A New Inverter Control Scheme for Induction Motor Drives Requiring Wide Speed Range

Mohamed Osama, *Student Member, IEEE,* and Thomas A. Lipo, *Fellow, IEEE*

***Abstract*—A new control scheme to extend the speed range of a four-pole induction machine is investigated. A three-phase stator winding is used with each of two coil groups per phase being independent resulting in a six-coupled circuit, six-terminal stator winding. Two inverters supply the machine with the required regulated currents to obtain the effect of either four-pole or two-pole windings. Four-pole operation is proposed from zero speed until the end of its constant power region. Employing contactorless pole changing to obtain two-pole operation extends the constant power region resulting in a doubling of the speed range for approximately the same inverter/machine rating.**

I. Introduction

With the passing of zero emission vehicle legislation, electric vehicles are emerging as an important market for induction motor drives. A rather special requirement of electric vehicle drives is the desirability of operating the drive continuously within a constant horsepower over a very wide 4 or 5 to 1 speed range corresponding to that of steady driving or "cruising." Hence, the issue of good efficiency during field weakened operation becomes one of paramount importance for electric vehicles. Fig. 1 shows a typical family of torque speed curves for variable-frequency operation of an induction machine assuming that the inverter voltage becomes a constant amplitude above one per unit (p.u.) speed and that a four-to-one field weakening range is required. It is clear from Fig. 1 that, since the torque varies as the square of the voltage, to reach a torque of 0.25 p.u. at four times rated speed the machine must be capable of 4 p.u. torque at rated speed. Since machines of normal design have only a 2–2.5 p.u. breakdown torque, such a machine must be oversized by roughly a factor of two simply to enable it to reach four p.u. speed in the field weakening range at rated power. Thus, it becomes apparent that machines designed for traction-type applications become bulky as the constant horsepower speed range increases. The intersection of the breakdown torque curve with torque at constant power curve can be extended by using an inverter with a larger voltage rating and increasing the voltage linearly with speed in the constant power region [1]. In this case, a four-to-one field weakening range for a 2 p.u. overload torque capability would require a maximum voltage of $\sqrt{2}$ times the rated motor voltage (which the motor insulation has to be able to withstand). The overload torque capability and hence the speed range, can also be increased by redesigning the machine slots to have a lower leakage inductance. The most practical method is decreasing the height-width ratio of the rotor slots and making their shape "tip-down" triangular instead of the more conventional deep bar "tip-up" triangular shape [2]–[4]. The main disadvantage of lowering the motor leakage inductance is an increase in the motor harmonic current components and thus an increase in the torque ripple and copper losses.

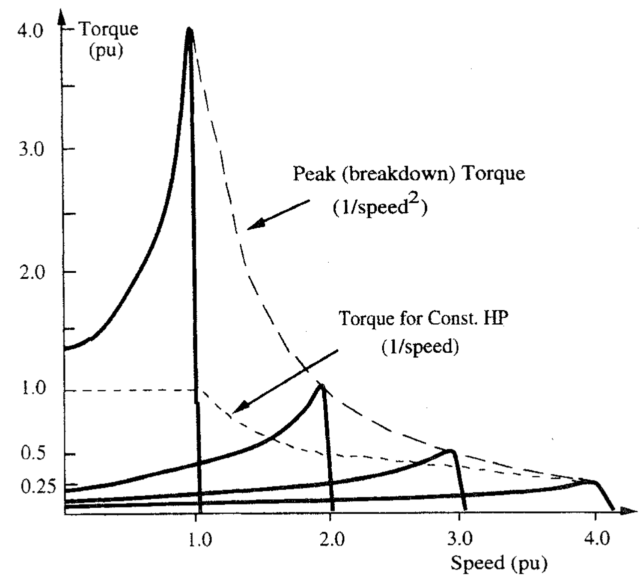


Fig. 1. Induction machine torque-speed curves during constant horsepower operation.

In addition to increasing the overload torque capability, a wider speed range has previously been accomplished by various pole changing and winding reconnection techniques involving contactor switching. The machine can be wound with two stator windings having a different pole number. When one winding is in use, the other is open circuited and vice versa. Another scheme is the pole change winding, where a single winding is reconnected to obtain a two-to-one pole ratio. In addition to reversing certain coil groups, the reconnection might include changing the coil groups from series to parallel and the connections among the phases from Y to Δ or vice versa depending on the desired torque-speed characteristics [5]. Another previously suggested technique is pole amplitude modulation where pole numbers differing by ratios other than

Paper IPCSD 95–88, approved by the Industrial Drives Committee of the IEEE Industry Applications Society for presentation at the 1995 Industry Applications Society Annual Meeting, Lake Buena Vista, FL, October 8–12. Manuscript released for publication January 9, 1996.

