

Direct Model Reference Control of an Induction Motor

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Abstract - High performance induction motor drive systems typically rely on field oriented control methods. However, achieving field oriented control requires machine specific knowledge, and tracking of drifting motor parameters in order to maintain control. This paper presents an alternative method of control based on a direct model reference adaptive control algorithm which does not require exact knowledge of motor parameters. The algorithm does not rely on maintaining a field oriented state, and is demonstrated to be robust with respect to parameter variations. The paper presents the control theory with experimental results. It is shown through experiment that the control approach is insensitive to motor saturation and parameter variations encountered in motors of similar rating and different manufacturer.

Introduction

High dynamic performance of the induction motor is the motivating factor for using field oriented control (FOC) methods. Control of the induction motor under FOC is reduced to that of a separately excited DC motor. The difficulty in this method lies in identification of the induction motor parameters which are necessary for control implementation.

The indirect FOC method is based on a linearizing scheme which relies on exact cancellations. Performance has been shown to deteriorate with parameter mismatch [1]. Similarly, the direct FOC is reliant on observer based methods to sense flux. These observers necessarily must assume knowledge of parameters of the induction motor, and thus synthesized flux variables would depart from actual flux with observer-plant mismatch [2].

To combat these problems various feedback correction and parameter adaption schemes have been proposed to achieve FOC [3]. However, many of the control schemes proposed are themselves dependent on the same parameters which vary with temperature and saturation. Others require custom motor configurations, disruptive probing signals, or special requirements which are not suitable either in terms of resulting performance, or in the desire to use standard induction motors.

If the goal of control is one of high dynamic performance, and low sensitivity to parameter variations for the standard induction motor, then a model reference adaptive control (MRAC) might be applied, without attempting to bring the motor into a field oriented state. The induction motor may be treated as a multi-input multi-output non-linear system to which the direct MRAC algorithm of [4],[5] is applied. This is the approach taken here. This paper differs from previous

efforts, in that high performance and robustness are achieved while no attempt is made to identify motor parameters.

Some basic theory and application of MRAC for induction motors is presented in the next two sections. Experimental results are then presented which show the performance of the motor under MRAC. Conclusions are then drawn based on the experimental results as to the strengths and weaknesses of this method.

Theory of Direct Model Reference Adaptive Control

In model reference algorithms, a model which the designer chooses is made to specify the dynamics of the controlled system. The selection of the model is limited only in that the speed of the dynamics of the model should not greatly exceed the dynamics of the system under control, otherwise large control efforts, might be required. Figure 1 shows a block diagram for a MRAC implementation.

An error signal is generated from the difference between the outputs of the model and plant. The model is driven by the reference input and the plant is driven by the controller which is adjusted by the error. Gains are modified within the controller such that the error is reduced. Adaption stops when the error reaches zero since the plant's outputs are now tracking those of the model. Thus the MRAC has forced the plant to behave like the model.

The particular MRAC applied to the induction motor is detailed in [4],[5] and is a direct adaptive method known as a simple adaptive controller (SAC). Unlike indirect adaptive control schemes, which attempt to identify plant parameters, the direct methods can rely on minimal knowledge of the plant to be controlled (see Fig. 1). Here each of the gains shown are comprised of a proportional plus integral term with the control law given as

$$\begin{bmatrix} K_x \\ K_u \\ K_e \end{bmatrix} = \begin{bmatrix} K_{xp} X_m^2 e + K_{xi} X_m \int (X_m e) dt \\ K_{up} U_m^2 e + K_{ui} U_m \int (U_m e) dt \\ K_{ep} e^3 + K_{ei} e \int (e^2) dt \end{bmatrix} \quad (1)$$

$$U_p = K_x + K_u + K_e \quad (2)$$

Where it can be seen that when the error goes to zero, the control is generated from the values stored by the integral terms only, and adaption stops.

