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Optimal Efficiency Control of an Induction Motor Drive

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ABSTRACT

This paper describes a practical method for achieving optimal efficiency over the complete operating range of a variable speed drive. The proposed system adaptively adjusts the flux level in the motor based upon a direct measurement of the power input to the drive. An internal field orientation torque control loop and a speed regulator are employed to maintain the load and speed requirements. Experimental results describing the efficiency optimization and the dynamic behavior of the drive at reduced flux are presented. The influence of the tuning of the field oriented controller on the efficiency of the drive is experimentally investigated.

INTRODUCTION

The increasing cost of electricity has sent many plant engineers searching for ways of reducing energy losses. Since electric motors in general and induction machines in particular consume a large fraction of all electric power, they are a prime target for improvement in efficiency. In 1977, Nola introduced the idea of improving the efficiency of induction motors operating at partial load by reducing the airgap flux level [1]. The purpose of this flux reduction was to maintain a better balance between the load dependent losses (i.e. the stator and rotor losses) and the load independent losses (i.e. the core losses). While in constant speed drives, flux control is achieved by adjusting the stator voltage, in variable speed drives it is achieved through a combination of stator voltage and frequency adjustments. This additional degree of freedom makes it possible to achieve maximum efficiency over the complete range of operation and expands the improvements in efficiency that can be achieved [2]. Moreover, it should be noted that an optimal efficiency controller for a variable speed drive is designed for operation in conjunction with an existing variable voltage, variable frequency converter. The energy savings are thus not reduced or offset by extraneous converter and harmonic losses as is the case for a Nola controller, except when the latter operates in combination with a phaseback controller used for soft-starting the induction motor.

In theory, maximum efficiency can be achieved over the complete torque and speed range by enforcing a precalculated relation between three motor variables. Kirschen et al. have used stator voltage, stator frequency and slip in their theoretical analysis [2] while Löser and Sattler [3] and Kim et al. [4] on the other hand have chosen stator current, slip frequency and speed. An obvious disadvantage of any of these approaches is that the calculation of the optimal control law requires a precise knowledge of the machine parameters including the variation of the core losses with frequency. Further problems result from the complexity of the control law and its dependence on magnetic saturation and rotor temperature [2,3]. Löser and Sattler have proposed an identification scheme [5] which corrects the effects of temperature variations but not the errors introduced by saturation and the uncertainty of the value of the parameters.

The purpose of this paper is to introduce a maximum efficiency control method which does not require knowledge of the machine parameters and which yields a true optimum at any load torque and speed. The proposed method is based upon the adaptive adjustment of the flux level using a field oriented controller and a direct measurement of the power input to the drive system. Experimental results obtained with a laboratory prototype are also presented. In many cases, optimal efficiency control results in operation at flux levels substantially below the rated value. Under these conditions, the dynamic behavior of the drive system is poor and the maximum torque which can be readily developed is greatly reduced. A simple but effective remedy to this problem is experimentally demonstrated.

POTENTIAL ENERGY SAVINGS

Prior to undertaking the design of an optimal efficiency controller, it is necessary to verify that the potential energy savings are sufficient to justify the added expense. A steady state equivalent circuit representing accurately the various sources of losses in an induction machine was developed. This model includes saturation, stray load losses, harmonic losses, skin effect in the rotor bars and the dependence of the core losses on frequency. Based on this model, the combination of stator voltage and frequency which produces the minimum amount of losses for a given value of speed and load torque can be calculated using a numerical search procedure. Figure 1 shows the difference between the power input obtained with conventional constant volts per hertz control and the minimum power input at various load torques and speeds for a specific 7.5 hp motor whose parameters are given in the Appendix. Figure 2 presents the same data in terms of the relative reduction in losses. It can be noted that the most significant energy savings are obtained at light loads and Figure 3 demonstrates that this gain derives