The authors are with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706-1691 USA.

Publisher Item Identifier S 0093-9994(96)03247-1.

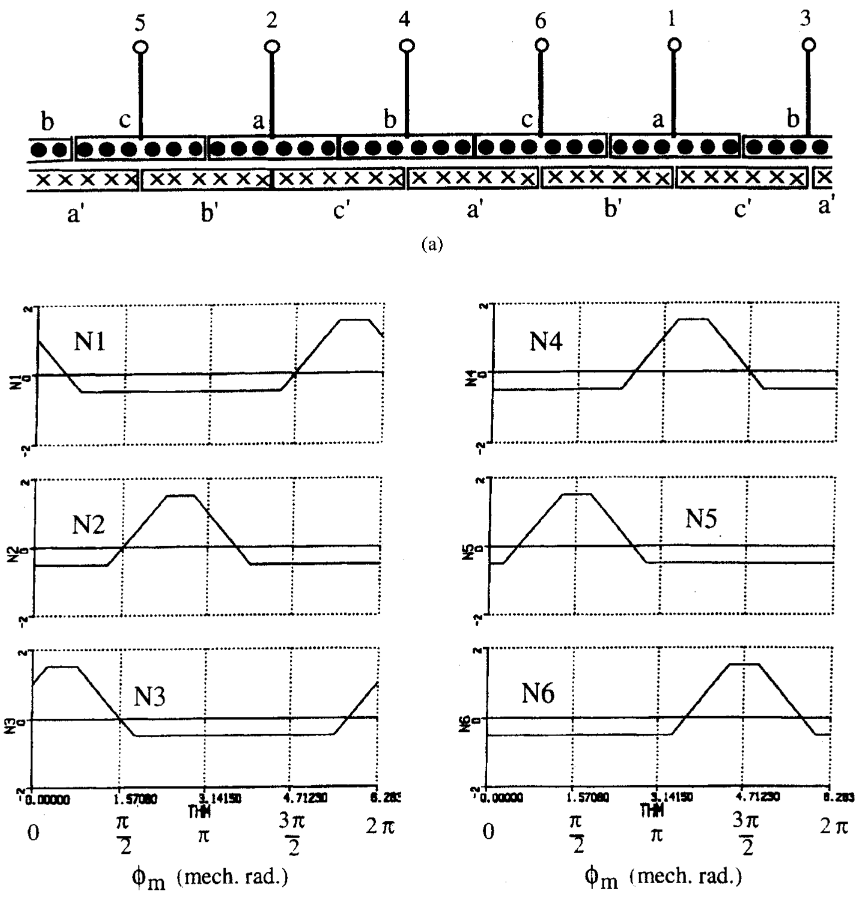


Fig. 2. (a) Winding distribution for 4-pole machine with 120° phase belt. (b) Normalized coil groups winding functions.

two are obtained by switching unsymmetrically distributed windings [6]. In this case, the poor air-gap magnetomotive force (MMF) distribution makes this technique impractical except when efficiency is of no concern. The speed range of an induction motor drive can also be extended by winding tap changing with contactors [7]. For lower speed range all the winding turns are used while for operation at high speeds the tapped turns only are used.

This paper proposes employing a new contactorless pole changing technique to extend the field weakening range of four pole induction machines. This method uses appropriate current regulation of the solid-state frequency converter to accomplish the pole changing function resulting in an efficient and reliable means of achieving a wide speed range.

II. Proposed Induction Machine Drive

The 36-slot stator winding shown in Fig. 2(a) is used to illustrate the operating principle of the proposed pole changing technique. The winding distribution is a full pitch double layer 120° phase belt having two coil groups per phase. Currents in each of the six stator coil groups are independent and thus their corresponding MMF's can be analyzed separately (1)–(6). Defining the winding function as the MMF spatial distribution for one ampere of current [8], the normalized winding function $N_i(\phi_m)$ of each of the six coil groups can be plotted as shown in Fig. 2(b). To obtain a balanced four-pole winding set, the three-phase winding functions are defined as

$$N_{a4} = N_1 + N_2 \quad (1a)$$

$$N_{b4} = N_3 + N_4 \quad (1b)$$

$$N_{c4} = N_5 + N_6 \quad (1c)$$

as illustrated in Fig. 3. Fig. 4 shows that a balanced two-pole winding set is obtained by defining the three-phase winding functions as