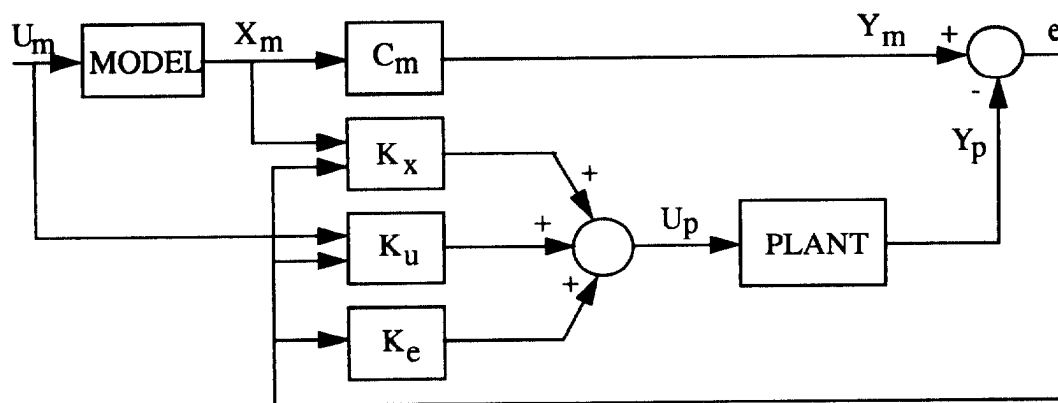


Figure 1 Model Reference Adaptive Control

Application of Model Reference Adaptive Control To Induction Motors

In [4],[5], it was shown that if the system to be controlled satisfied two sufficiency conditions then the system controlled by the MRAC would be guaranteed stable. The requirements were for the system to be linear in control. This can be demonstrated for the ideal induction motor where stator currents and slip are control variables, and rotor fluxes and rotor speed are chosen as states. The second sufficiency condition is that the plant under the closed loop control of a positive definite feedback matrix be strictly passive. This feedback gain is not needed for the implementation of the control, but is only necessary to show the MRAC will be guaranteed stable when applied to the plant.

The actual motor is subject to more non-linearities which violate the first assumption of linearity in control, making demonstration of the second sufficiency condition academic. The two main nonlinearities are current source saturation and motor iron saturation. The additional non-linearities do not preclude the stable operation of the motor under the MRAC, but do not allow the use of the stability analysis presented in [5].

For the induction motor subject to the saturation non-linearities, one possible method to demonstrate stability would be through the use of a Lyapunov function, and then to show that the region of convergence to the stable equilibrium is included in the region of state space on which the system would be expected to operate. This method is complicated because no systematic method exists for selection of Lyapunov function candidate, and the region of convergence that can be shown for a system is dependent upon the particular Lyapunov function used in the analysis. Although local asymptotic stability can be demonstrated by this method, it remains to be shown that the system is stable in the region of interest.

For the problem of velocity control of the induction motor, a reference model was chosen as a second order transfer function with one zero and two poles, such that there would be zero steady state error for step changes in the reference input.

Only velocity is used as a feedback quantity from the induction motor. Velocity feedback is a convenient choice for velocity control, however other quantities (such as torque, position, stator voltage) might be fed back depending on the objective of the control. Certainly, once good velocity response and tracking is obtained, position control becomes a matter of closing a position loop with a linear compensator designed for the model.

Simulation studies for the control and plant considered combinations of discrete control, continuous control, magnetic saturation, current saturation, and semiconductor switching (finite current tracking error). Saturation of the current source was modeled as a hard limiter on the current commands. Motor iron saturation was modeled by the cross-coupled saturation model developed in [7]. All models studied showed good tracking of the model by the induction motor in the presence of changing motor parameters once appropriate gains were established, provided the controls did not remain in saturation for extended periods of time. Further, all studies showed that corresponding commanded currents and slips were all similar in nature.

Although stability is an important issue, performance is always the motivating factor for the use of a control system. From all the simulations and experimentation performed, maintenance of stability has not been a problem.

The difficulty in tuning controller gains arises from the fact that with three inputs to the plant and a model with two states, there are 24 gains to be set. Once a set of gains are chosen simulation and examination of the individual components of the control U_p allows the designer to understand which components are dominant. Adjustment of gains, with noted trends in the resulting response leads to an understanding as to how changes in gains effect the performance and control effort.

Choosing larger gains will in general force better tracking, but at the cost of higher control effort, increased sensitivity of the control to noise, and increased possibility of control saturation. For example, in the extreme case where the integral

gains are brought to zero, some steady state error must be present based on Eqns 1 and 2. For the case where proportional gains are brought to zero, dynamic tracking will be sluggish. Excessive proportional or integral gains may lead to saturation of the controls. In addition, large proportional gains will cause the system to become more sensitive to any noise present in the feedback signal. The major concern over continued control saturation is the possibility of windup in the integrator terms which keep the control in saturation. The continued saturation of the controls has a negative impact on the performance of the system, such that tracking may not be maintained.