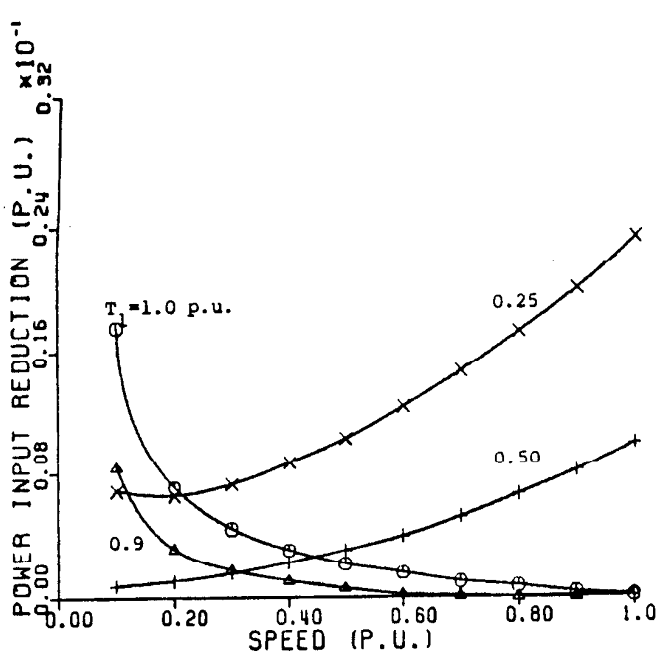

Fig. 1: Calculated reduction in power input for the 7.5 hp test motor (in p.u.).

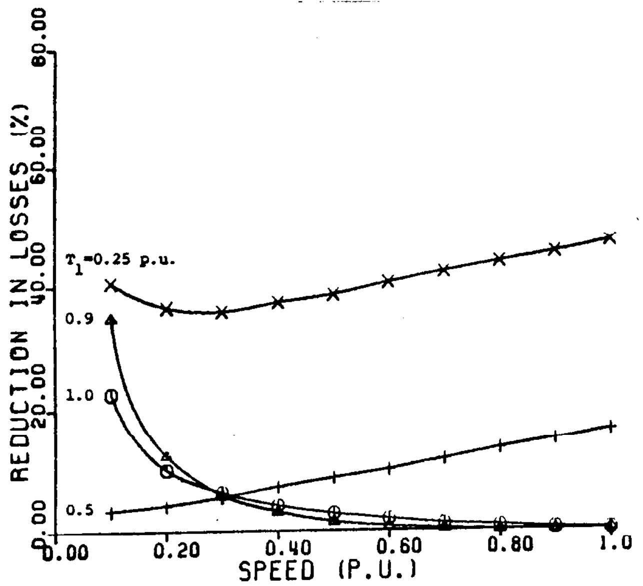

Fig. 2: Calculated relative reduction in losses for the 7.5 hp test motor.

essentially from a decrease in core losses stemming from a cut-back in the machine flux level below the rated value. (The rated flux level is approximately 0.9 p.u. for this particular motor). On the other hand, a small increase in flux beyond the rated level substantially reduces the losses for large loads at low speeds. This improvement is derived from a reduction in stator and rotor ohmic losses. [2,6]

While the theoretical study of Ref. 2 shows that substantial energy savings can be achieved through optimal control of the flux level in the induction machine, the on-line implementation of this principle in a variable speed drive presents many problems. The relation between the input variables (stator voltage and frequency or stator current and rotor frequency) and the output variables (shaft speed and torque) which maximizes efficiency is a complex function of the machine parameters and is heavily influenced by saturation. It would therefore be difficult to program and the ensuing errors would result in sub-optimal efficiency.

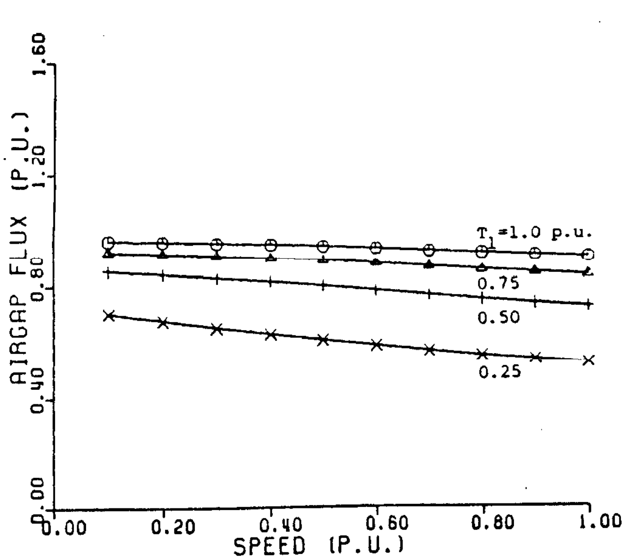

Fig. 3: Calculated optimal airgap flux for the 7.5 hp test motor.

