Research Report

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

M.O.E. Mohamed, T.A. Lipo

Wisconsin Power Electronics Center
University of Wisconsin-Madison
Madison WI 53706-1691

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Center
2559D Engineering Hall
1415 Johnson Drive
Madison WI 53706-1691

A NEW INVERTER CONTROL SCHEME FOR INDUCTION MOTOR DRIVES REQUIRING WIDE SPEED RANGE

Mohamed Osama Thomas A. Lipo

Department of Electrical and Computer Engineering
University of Wisconsin - Madison
1415 Johnson Drive
Madison, WI 53706-1691 USA
Tel: (608) 262-0287, Fax: (608) 262-1267

Abstract- A new control scheme to extend the speed range of four pole induction machines is investigated. A three phase stator winding is used with each of the two coil groups per phase being independent resulting in a six coil, six terminal machine. 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 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 speed and that a four to one field weakening range is required. It is clear from the figure that since the torque varies as the square of the voltage, to reach a torque of 0.25 per unit at four times rated speed the machine must be capable of 4 per unit torque at rated speed. Since machines of normal design have only a 1.5 to 2.5 per unit breakdown torque, such a machine must be oversized by roughly a factor of two simply to enable it to reach four per unit 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.

In addition to simply over-sizing the machine, a wider speed range has previously been accomplished by various pole changing 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 [1]. Another previously suggested technique is pole amplitude modulation where pole numbers differing by ratios other than two are obtained by switching unsymmetrically distributed windings [2]. In this case, the poor air gap 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[3]. For lower speed range all the winding turns are used while for operation at high speeds the tapped turns only are used.

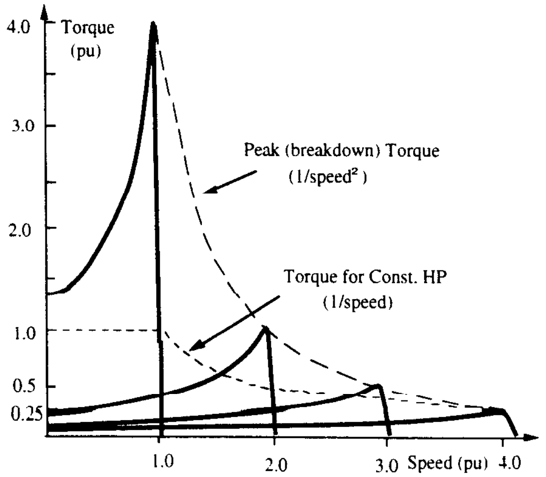

Fig. 1 Induction machine torque-speed curves during constant horsepower operation