The current commands sent to the inverter are based on a transformation from the synchronously rotating reference frame to the machine terminal reference frame, which requires an electrical angle. The electrical angle is obtained from the integration of the electrical angular frequency w_e which is related by the slip to the rotor speed $w_e = w_{sl} + w_r$

Experimental Results

The induction motor was controlled by MRAC running on a PC based DSP platform. Current saturation was included to limit peak current below five times rated current of the 1 hp machine used. The experimental results represent the direct axis current i_{ds} set to zero, with control applied through i_{qs} and w_{sl} . Figure 2 displays the model output, and shaft speed of the motor from start-up, where the reference speed is a step change. The corresponding commanded current for a typical phase is displayed in Fig 3. It will be noted that the initial current will drive the motor into saturation, which is used to advantage to obtain momentarily greater than rated torque [8] to quickly accelerate the motor.

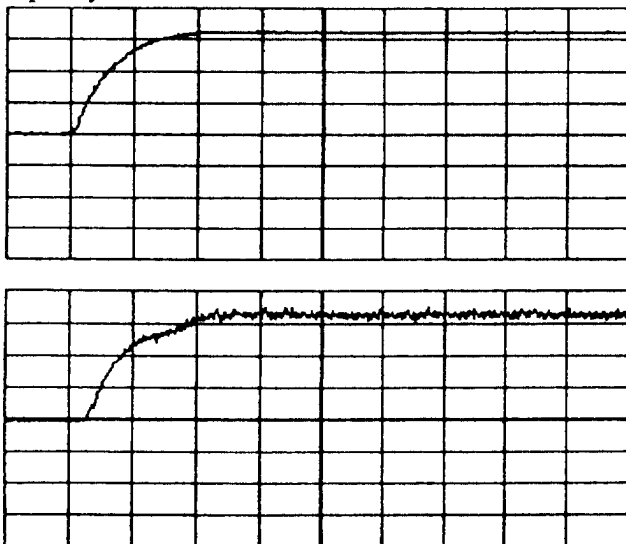


Figure 2: Response of model (top trace) and motor (bottom trace) to an 800 rpm step applied at 0.1 sec. (0.1 s/div)

A more complex speed reference is generated as a series of step changes, where Fig. 4 displays the model reference

output and motor speed. In general, with the exception of some error during transients, tracking of the reference displays finite error for tracking of ramps and zero steady state tracking error for constant command. The transient response is slower in cases where low speed references must be tracked, as noted from the response to the 200rpm step in Fig. 4. This is due to the reduction in the adaption gains as the magnitude of the terms in Eqn. 1 become small with decreasing reference input. Increasing gains of the experimental system will allow better performance at low speeds, but make the system susceptible to spurious adaptations due to noise, as well as control saturation at high speeds.

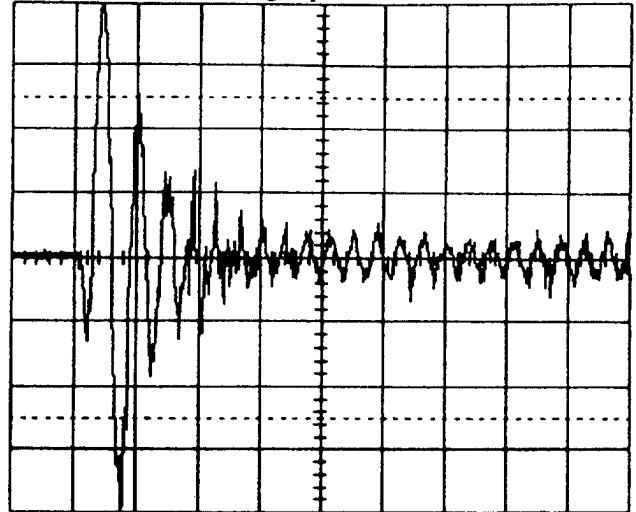


Figure 3: Typical commanded phase current for 800 rpm step in reference speed (8A/div, 0.1 s/div)



Figure 4: Response of model (top trace) and motor (bottom trace) to reference step of 800 rpm at 0.5 sec., step to -400 rpm at 1.5 sec., step to 200 rpm at 2.5 sec., step to -800 rpm at 3.5 sec., (0.5 s/div)

To investigate the adaption properties of the algorithm, five motors of design class B, with four poles, and similar

frame size, but different horsepower (values of 1, 1.5 and 2 hp) and manufacturer were substituted, and the experiment of Fig. 4 rerun with the same gains. The resulting tracking performance was very similar to that displayed in Fig. 4 for all motors tested, with the implication that the gains chosen had not been tuned uniquely to a motor, but that the system is able to adapt for different motor parameters.