Although an accurate computation of the solid state converter losses is possible [7], it is a long and cumbersome process which depends entirely on the type of converter used. It will be shown in the following section how these losses can be included in the efficiency optimization.

DESIGN OF AN OPTIMAL EFFICIENCY CONTROLLER

In order to avoid the problems associated with a feedforward efficiency optimization, another approach based on adaptive control can be used. For a given load, if the shaft torque or speed is maintained constant, the efficiency of the drive will be maximum when the power measured at the input of the system is minimum. An adaptive controller (Fig. 4) thus can steer the system to its optimum operating point by iteratively adjusting an actuating variable c(t) until it detects a minimum in the measured power input. This method has the following advantages:

- A genuine optimum is obtained for all values of speed and torque.
- This optimum includes the converter losses.
- Knowledge of the parameters of the motor and the inverter is not required.

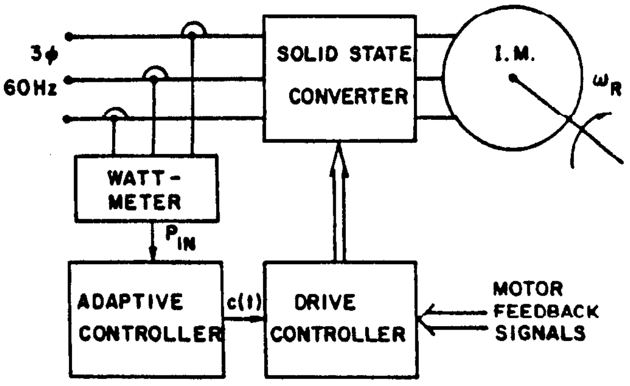

Fig. 4: Block diagram representation of the proposed adaptive optimal efficiency controller.

- Such a control strategy is perfectly robust in the sense that it is totally insensitive to variations in the motor parameters such as an increase in rotor resistance due to a rise in machine temperature.

The presence of an adaptive efficiency optimization loop imposes several important constraints on the drive controller:

- An input variable directly related to the repartition of the motor losses must be available for use in the efficiency optimization loop.
- A torque or speed control loop must maintain the power output of the motor constant during the optimization.
- Ideally, these two loops should be decoupled. Since a total decoupling is probably impossible, it can be approximated by making the response time of the torque or speed loop much shorter than the interval of time separating two iterations of the adaptive controller.
- The drive system must maintain satisfactory dynamic performance even when the motor operates at reduced flux.

The class of controllers using the principle of field orientation meets these constraints. A drive system is said to be field oriented if the stator current is controlled as a vectorial quantity and if, through feedback of the rotor flux position or appropriate choice of the slip frequency, the d-axis of the synchronously rotating reference frame is aligned with the rotor flux [8,9]. Formally, setting

$$\lambda_{qr} = 0 \tag{1}$$

in the machine equations expressed in the synchronously rotating reference frame: (All quantities are in per unit)

$$v_{qs} = r_s\, i_{qs} + p\,\lambda_{qs} + \omega_e\,\lambda_{ds} \tag{2}$$

$$v_{ds} = r_s\, i_{ds} + p\,\lambda_{ds} - \omega_e\,\lambda_{qs} \tag{3}$$

$$0 = r_r\, i_{dr} + p\,\lambda_{qr} + (\omega_e - \omega_r)\,\lambda_{dr} \tag{4}$$

$$0 = r_r\, i_{qr} + p\,\lambda_{dr} - (\omega_e - \omega_r)\,\lambda_{qr} \tag{5}$$

