaction is negligible, stator winding is symmetrical, the resistances and inductances of the motor windings are constant and motor exhibits no cogging torque.

978-1-4244-5441-9/09/$26.00 ©2009 IEEE

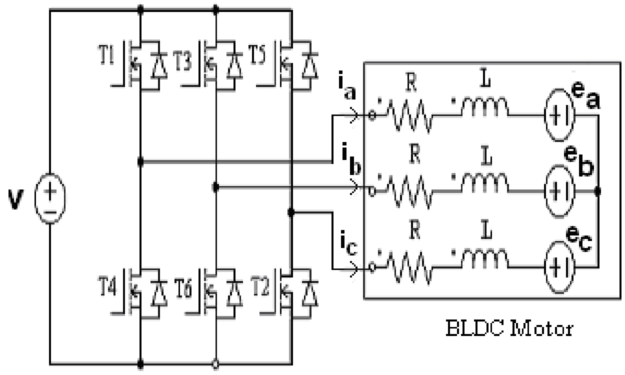

Fig. 1. PWM inverter and equivalent circuit of BLDC motor.

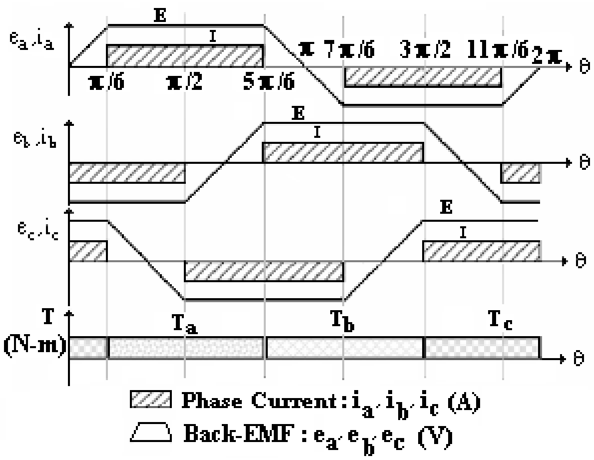

Fig.2. Signal Waveforms of a BLDC motor

The voltage equation matrix for the BLDC motor [21] can be represented by,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{pmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{pmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where R is per phase resistance, L=*l*-M with *l* is the self and M is the mutual inductance for the individual coils, i_a, i_b, i_c are phase currents and e_a, e_b, e_c are back EMFs and v_a, v_b, v_c are phase voltages for the three phases respectively. The generated electromagnetic torque of the BLDC motor can be expressed as,

$$T = \frac{\left(e_a i_a + e_b i_b + e_c i_c\right)}{\omega} \quad (2)$$

Where ω is the angular speed (mechanical) in rad/sec.

Considering $e_a = e_b = e_c = E$ and $v_a = v_b = v_c = V$ the above equation (1) can be modified as,

$$\begin{bmatrix} V \\ V \\ V \end{bmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{pmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{pmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} E \\ E \\ E \end{bmatrix} \quad (3)$$

And the torque equation of the BLDC motor can be expressed as,

$$T = \frac{E\left(i_a + i_b + i_c\right)}{\omega} \quad (4)$$

The Brushless DC motor works on a principle like that of the brush DC machine, hence the name. One can think of it as an inside out DC motor in which the field windings are replaced with permanent magnets and moved from the frame to the shaft. The armature still consists of multiple windings and is moved from the shaft to the frame. In effect the "fields" now rotate and the "armature" stays still. Because of the obvious mechanical similarity to the AC motor, however, the parts are referred to as Stator and Rotor. The power section of the controller is nearly identical to the Vector Inverter and uses a PWM method of current control but the similarity stops there. The current is not controlled sinusoidally, but trapezoidly. Current is also only conducted in two of the three motor wires at a time instead of being conducted in all three of the wires at a time vectorially. Brushless DC is very simple compared to a Vector Drive.

III. MODELING OF INDUCTION MOTOR

In this section modeling of the induction motor with stator fixed reference frame is investigated [22]. The stator d-q axis flux linkage equations in synchronous reference are given by:

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (5)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (6)$$

Where L_s and L_m are the stator and mutual inductance for the motor respectively.

The rotor flux orientation principle gives $\psi_{qr} = 0$ and neglecting the leakage inductance parameters in the rotor circuit, the d-axis rotor current in synchronous reference frame i_{dr} becomes zero. With these assumptions made for simplification, the above flux linkage equations (5) and (6) gets modified to:

$$\psi_{ds} = L_s i_{ds} \quad (7)$$

$$i_{qs} = -i_{qr} \quad (8)$$

Based on the above assumptions a simplified equivalent circuit with the equivalent core loss resistance connected in series is formed and shown in Fig. 3.