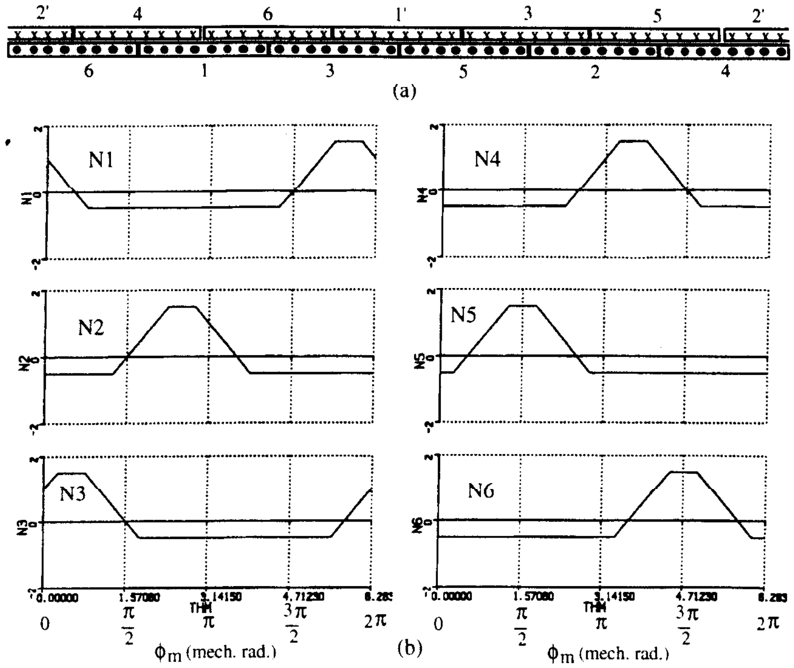

Fig. 2 a) Winding diagram for a 2/4 pole machine with 8 slot phase belts assuming 48 slots and double layer winding, b) Winding functions for the six coil groups.

II. PROPOSED INDUCTION MACHINE DRIVE

This paper proposes employing a new contactorless pole changing technique to extend the field weakening range of four pole induction machines. The 48 slot stator winding shown in Fig. 2a is used to illustrate the operating principle. The winding distribution is a double layer 120^o phase belt having two coil groups per phase. Currents in each of the six stator coil groups are independent and thus their corresponding MMFs can be analyzed separately (1-6). Defining the winding function as the MMF spatial distribution for one ampere of current [4], the normalized winding function $(N_i(\phi_m))$ of each of the six coil groups can be plotted as shown in Fig. 2b. To obtain a balanced 4 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 2 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 Fig. 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 & 5 while inverter 2 supplies coil groups 2, 3 & 6. Both inverters are current regulated to force 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.

TABLE I
COIL GROUPS CURRENT REFERENCES ACCORDING TO MODE OF OPERATION

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

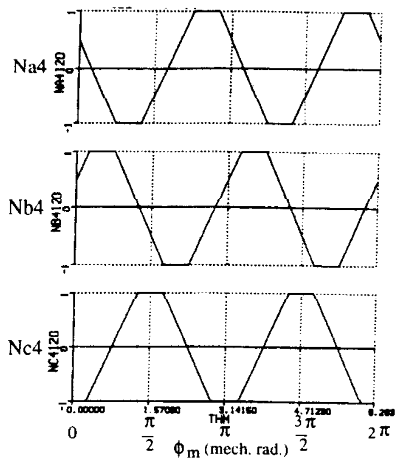

Fig. 3 Normalized winding functions of 2/4 pole machine for 4 pole realization

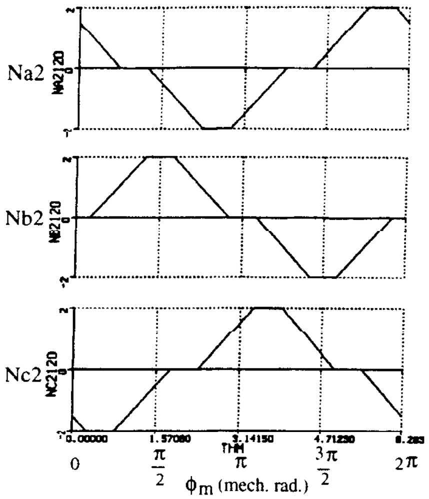

Fig. 4 Normalized winding functions of 2/4 pole machine for 2 pole realization

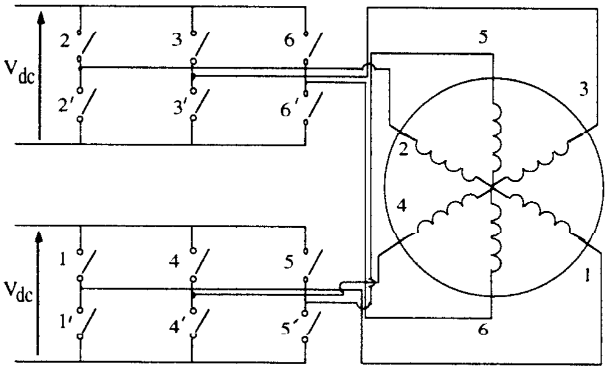

Fig. 5 Proposed drive topology supplying stator winding of six coil machine

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 modes, the per phase equivalent circuit parameters and hence the motor performance are different. The stator and rotor resistances are independent of mode of operation since the same stator winding and rotor cage are used.