$$\lambda_{qs} = L_s\, i_{qs} + L_m\, i_{qr} \tag{6}$$

$$\lambda_{ds} = L_s\, i_{ds} + L_m\, i_{dr} \tag{7}$$

$$\lambda_{qr} = L_m\, i_{qs} + L_r\, i_{qr} \tag{8}$$

$$\lambda_{dr} = L_m\, i_{ds} + L_r\, i_{dr} \tag{9}$$

$$T_e = \frac{L_m}{L_r}\,(\lambda_{dr}\, i_{qs} - \lambda_{qr}\, i_{ds}) \tag{10}$$

one finds the slip frequency needed to maintain the field orientation of the reference frame:

$$(\omega_e - \omega_r) = \omega_s = \frac{L_m}{L_r}\,\frac{r_r\, i_{qs}}{\lambda_{dr}} \tag{11}$$

Under these conditions, the instantaneous electromagnetic torque is given by:

$$T_e = \frac{L_m}{L_r}\,\lambda_{dr}\, i_{qs} \tag{12}$$

and the rotor flux by

$$(r_r + p\,L_r)\,\lambda_{dr} = r_r\, L_m\, i_{ds} \tag{13}$$

Equations 12 and 13 suggest that the torque and the rotor flux can be controlled by the q and d-axis components of the stator current, repectively. Since current regulated, pulse width modulated (C.R.P.W.M.) inverters and current source inverters (C.S.I.) allow for independent control of both components of stator current, it is possible to adjust the rotor flux until maximum efficiency is reached while regulating the torque or the speed. The decoupling between the two loops is not complete and changes in flux will create disturbances in the torque. Since the coupling is only unilateral, this problem can be readily overcome by making the response time of the torque or speed control loop much faster than the time constant governing the flux variations.

Figure 5 shows a block diagram representation of the laboratory prototype. The field oriented controller used is of the indirect type, i.e. it relies on a measured value of the shaft speed and a value of the slip frequency calculated using (11) to realize field orientation. Two Hall effect sensors mounted in a two wattmeter configuration measure the power input on the source side of the rectifier. This instantaneous measurement is digitally filtered (averaged) by an 8 bit microprocessor system which also handles the adaptive control and the slip frequency calculation. Another 8 bit microprocessor system controls the speed while the remaining functions are implemented using dedicated logic and linear circuits. Additional design information can be found in [6] and [10].

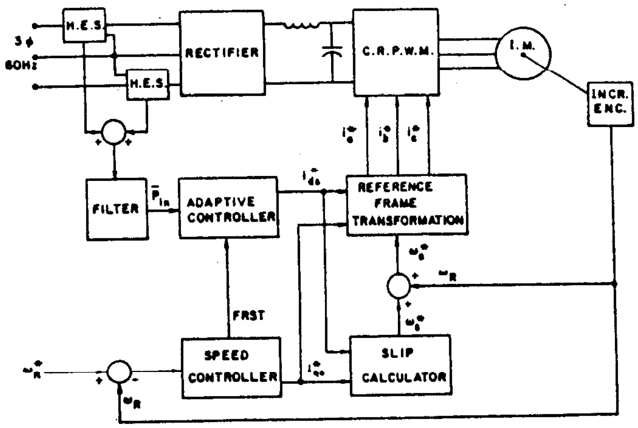

Fig. 5: Block diagram representation of the prototype system. (H.E.S. : Hall-Effect Sensor, FRST: Flux Reset command).

EXPERIMENTAL RESULTS

Figure 6 illustrates a typical efficiency optimization for a light load condition. The 3 hp test motor whose parameters are given in the Appendix rotates at 900 r/min and the load torque is approximately 0.1 p.u.. The flux is initially set at its rated value and is adjusted by the adaptive controller in steps of 3.3% of rated value. After 19 steps and about 30 seconds, the controller decreases the flux beyond the optimal value and detects an increase in power input. The following step in the search is thus taken in the opposite direction. The search procedure cannot stop at this point because the system must be able to detect and react to a load change or a shift in the location of the optimum due to a drift in the machine temperature. The controller thus continues to impose small changes in the rotor flux reference. Figure 7 shows the variation in the torque producing component of the stator current required to maintain the speed constant.