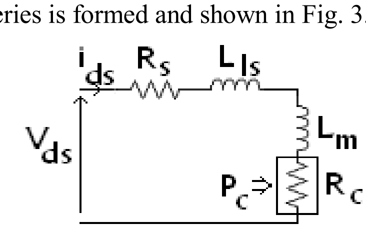

Fig. 3. (a) d-axis equivalent circuit

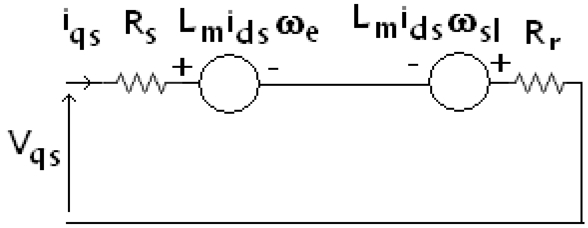

Fig. 3. (b) q-axis equivalent circuit

The developed torque equation of the motor can be expressed as

$$T_e = \frac{3}{2}\frac{P}{2} L_m i_{ds} i_{qs} \quad (9)$$

Where P is the number of poles.

The output power for the motor is given by

$$P_0 = \omega_r T_e \quad (10)$$

Where ω_r is the mechanical speed of the rotor in rad/sec.

The machine efficiency can be expressed as,

$$\eta = \frac{P_0}{P_0 + Losses} \quad (11)$$

Where the losses consist of stator copper loss, rotor copper loss, friction, windage and stray losses. The friction, windage and stray losses are about 15-20 % of the total losses approximately and hence are neglected for simplicity of the loss model of the machine. Therefore, the machine losses will consist of mainly copper losses and core losses.

Induction motors are essentially constant speed motors, if connected to constant voltage and frequency source. The operation speed for induction motor is directly related to the synchronous speed. If load torque increases, the drop in speed will be very small, which is convenient for constant speed applications.

Currently, the main speed control techniques for three-phase induction motors are vector control, which employs digital signal processors, and PWM [23]. By far, the open-loop PWM is the easiest technique to implement, if motor speed does not need to be very accurate, as is the case on EVs, where the driver controls the speed through the accelerator pedal.

IV. EXPERIMENTAL RESULTS

Experiments were performed with a brushless dc motor available in the laboratory with the specifications as given in Table-1. The power circuit and the control block diagram is shown in Fig. 4. Output pulses from DSP TMS320F2407 are fed to driver circuit prior to driving the MOSFET. A torque transducer Model No TRS605 of FUTEK make mounted on the shaft was used to measure the torque. Also a Tektronics make Digital Storage Oscilloscope of 200MHz, Model No TDS 2022B was used for storing the waveforms of the torque and currents etc. The dc bus voltage of the inverter was controlled through MOSFET in buck mode. The inverter circuitry includes 6 N-channel power MOSFETs and their gate drives (IR2130) manufactured by International Rectifier Inc.. The MOSFETs used are 2SK727 with 900V, 6A rating. To verify the results obtained through simulation, the reference of 1500 rpm was provided to the motor both 120^0 mode of conduction. The plot of current for 1500 rpm reference with 120^0 conduction mode are given in Fig. 5, which confirms the result obtained through simulation. The BLDC motor specifications are as given in Table I.

PWM duty cycle control technique enable greater efficiency and versatility of the Brushless DC motor to provide flexible control and novel cyclic operation, as well as better protection schemes for the motor and control circuits. The high efficiency, higher power densities and reliability make BLDC motors an ideal choice for battery-operated motor applications because the combination of power electronics and innovative control techniques provide a high performance, efficient, compact and low cost solution.