$$N_{a2} = N_1 - N_2 \quad (2a)$$

$$N_{b2} = N_5 - N_6 \quad (2b)$$

$$N_{c2} = N_4 - N_3. \quad (2c)$$

The basic pole changing concept introduced in this paper is to attain the desired MMF distribution of Figs. 3 and 4 by reversing the necessary coil groups currents instead of reversing their connections (winding functions). As illustrated in Fig. 5, two inverters are required to supply this six-coil three-phase machine, with each inverter supplying 3 coil groups belonging to 3 different phases. Inverter 1 feeds coil groups 1, 4, and 5 while inverter 2 supplies coil groups 2, 3, and 6. Both inverters are current regulated to force

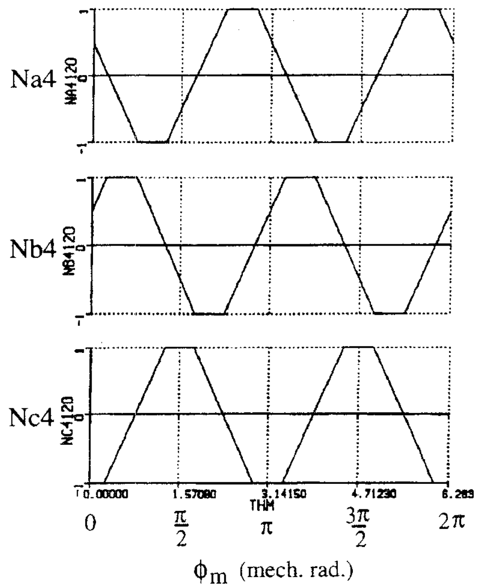


Fig. 3. Normalized phase winding functions for 4-pole connection.

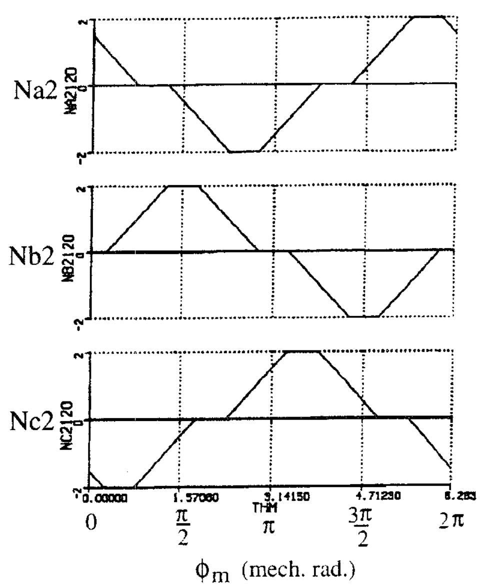


Fig. 4. Normalized phase winding functions for 2-pole connection.

balanced sinusoidal currents of the desired amplitude and phase relationships. The number of poles of the machine is changed by merely reversing the direction (polarity) of the currents supplied from one inverter with respect to the currents from the other, as defined in Table I. The inverters can be supplied with two isolated dc supplies as shown in Fig. 5 or a single dc bus can be used and the neutrals of the two three-phase groups isolated.

III. Induction Machine Parameters and Performance Comparison

Though the same magnetic structure and electrical connections are maintained in both the 4-pole and 2-pole operation

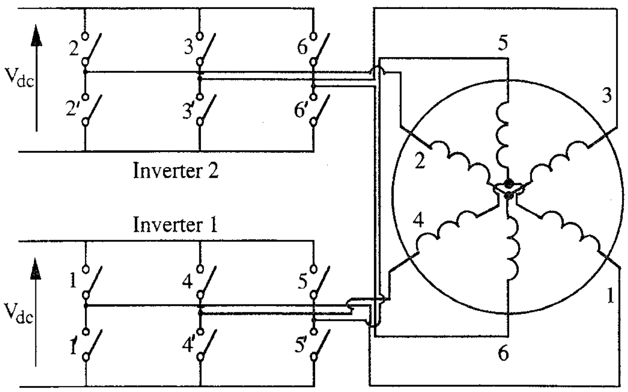


Fig. 5. Proposed drive topology supplying stator winding of six-coil machine.