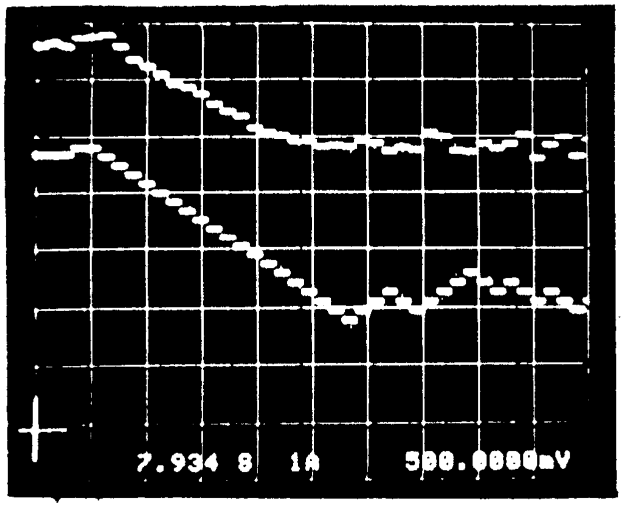

Fig. 6: Efficiency optimization at 900 r/min and 0.1 p.u. torque with the 3 hp test motor. Upper trace: speed. Lower trace: i_{ds}^*.

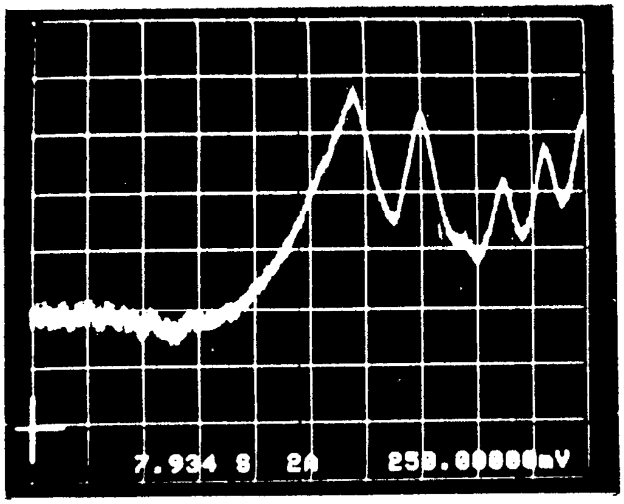

Fig. 7: Efficiency optimization at 900 r/min and 0.1 p.u. torque with the 3 hp test motor. Trace: i_{qs}^* .

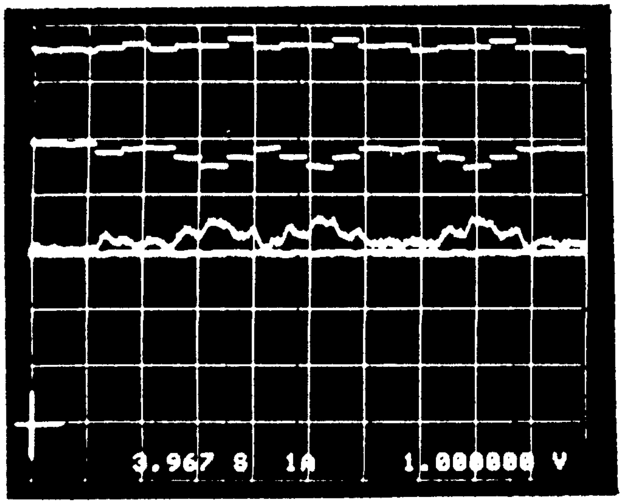

Fig. 8: Efficiency optimization at 600 r/min and 0.8 p.u. torque with the 3 hp test motor. From top to bottom: power input, i_{ds}^*, i_{qs}^*, speed.

Figure 8 illustrates the optimization for a load torque of about 0.8 p.u. Again, the rotor flux is initially at its rated value but remains close to this level as could be predicted from Fig. 3. It can also be seen that the speed is unaffected by the flux variations. The relative reduction in losses achieved experimentally has been plotted on Fig. 9 as a function of the load torque for a speed of 600 r/min and a frequency of approximately 20 Hz. Note that approximately a 50 % reduction in losses is possible at loads below 0.1 p.u.