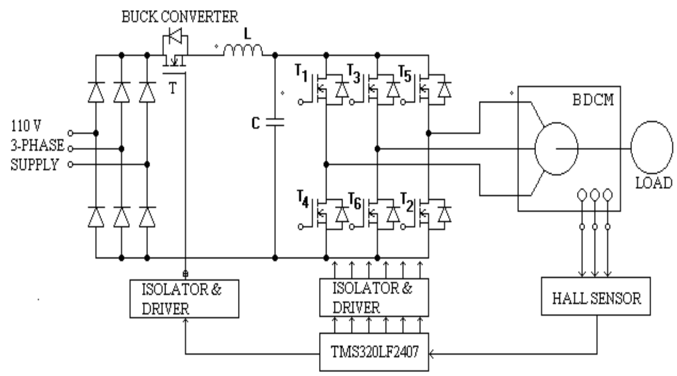

Fig.4. Power circuit and control block diagram with TMS320LF2407 for BLDC motor

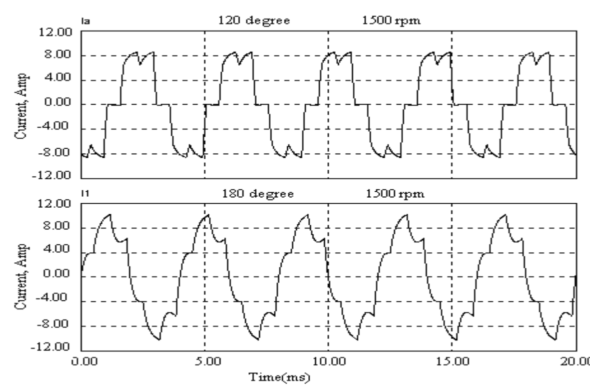

Fig.5. Current Vs. time for speed reference of 1500 rpm

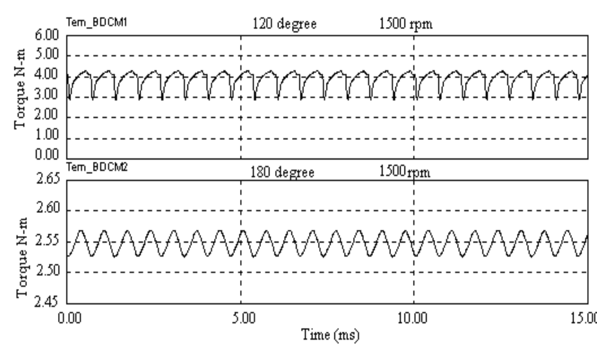

Fig.6. Torque Vs. time for speed reference of 1500 rpm

The algorithm was simulated in the MATLAB/Simulink7.5 environment and then experiments were performed with TMS320F2407A DSP. The specification of the induction motor used both for simulation as well as for experiment is shown in Table-II. The control block diagram for the experiment is shown in Fig.7. Fig. 8 shows the plot of motor efficiency Vs. load of the machine as a percentage of full load with the motor running at 1500 rpm. The simulation and the experimental results show a close agreement for the motor efficiency, which shows also the suitability of the proposed algorithm.

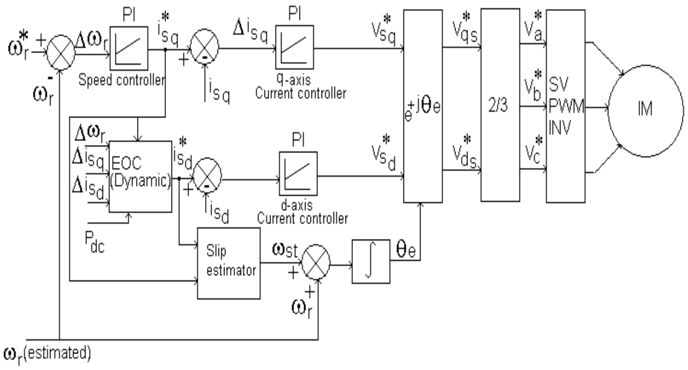

Fig. 7. Block diagram of the control scheme

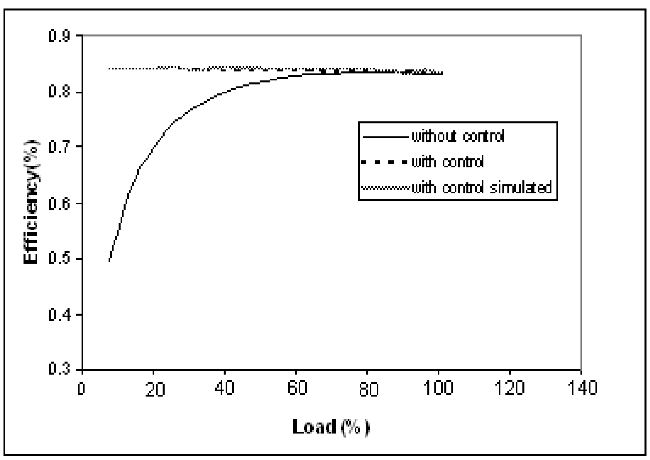

Fig. 8. Plot of motor efficiency vs. load (% full load) with speed constant at 1500 rpm

In Fig. 9, the plot of BLDC motor efficiency under 120^0 conduction mode Vs. load as a percentage of full load at rated speed is shown which appears to marginally higher at lower loads but nearly equal to induction motor at full load.