TABLE I
Coil Groups Current References According to Mode of Operation

	Ref. Current	4 pole mode	2 pole mode
Inverter 1	i_1^*	i_a^*	i_a^*
	i_4^*	i_b^*	i_c^*
	i_5^*	i_c^*	i_b^*
Inverter 2	i_2^*	i_a^*	$-i_a^*$
	i_3^*	i_b^*	$-i_c^*$
	i_6^*	i_c^*	$-i_b^*$

modes, the per phase equivalent circuit parameters and hence the motor performance are different. For the same current level, the stator and rotor resistances are independent of mode of operation since the number of turns per phase is the same. Consequently, the copper losses are also expected not to vary with the mode of operation. The rotor resistance would vary only with the slip frequency which is decided by the control strategy (Section IV).

A. Magnetic Circuit

Normally a two-pole motor needs a yoke section twice that of a four-pole motor to allow the same air-gap flux density [9]. Meanwhile, the ratio between the winding factors for two-pole and four-pole connections of 120° phase belt winding is $k_{w2} \approx 0.8k_{w4}$. Thus for the same magnetic structure and air-gap flux density, the yoke flux density and air-gap flux linkage for two-pole operation are 2 times and 1.6 times that of four-pole operation, respectively. As a result, the stator and rotor teeth are expected to have higher saturation in four-pole mode while core saturation is higher in two-pole operation mode.

For the same speed, the supply frequency for two-pole mode is half that of four-pole mode, so for the same air-gap flux density, the core losses would be approximately the same provided that deep saturation is avoided.

Neglecting saturation and comparing the MMF distributions of Figs. 3 and 4, it can be deduced that the phase inductance for two-pole operation is about 2.8 times that of four-pole operation mode. In a balanced three-phase set, the third harmonic MMF and its multiples sum to zero and do not contribute to the resultant air-gap flux, thus the magnetizing inductance ratio is calculated to be 2.67 (for 120° phase belt). The actual magnetizing inductance ratio is dependent on the operating point and hence upon the level and location of saturation.

For a full pitch winding, the stator mutual slot leakage for two-pole operation is zero, resulting in a slight decrease in the total slot leakage. Meanwhile, the end-winding and zig-zag leakage are approximately the same in both modes of operation. Due to the presence of the squirrel cage rotor, the harmonic leakage can be considered as nearly zero in both modes of operation. Thus, for the same current level, the mode of operation has negligible effect on the total per phase leakage inductance.

B. Speed Range

The breakdown torque of an induction machine can be approximated as

$$T_{pk} \approx \frac{3V_s^2}{4(L_{ls}+L_{lr})}\frac{P}{\omega_e^2} \tag{3}$$

where

- V_s rms fundamental stator phase voltage;
- ω_e supply angular frequency (elec. rad/s);
- L_{ls} stator leakage inductance;
- L_{lr} rotor leakage inductance (referred to stator);
- P number of poles.

Fig. 6 shows the torque capability curves for a machine with 2 p.u. overload capability in the case of both four-pole and two-pole mode of operation. It is clear that such a machine is typically capable of 2 p.u. speed for four pole operation. From (3), the breakdown torque for constant torque two pole operation is one half the breakdown torque for four pole operation at rated speed. At the same time with two pole operation, the motor is capable of producing only one-half the air gap flux density as the four pole configuration if the yoke flux density is to remain constant and not result in deep saturation. The air gap flux density must be limited to 0.5 p.u. resulting in the motor torque never exceeding about one half the rated value of the four pole case. Hence, if constant power operation for the machine in the two pole mode starts at 3600 r/min, the breakdown torque and torque for constant horsepower would intersect at 4 p.u. speed (7200 r/min), as shown in Fig. 6(b). Since this machine has a four-pole construction, the rotor diameter is somewhat larger than for a conventional design two-pole machine and thus has a lower mechanical limit on the rotor angular speed for the same maximum attainable peripheral speed. Therefore the upper bound on speed may ultimately be of mechanical not electrical origin.

IV. Control Strategy

Consider again the case where a four to one field weakening range is required with a maximum speed of 7200 r/min, i.e., a base speed of 1800 r/min. The proposed machine with a 2/4 pole capability designed with only a conventional 2.0 p.u. breakdown torque can be used. Below base speed (60 Hz), the machine is excited with four poles and electromagnetic torque up to and including rated speed is obtained by conventional control (field oriented control, for example) so that the voltage increases linearly with supply frequency to keep the air gap and yoke flux density approximately constant (at their rated value). Both the current and the slip frequency are almost constant in this region of operation when the torque is held constant. This method of control is possible until the ac voltage reaches the maximum value available from the inverter. Above the base speed the motor is operated at constant voltage and power, almost constant current and the slip frequency is increased to maintain the maximum value of output power approximately constant. The gap and yoke flux density decrease inversely with speed (field weakening). Such an almost constant power region continues until the motor reaches breakdown at its slip limit, which occurs approximately at 3600 r/min for a motor with a 2 p.u. breakdown torque.