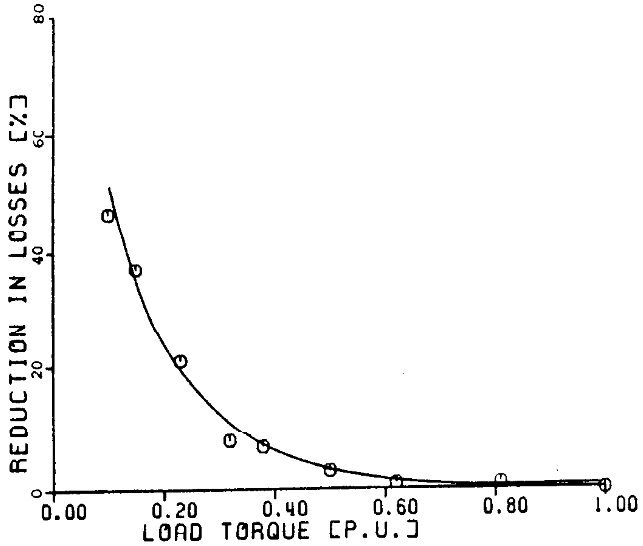

Fig. 9: Measured relative reduction in losses for the 3 hp test motor at 600 r/min.

SYSTEM RESPONSE TO SUDDEN LOAD CHANGES

Unlike conventional field oriented drives, the proposed system operates often at a reduced flux level. The impact of this reduction on the damping of the speed controller and on the maximum torque which can be developed must be investigated and appropriate remedies described. Assuming that the load is governed by:

$$J \frac{d\omega_r}{dt} + B\,\omega_r = T_e - T_l \tag{14}$$

and that the speed regulator is of the proportional plus integral type:

$$i_{qs}^* = K_p[(\omega_r^* - \omega_r) + K_i \int_0^t (\omega_r^* - \omega_r)\, dt] \tag{15}$$

the small signal transfer function relating the speed to its reference in a field oriented drive is:

$$\Delta\Omega_r = \frac{\frac{K_p\,\lambda'_{dro}}{J}(s + K_i)\,\Delta\Omega_r^*}{s^2 + (\frac{B + K_p\,\lambda'_{dro}}{J})\,s + \frac{K_i\,K_p\,\lambda'_{dro}}{J}} \tag{16}$$

where

$$\lambda'_{dro} = \frac{L_m}{L_r}\lambda_{dro} \tag{17}$$

and λ_{dro} is the value of the flux around which the linearization is carried out. From (16) it is clear that the damping of the system decreases with the rotor flux level.

However, due to the simplicity of the dynamics of field oriented drives, this reduction can be compensated by a proportional increase in the proportional gain of the speed controller [11].

Equation (12) shows that the maximum torque which can be readily developed by the drive is not only proportional to the maximum q- axis current which the inverter can supply but also to the rotor flux. To illustrate this problem, the unloaded motor was accelerated between 450 and 900 r/min. With the flux set at rated value (Fig. 10) the speed controller commands maximum i_{qs}^* for 160 ms and the speed rise time is 129 ms. At half of the rated flux (Fig. 11) the speed controller has to command maximum current for 320 ms and the speed rise time is 205 ms, a 60% increase. A simple solution consists in resetting i_{ds}^* at the value corresponding to rated flux whenever the speed controller commands the maximum value of i_{qs}^*. In this case (Fig. 12) maximum i_{qs}^* is needed for only 240 ms and the rise time is reduced to 154 ms. The remaining difference compared to the response at rated flux is caused by the fact that the flux buildup is governed by the rotor time constant. Feedforward compensation could further reduce this difference if the inverter were capable of supplying the required forcing current. The improvement in performance will be even more significant in drives having a low torque to inertia ratio.

INFLUENCE OF MOTOR PARAMETERS DEVIATIONS

The field oriented controller used for these experiments relies on an estimated value of the rotor time constant $T_r = L_r / r_r$. Recently published theoretical results [12] suggest that the motor efficiency is typically maximum for a value of the estimated time constant slightly different from the actual value when the controller is tuned for rated motor flux. An experimental verification of this prediction was carried out using the experimental system. This test is summarized in Fig. 13 where the variation in power input for a given load is plotted as a function of the ratio $T_r^* / \tilde{T}_r$ of the parameter value used for the controller to the best estimate of the rotor time constant. This graph confirms that a major problem associated with the detuning of field oriented controllers is a substantial increase in the motor losses. Values of the ratio $T_r^* / \tilde{T}_r$ smaller than unity result in higher slip frequencies and lower flux. On the other hand, values of $T_r^* / \tilde{T}_r$ greater than unity result in lower slip frequencies and higher flux. Power input could thus be used as an indication of the tuning of the field oriented controller in an adjustment procedure which does not require any torque or speed measurement.