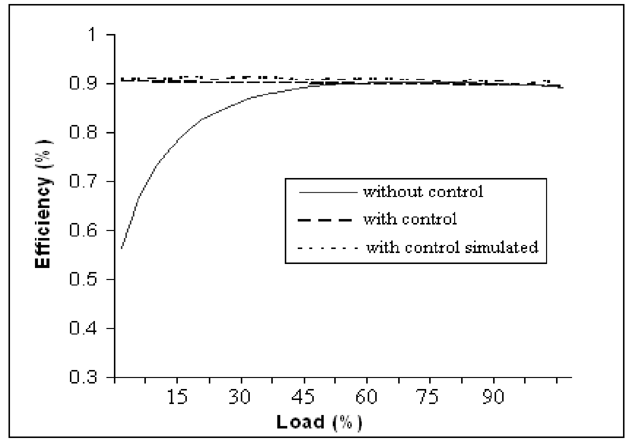

Fig. 9. Plot of BLDC motor efficiency vs. load (% full load) with speed constant at 1500 rpm.

Comparisons of efficiency, torque, currents

Actual data was taken in a test to determine the comparison of a Brushless DC type drive and Induction motor drive for the purpose of determining efficiency, speed & torque. The results show Brushless DC efficiency increases over induction motor type.

In the low power range and in applications requiring variable speed control, adopting BLDC motor can lead to efficiency improvements of up to 10% to 15% when compared with AC induction motors, and allow the possibility of 90% operating efficiency.

At the same time, BLDC motors are more energy efficient than induction motor. This arises because the motors eliminate the excitation circuit losses and does not suffer from friction due to the brushes. The enhanced efficiency is more apparent in the low-load region of the motors performance curve.

In addition, BLDC motor for the same mechanical work output will always be smaller than an AC induction motor. This arises because the motor inherent construction facilitates better thermal efficiencies, thus the motor body has less heat to dissipate.

TABLE I
BRUSHLESS DC MOTOR SPECIFICATIONS

Motor type	Surface permanent magnet type brushless DC motor
Rated Power	400 W
Rated Voltage	48 V DC
Rated Speed	1500 rpm
No. of Poles	4
Winding	3-phase star connection
Resistance	2.5 Ω
Inductance	11.2 mH

TABLE II
INDUCTION MOTOR SPECIFICATIONS

Motor type	Inverter-driven induction motor
Rated Power	0.5 HP
Rated Voltage	110 V
Rated Speed	1440 rpm
No. of Poles	4
Winding	3-phase star connection
Resistance R_s	10 Ω
Inductance L_m	1.15 H

V CONCLUSION

In this paper, comparison of performances of BLDC machine and induction motor operated in efficiency optimization mode for an electric vehicle drive is presented. The BLDC motor driver system is using a PWM controller and the induction motor drive also fed from a PWM Inverter providing vector controlled base efficiency optimization technique. Computer simulation results obtained confirm that both the BLDC motor as well as the induction motor is well suited for electric vehicular applications. The induction motor control requires a little complicated controller compared to that of BLDC drive. But the induction motors are more rugged and less costly than BLDC motor of equivalent rating.

REFERENCES

[1] S. E. Lucena, M.A. Marcelono and F.J. Grandinetti, "Low-Cost PWM Controller for an Electric Mini-Bja Type Vehicle," J. of the Braz. Soc. Of Mech Sci & Engg., vol. 29, no. 1, pp. 21-25, Jan-Mar. 2007.

[2] Carlson, R., Lajoie-Mazenc, M., and Fagundes, J.C.D.S.: 'Analysis of torque ripple due to phase commutation in brushless DC machines,' IEEE Trans. Ind. Appl., 1992, 28, (3), pp. 632-638.

[3] C. Chakraborty and Y. Hori, "Fast Efficiency Optimization Techniques for the Indirect Vector-Controlled Induction Motor Drives," IEEE Trans. Ind. Applicat, vol. 39, no. 4, pp1070-1076, July/August 2003.

[4] R.Yanamshetti, S.S.Bharatkar, D.Chatterjee and A.K.Ganguli, "A Dynamic Search Technique For Efficiency Optimization For Variable Speed Induction Machine," in Proc. IEEE ICIEA'09, Xian, China, 2009, pp 1038-1042.