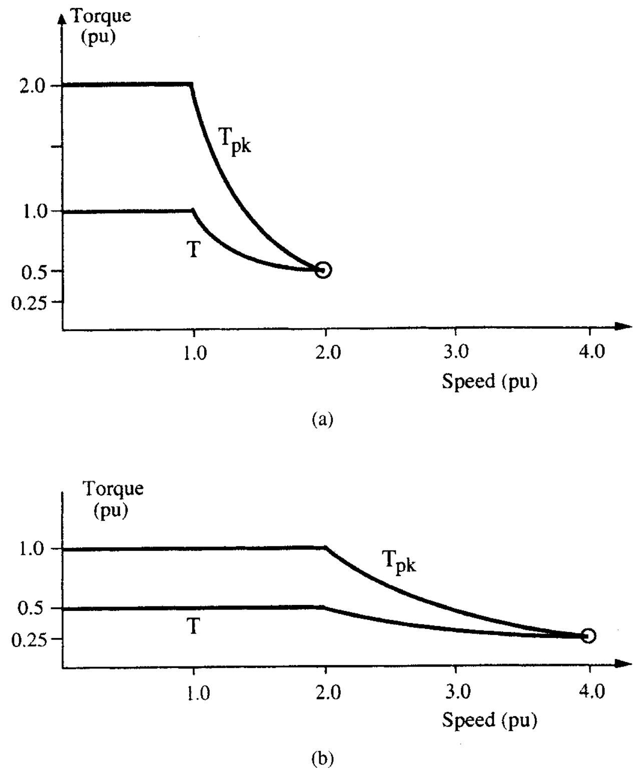


Fig. 6. Torque capability curves for (a) 4-pole operation and (b) 2-pole operation.

Thus, if "electronic" pole changing is performed from four pole operation to two pole operation at 3600 r/min, while preserving the same air gap flux density and current levels, constant power is maintained. The slip frequency drops back to its rated value and starts to increase again with speed. The resultant motor characteristics will be as illustrated in Fig. 7.

Overall, the proposed control strategy provides the following advantages:

1) Constant power mode operation can now be extended to four p.u. speed, even though the breakdown torque of the machine is two per unit. Taking into account the

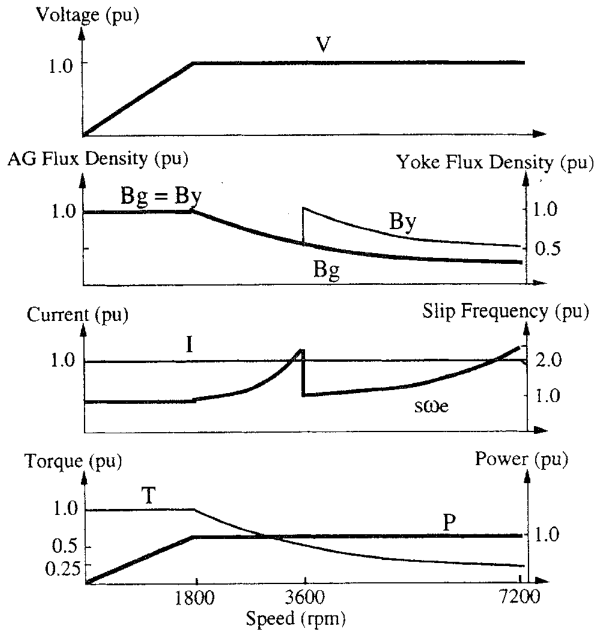


Fig. 7. Proposed control strategy with pole changing at 3600 r/min.