SUMMARY AND CONCLUSIONS

This paper has described a practical method for online optimization of the efficiency of a variable speed induction motor drive. The proposed system makes use of a direct measurement of the power input and an adaptive control strategy. In this manner knowledge of the machine parameters is not required and the problems resulting from the dependence of these parameters on saturation and rotor temperature are avoided. A field oriented drive system was chosen as the vehicle for the implementation of this strategy because it provides a direct access to the flux level in the machine. Moreover,

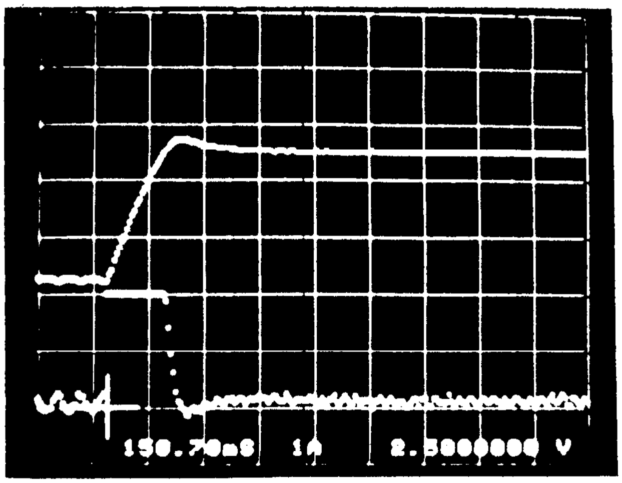

Fig. 10: Response of the speed controller when the motor operates at rated flux. The speed reference is increased from 450 to 900 r/min. Upper trace: speed. Lower trace: i_{qs}^*.

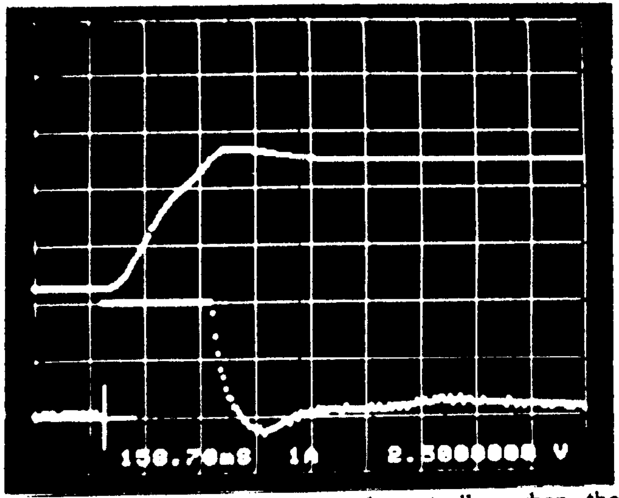

Fig. 11: Response of the speed controller when the motor operates at half of rated flux. The speed reference is increased from 450 to 900 r/min. Upper trace: speed. Lower trace: i_{qs}^*.

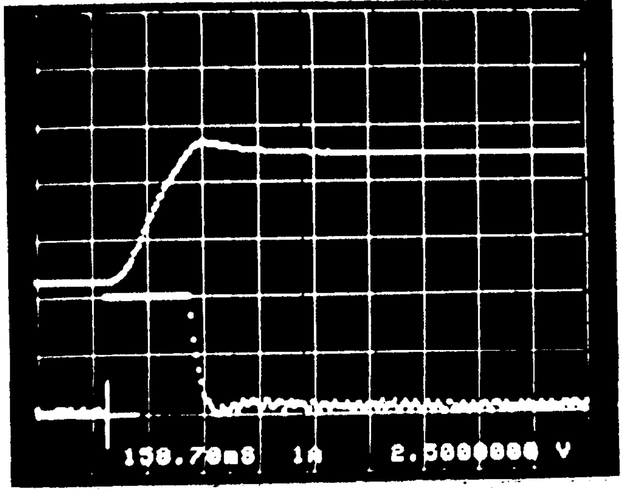

Fig. 12: Response of the speed controller when the motor operates at half of rated flux and i_{ds}^* is reset at its rated value when i_{qs}^* reaches its limit. The speed reference is increased from 450 to 900 r/min. Upper trace: speed. Lower trace: i_{qs}^*.