[5] Fernando Rodriguez and Ali Emadi, "A Novel Digital Control Technique for Brushless DC Motor Drives," IEEE Trans. Ind. Electron., vol. 54, no. 3, pp. 2365-2373, Oct. 2007.

[6] P. Pillay and R. Krishnan, "Application Characteristics of Permanent Magnet Synchronous and Brushless DC Motors for Servo Drives," IEEE Trans. Ind. Appl., vol. 27, no. 5, pp. 986–996, Sep./Oct. 1991.

[7] Y. Liu, Z. Q. Zhu, and D. Howe, "Direct Torque Control of Brushless DC Drives with Reduced Torque Ripple," IEEE Trans. Ind. Appl., vol. 41, no. 2,pp. 599–608, Mar./Apr. 2005.

[8] D. K. Kim, K. W. Lee, and B.-I. Kwon, "Commutation torque ripple reduction in a position sensorless brushless DC motor drive," IEEE Trans.Power Electron., vol. 21, no. 6, pp. 1762–1768, Nov. 2006.

[9] C. W. Lu, "Torque Controller for Brushless DC Motors," IEEE Trans. Ind. Electron., vol. 46, no. 2, pp. 471–473, Apr. 1999.

[10] P. Pillay and R. Krishnan, "Modeling of Permanent Magnet Motor Drives," IEEE Trans. Ind. Electron., vol. 35, no. 4, pp. 537–541, Nov. 1988.

[11] D. S. Kirschen, D. W. Novotny, and T. A. Lipo, "Optimal efficiency control of an induction motor drive," *IEEE Trans. Energy Conversion*, vol. EC-2, pp. 70–76, Mar. 1987.

[12] F. Abrahamsen, F. Blaabjerg, J. K. Pedersen, and P. B. Thogersen, "Efficiency optimized control of medium-size induction motor drives," in *Conf. Rec. IEEE-IAS Annu. Meeting*, Rome, Italy, 2000, pp. 1489–1496.

[13] F. Abrahamsen, J. K. Pedersen, and F. Blaabjerg, "State-of-art of optimal efficiency control of low cost induction motor drives," in *Proc.Power Electronics and Motion Control Conf. (PEMC'96)*, vol. 2, Budapest, Hungary, 1996, pp. 163–170.

[14] J. M. Moreno-Eguilaz and J. Peracaula, "Efficiency optimization for induction motor drives: Past, present and future," in *Proc. Electrimacs'99*, Lisbon, Portugal, 1999, pp. I.187–I.191.

[15] H. R. Andersen and J. K. Pedersen, "Low cost energy optimized control strategy for a variable speed three-phase induction motor," in *Proc. IEEE PESC'96*, Baveno, Italy, 1996, pp. 920–924.

[16] S. K. Sul and M. H. Park, "A novel technique for optimal efficiency control of a current source inverter fed induction motor," *IEEE Trans.Power Electron.*, vol. 3, pp. 192–199, Mar. 1988.

[17] D. S. Kirschen, D. W. Novotny, and T. A. Lipo, "On line efficiency optimization of a variable frequency induction-motor drive," *IEEE Trans. Ind. Applicat.*, vol. IA-21, pp. 610–616, July/Aug. 1985.

[18] M. Ta-Cao and Y. Hori, "Convergence improvement of efficiency-optimization control of induction motor drives," in *Proc. IEEE-IAS Annu. Meeting*, Rome, Italy, 2000, CD-ROM, Paper 38-04.

[19] R. D. Lorenz and S. M. Yang, "Efficiency optimized flux trajectories for closed-cycle operation of field-orientation induction machine drives," *IEEE Trans. Ind. Applicat.*, vol. 28, pp. 574–580, May/June 1992.

[20] S.N.Vukosavic,and E.Levi,"Robust DSP-Based Efficiency Optimization of a Variable Speed Induction Motor Drive," *IEEE Trans. Ind. Applicat*, vol. 50, no. 3, pp 560-570, June 2003.

[21] Krishnan, R.: 'Electric Motor Drives: Modeling, Analysis, and Control'(Prentice Hall, India, 2006)

[22] Bimal K.Bose, Modern Power Electronics and AC Drivers. Prentice Hall, 2002.

[23] Rashid, M. H., 1993, "Power Electronics – Circuits, Devices, and Applications". Prentice Hall, Upper Saddle River 2nd ed..