A. Magnetic Circuit

Normally a 2 pole motor needs a yoke section twice that of a 4 pole motor to allow the same air gap flux density [5]. Thus for the same magnetic structure and yoke flux density, the air gap flux density for 2 pole operation is half that of four pole operation, while the air gap flux linkage is the same in both modes of operation. As a result, the stator and rotor teeth are expected to have higher saturation in four pole operation while core saturation is higher in 2 pole operation mode.

For the same speed, the supply frequency for 2 pole operation mode is half that of 4 pole operation, so the core losses would be less in the 2 pole mode provided that deep saturation is avoided.

Neglecting saturation and comparing the MMF distributions of Fig. 2 and 3, it can be deduced that the magnetizing inductance for 2 pole operation is about 2.8 times that of 4 pole operation mode. The actual magnetizing inductance ratio is dependent on the operating point and hence the level and location of saturation.

The harmonic leakage inductance (due to MMF space harmonics) is higher for the 2 pole operation mode but the main leakage flux components (slot, end-winding and zigzag leakage) are independent of the operating mode. Thus the mode of operation has negligible effect on the machine leakage inductance.

B. Speed Range

The breakdown torque of an induction machine can be approximated as:

$$T_{pk} = \frac{3}{2\omega_{sm}} \frac{V_s^2}{\omega_{se}\left(L_{ls} + L_{lr}\right)} \tag{3}$$

where :

V_s: rms fundamental stator phase voltage
ω_{sm}: rotor synchronous angular velocity (mech. rad./sec.)
ω_{se}: supply angular frequency (elec. rad./sec.)
L_{ls}: stator leakage inductance
L_{lr}: rotor leakage inductance (referred to stator)

From (3), the breakdown torque for constant torque 2 pole operation is clearly one half the "rated" breakdown torque for 4 pole operation. Thus if constant power operation for the machine in 2 pole mode starts at 3600 rpm, the breakdown torque at 7200 rpm would be 1/8 the machine rated breakdown torque. Hence, a machine with 2 pu torque capability would have the breakdown torque and torque for constant horsepower intersect at 2 pu speed for 4 pole operation and 4 pu speed (7200 rpm) for 2 pole mode. Since this machine has a 4 pole construction, the rotor diameter is somewhat larger than for a conventional design 2 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 rpm, i.e. a base speed of 1800 rpm. The proposed machine with a 2/4 pole capability designed with only a conventional 2.0 per unit breakdown torque can be used. Below base speed (60 Hz), the machine is excited with 4 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 rpm for a motor with 2 p.u. breakdown torque.

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. Thus if "electronic" pole changing is performed from 4 pole operation to 2 pole operation at 3600 rpm, the resultant motor characteristics will be as illustrated in Fig. 6.

Overall, the proposed control strategy provides the following advantages:

1) Constant power mode operation can now be extended to four per unit speed, even though the breakdown torque of the machine is two per unit. Taking into account the better winding factor of conventional design 60^o 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 rpm. 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 rpm.

4)The magnetizing inductance for two pole operation is roughly 2.8 times its value in the case of four pole operation. Hence, if pole changing occurs at 3600 rpm, the magnetizing current for 2 pole operation will be only 5 /7 that of 4 pole operation to maintain the same air gap flux density at 3600 rpm resulting in a potential efficiency improvement as the transition is made at 3600 rpm.

5) 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 [5,6].