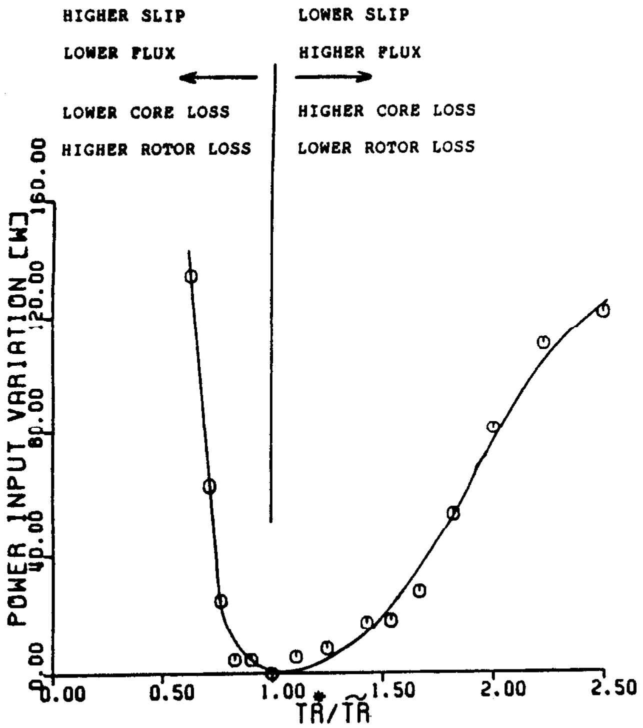

Fig. 13: Variation in power input as a function of the ratio of the rotor time constant used by the controller to the best estimate of this constant for the 3 hp test motor operating at 600 r/min and 1.0 p.u. torque.

the torque and flux commands are only unilaterally coupled in field oriented controllers. This property is essential to the stability of the system and the preservation of satisfactory dynamic performance.

A prototype system was built and tested in the laboratory. The main conclusions that can be drawn from these experiments are itemized below:

- Tuning of a field oriented controller can have a significant impact on the efficiency of the drive.
- Field orientation can be adequately maintained during flux variations, even with a controller of the indirect type.
- A measurement of the power input sufficiently stable and accurate to realize a true efficiency optimization can be obtained by use of digital filtering.
- The efficiency optimization does not create significant disturbances in the shaft speed.
- For drives having a small torque to inertia ratio, a satisfactory dynamic response from a low flux operating point can be achieved by resetting the flux command at its rated value whenever the torque command reaches its limit. For drives having a large torque to inertia ratio, the rotor time constant is a substantial fraction of the desired response time. A feedforward compensator and an inverter with a larger instantaneous current rating would thus be required to achieve a faster flux increase and thus obtain a faster dynamic response.

ACKNOWLEDGEMENT

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APPENDIX: MACHINE PARAMETERS

7.5 hp Motor

Nameplate Data:

7.5 hp 208/220/440 V 21/20/10 A

1725 RPM 60 Hz 3 phase 1.15 SF

Per Unit Parameters:

$r_s = 0.023 \quad L_{ls} = 0.1045$

$r_r = 0.014 \quad L_{lr} = 0.1045$

$r_{mo} = 24.57 \quad L_{mo} = 1.4686$

3 hp Motor

Nameplate Data:

3.0 hp 208/230/460 V 8.4/4.2 A

Y connected 60 Hz 3 phase

Per Unit Parameters:

$r_s = 0.0497 \quad L_{ls} = 0.0550$

$r_r = 0.0323 \quad L_{lr} = 0.0288$

$L_{mo} = 1.213$