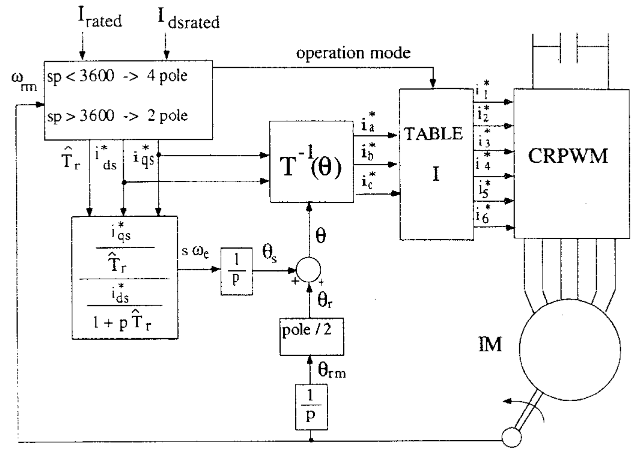


Fig. 8. Proposed induction machine drive with indirect field oriented control used in simulation model.

better winding factor of conventionally designed 60° phase belt machines, the size and weight of this new machine is expected to be roughly 60% the size and weight of a machine of conventional design used for the same purpose.

2) Operation at rated torque is attainable until 1800 r/min. A comparable two pole motor would require twice the yoke thickness if used for this task.
3) The machine stator and rotor yokes are now fully utilized by having the flux density in the yoke jump back to its rated value to initiate a second field weakening region beyond 3600 r/min.
4) The motor is operated at a high efficiency over a wide speed range since four-pole machines are, in general, more efficient than two-pole machines at lower speed and less efficient at higher speeds [9], [10].

V. Results

A. Simulation Results

Fig. 8 shows a block diagram for the simulation model of the proposed induction machine drive with indirect field oriented control. The induction machine is simulated in the actual physical (rather than the transformed $d-q$) variables using the multiple coupled circuit approach [11]. To demonstrate the torque and power capability of the induction machine drive, the current magnitude is fixed at its rated value (I_{rated}). The rated flux level (d-axis current $I_{ds\text{rated}}$) together with the speed feedback are used to determine the d and q axes reference currents (I_{ds}^* and I_{qs}^*) and the estimate for the rotor time constant ($\hat{T}_r$) needed for the field oriented controller.

Fig. 9 shows the simulation results for the acceleration of a 100-hp machine with "electronic" pole changing at 3600 r/min.

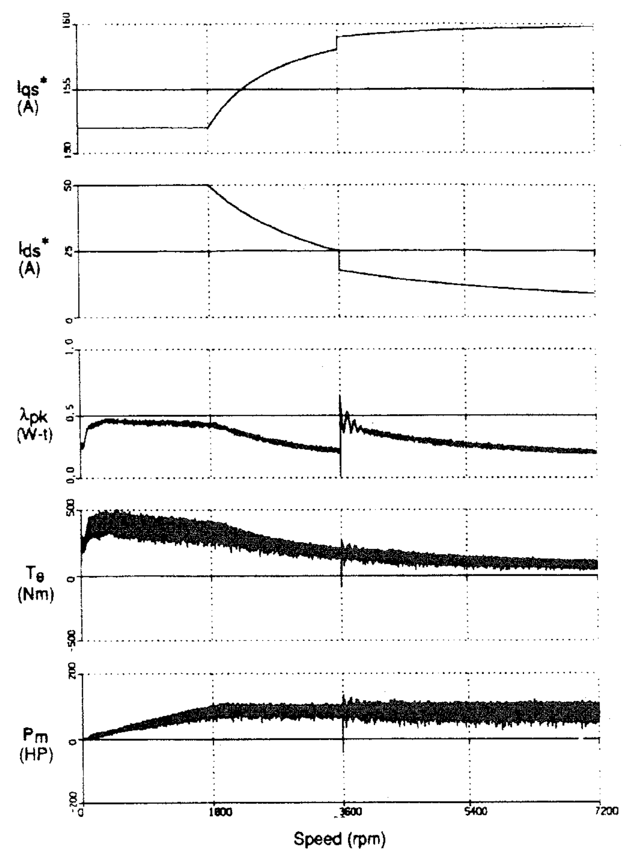


Fig. 9. Simulation results for free acceleration of proposed drive with IFO control. From top: q and d axes current commands; peak flux linkage; torque; power.

During pole switching, the d-axis current reference changes to restore the air-gap flux linkage (yoke flux density) to its rated value to start a new field weakening range as explained earlier. With the exception of the transient during pole changing, the simulation results agree well with the proposed characteristics of Fig. 7.