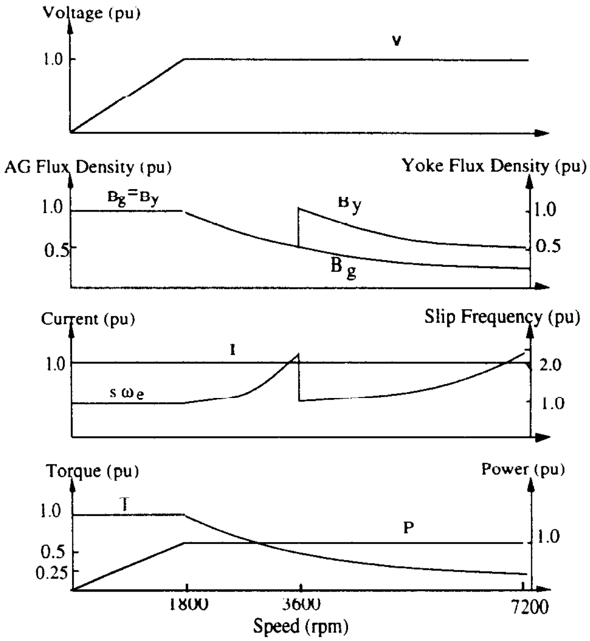

Fig. 6 Variation from top to bottom a) Voltage, b) Air gap flux density, c) Current and slip frequency and d) Torque and power as a function of speed for 4:1 Field weakening range using a machine with electronic two/four pole changing capability.

V. RESULTS

A. Simulation Results

Fig. 7 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 [7]. To illustrate 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 $I_{dsrated}$) 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. 8 shows the simulation results for the free acceleration of a 100 HP machine with "electronic" pole changing at 3600 rpm. 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. 6.

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 [8]. Fig. 9 illustrates the switching transient, which lasts for about one rotor time constant. Though the torque drops from 200 Nm to -100 Nm, there is minimal effect on speed due to the motor 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. Fig. 10 shows coil group 2 reference and actual currents during a pole changing transition using, in this case, a hysteresis type current regulator.

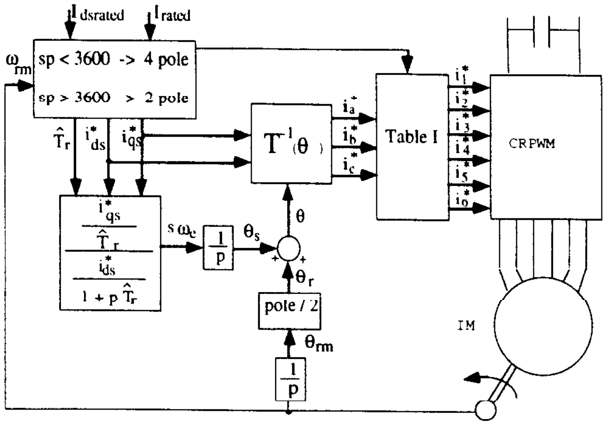

Fig. 7 Proposed induction machine drive with indirect field oriented control used in simulation model