The effect of torque disturbances was investigated during steady state operation. With reference to Fig. 5, the motor is initially operating at a steady state speed of 800rpm. At time 0.225s, a load torque of 0.5 p.u. is applied, which results in a 90 RPM speed fluctuation which forces adaption to compensate. The motor torque is then removed at time 0.95s which results in a 60 rpm transient. The control can be seen to drive the motor to the correct steady state speed in the case of the load torques, and in fact can be used to operate the motor in overloaded conditions for short periods of time.

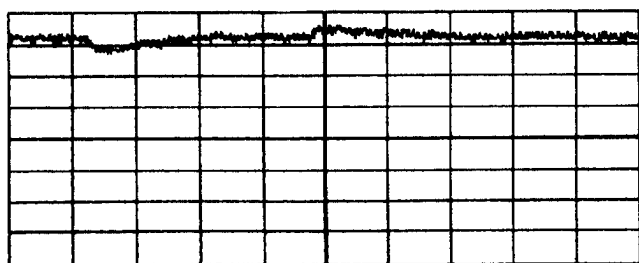


Figure 5: Response of induction motor to application of 0.5 p.u. torque at 0.225 sec and removal of torque at 0.95 sec. (steady state speed of 800 rpm, 0.2s/div).

From experimentation with the control algorithm two weaknesses became apparent. The control is dependent on the product of model states and error. With the control tuned properly for a step response at a given speed, the dynamic response at other speeds may be variable. At low commanded speed, the magnitude of the control is low, and the tracking may become sluggish. At high commanded speeds the control may saturate which may lead to a windup of the integrators which determine the slip, which in turn will lead to a loss of tracking.

The performance of the system is a tradeoff between range of tracking and speed of response. Higher gains will lead to good tracking, but may limit the range over which problems with integrator windup does not occur. Low gains will lead to a wider range of tracking, but a sluggish response to sudden changes in reference.

Conclusions

An algorithm based on direct MRAC is presented for robust velocity control of an induction motor. The algorithm assumes only approximate knowledge of motor parameters for initial tuning, and requires no special sensors, thereby making it appropriate for "off the shelf" motors. The algorithm is computationally simple and has been discretized for

digital implementation. Further, the algorithm is insensitive to fluctuations in loading and motor parameters that have caused problems in control schemes requiring motor specific knowledge such as FOC.

Work remains to determine that the algorithm is stable for a given range of possible parameter variations, though the work to date suggests that algorithm stability is not difficult to maintain. Additionally, the choice of gains might be made based on a more rigorous mathematical basis.

The algorithm may be used to robustly control the induction motor with high dynamic performance over a limited range of speeds. To extend the speed range of the algorithm it is necessary to either reduce the dynamic performance by lowering the magnitude of gains or to use a lower set of gains at high speeds. The later approach, where discrete gains are used dependent on the environment of the plant (in this case the magnitude of the speed reference), is known as gain scheduling. Although the performance for individual gains and speeds could be shown, the performance and stability of the system incorporating gain scheduling with the MRAC must be established.

Another possibility is to alter the algorithm when saturation is encountered. The problem is somewhat analogous to windup in a PI controller, but a solution as simple as stopping integration does not yield satisfactory results.

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Table 1: List of Symbols for MRAC

MRAC Quantities	Subscripts
K - gain	m - model
X - state	p - plant
C - output matrix	x - state
U - input	u - input
Y - output	e - error
e - error	p - proportional
	i - integral

Table 2: List of Symbols for Induction Motor Model

Induction Motor Model Quantities	Subscripts
R - resistance	q - quadrature axis
L - inductance	d - direct axis
V - voltage	s - stator
i - current	r - rotor
P - number of pole pairs	sl - slip
J - rotor and load inertia	e - stator electrical
λ - flux	m - mutual
ω - angular frequency	
S - d/dt, time differential	