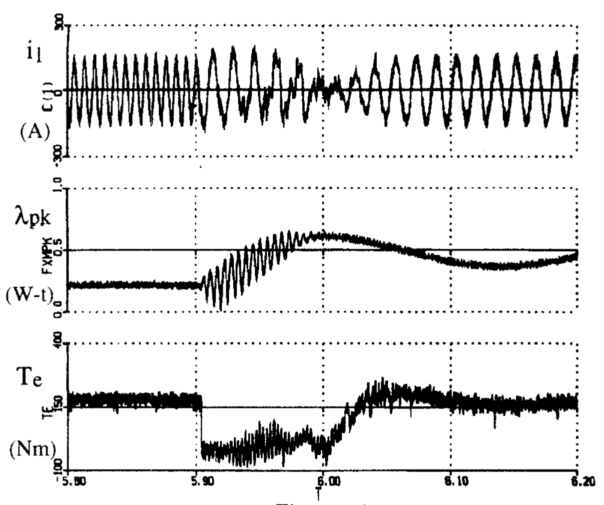


Fig. 10. Simulation results for pole changing transient. Top: Coil group 1 current. Middle: Peak flux linkage. Bottom: Torque.

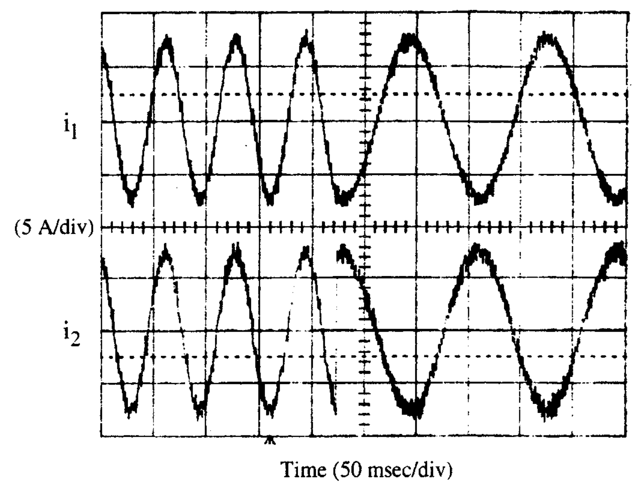


Fig. 11. Experimental results: Coil groups 1 and 2 currents.

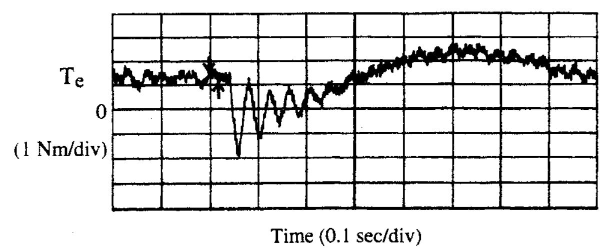


Fig. 12. Experimental results: Torque transient during pole changing.

During pole-switching the air-gap field will consist of two portions: the decaying field of the outgoing pole number being sustained by the rotor currents, and the increasing field of the incoming pole number, being excited by the supply [12]. Fig. 10 illustrates the switching transition with the four-pole rotor variables decay governed by the four-pole mode rotor open circuit time constant ($T_{r4} = 144$ ms) and the two pole rotor variables buildup characterized by the two pole mode rotor open circuit time constant ($T_{r2} = 379$ ms). During the overlap of T_{r4} and T_{r2}, the machine "back EMF," (indicated by the rotor flux linkage components) increases, resulting in a dynamic overmodulation and thus a transient loss of the current regulation as demonstrated in the plots. Both the loss of the stator current regulation and the rotor flux transient contribute to a torque transient. Though the torque drops from 175 N·m to −25 N·m, there is minimal effect on speed due to the motor and load inertia.

B. Experimental Results

The proposed pole changing scheme has been experimentally verified in the laboratory. The hardware circuit consisted of a 4-kW 36-slot 120° phase belt machine supplied from two MOSFET bridge inverters. To date the experimental control implementation has involved only current regulation (without field orientation). Fig. 11 shows coil groups 1 and 2 currents during a pole changing transition using, in this case, a hysteresis-type current regulator. Unlike Fig. 10, current regulation is not lost because of sufficient dc bus voltage at this operating point. Fig. 12 shows the corresponding torque transient.

VI. Conclusion

A control scheme to extend the speed range of four-pole induction machines has been proposed and verified in this paper. It has been shown that continuous wide speed range can be attained with the following advantages over previous techniques. Neither the machine nor the inverter is oversized. There is no change required in the magnetic structure of the machine and no special windings are added. There is also no need for a switching device for winding change such as a contactor and no need for winding tapping. On the other hand, the main limitations of such a drive are the need to access the individual machine coil groups, the additional control complexity and doubling of the number of inverter switches.