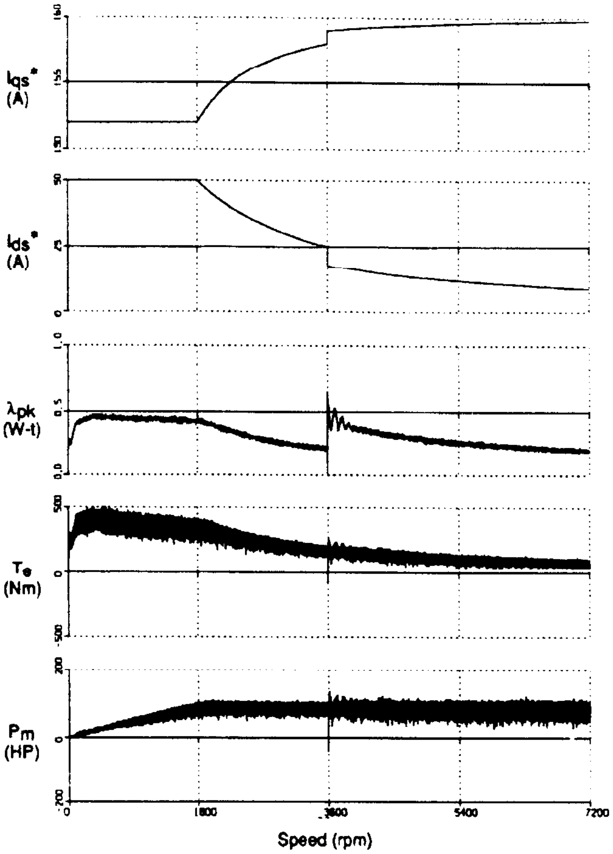

Fig. 8 Simulation results for free acceleration of proposed drive with IFO control. a) & b) q and d axes current commands c) Peak flux linkage, d) Torque, e) Power

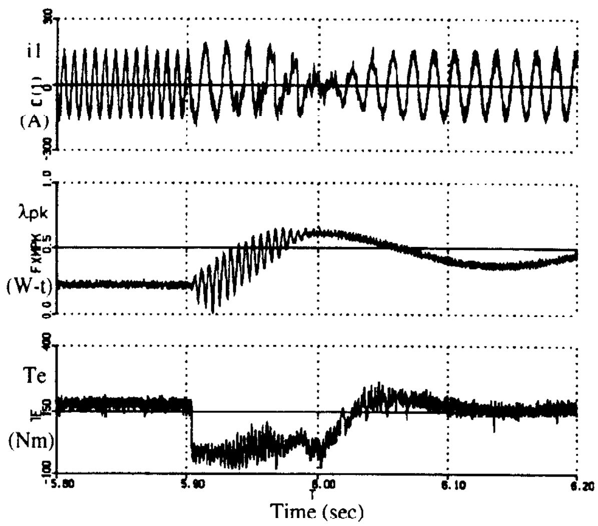

Fig. 9 Simulation results for pole changing transient. a) Coil group 1 current b) Peak flux linkage c) Torque.

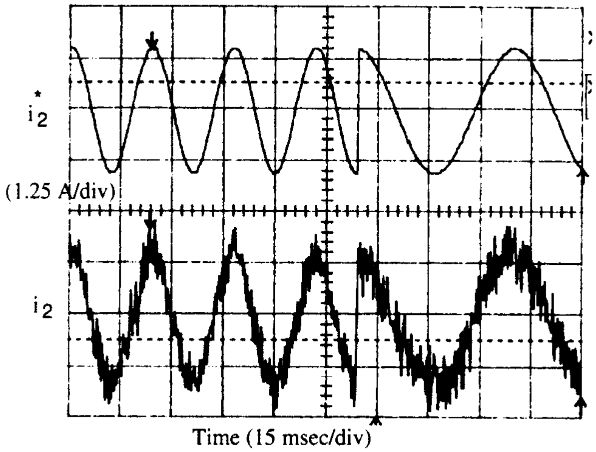

Fig. 10 Experimental results: Coil group 2 reference and actual currents.

VI. CONCLUSIONS

A control scheme to extend the speed range of four pole induction machines has been proposed and verified. Continuous wide speed range can be attained with the following advantages over previous techniques. The machine is not over-sized and no special windings are added. There is no need for a switching device for winding change such as a contactor and no need for winding tapping. On the other hand there are several limitations introduced by this scheme including the requirement to access six leads of the machine. While the use of two inverters (each having half the rating of a conventional drive inverter) can be considered as a disadvantage, it should be mentioned that several electric vehicle applications already adopt a dual inverter approach for the purpose of improving reliability [9].

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APPENDIX

Parameters of the machine used in the simulation study:

460 volt, 60 Hz, 100 Hp, 4 pole induction motor with parameters:

L_{ls} = 0.4 mh	L_{lr} = 0.4 mh
R_s =0.031 Ω	R_r = 0.134 Ω
L_m = 18.9 mh	J = 4.449 kg m^2