Appendix
Parameters of the Machine Used in the Simulation Study

460-V, 60-Hz, 100-hp, 4-pole induction motor with the following parameters:

$$L_{ls} = 0.4 \text{ mh} \qquad L_{lr} = 0.4 \text{ mh}$$
$$R_s = 0.031\ \Omega \qquad R_r = 0.134\ \Omega$$
$$L_m = 18.9 \text{ mh} \qquad J = 4.449 \text{ kg m}^2$$

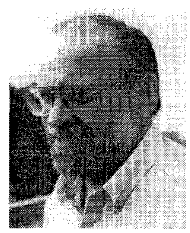
References

[1] A. Boglietti, P. Ferraris, M. Lazzari, and F. Profumo, "A new design criteria for spindle induction motors controlled by field oriented technique," *Electric Mach., Power Syst.*, vol. 21, pp. 171–182, 1993.
[2] Z. Zhao, L. Xu, and A. El-Antably, "Strategies and a computer aided package for design and analysis of induction machines for inverter-

driven variable speed systems," in *Conf. Rec. IEEE-IAS Annu. Meeting*, 1995, pp. 523–529.
[3] H. S. Rajamani and R. A. McMahon, "High frequency, three phase induction motors for wide speed range applications," in *EPE Conf.*, Sevilla, Spain, 1995, pp. 2.871–2.876.
[4] Y. Akiyama and K. Takaku, "A study of the most suitable design of inverter-driven induction motors," in *PCIM*, June 1994, pp. 38–44.
[5] P. L. Alger, *Induction Machines*, 2nd ed. New York: Gordon and Breach, 1970.
[6] G. H. Rawcliffe, R. F. Burbidge, and W. Fong, "Induction-motor speed-changing by pole-amplitude modulation," *Proc. Inst. Elect. Eng.*, vol. 105, no. 8, pp. 411–419, Aug. 1958.
[7] T. Kume, T. Iwakane, T. Sawa, T. Yoshida, and I. Nagai, "A wide constant power range vector-controlled ac motor drive using winding changeover technique," *IEEE Trans. Ind. Applicat.*, vol. 27, no. 5, pp. 934–939, Sept./Oct. 1991.
[8] T. A. Lipo, "Theory and control of synchronous machines," *ECE 511 Notes*, Univ. Wisconsin, Madison, WI, 1991.
[9] J. Oldenkamp and S. Peak, "Selection and design of an inverter driven induction motor for a traction drive system," in *Conf. Rec. IEEE IAS Annu. Meeting*, 1983, pp. 743–748.
[10] F. Liang, D. Novotny, R. Fei, and X. Xu, "Selection of the pole number of induction machines for variable speed applications," in *Conf. Rec. IEEE IAS Annu. Meeting*, 1993, pp. 367–373.
[11] M. Osama and T. A. Lipo, "A new induction machine model for analysis of eccentric rotor magnetic pull," in *Proc. Symp. Power Electronics, Electrical Drives, Advanced Electrical Motors (SPEEDAM)*, vol. 1, pp. 173–177, 1994.
[12] S. Williamson, M. A. Mueller, J. F. Eastham, and L. H. Lim, "Transient unbalanced magnetic pull in change-pole induction motors," in *Int. Conf. Electrical Machines: Design and Applications*, London, 1985, pp. 261–265.

Mohamed Osama (S'95) received the B.S. degree in electrical power engineering from Cairo University, Cairo, Egypt, in 1991 and the M.S. degree in electrical engineering from the University of Wisconsin-Madison in 1994. He is currently working toward the Ph.D. degree at the University of Wisconsin-Madison.

His areas of interest include electrical machines analysis and modeling, and ac machine drives.



Thomas A. Lipo (M'64–SM'71–F'87) is a native of Milwaukee, WI.

From 1969 to 1979 he was an electrical engineer in the Power Electronics Laboratory of Corporate Research and Development of the General Electric Company, Schenectady, NY. He became Professor of Electrical Engineering at Purdue University, West Lafayette, IN, in 1979. In 1981 he joined the University of Wisconsin, Madison, in the same capacity, where he is presently the W. W. Grainger Professor for Power Electronics and Electrical Machines.

Dr. Lipo has received the Outstanding Achievement Award from the IEEE Industry Applications Society, the William E. Newell Award of the IEEE Power Electronics Society, and the 1995 Nicola Tesla IEEE Field Award from the IEEE Power Engineering Society for his work. Over the past 30 years he has served IEEE in numerous capacities including President of the Industrial Applications Society.