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Abstract-This paper introduces a novel method for indirect field orientation control of induction machine which uses reactive energy stored in rotor windings to modify the estimated rotor time constant T_r. Field orientation is achieved by means of minimizing the perturbation of reactive power associated with rotor flux. The basic approach together with a practical implementation scheme are introduced in this paper. Simulation results are also given to demonstrate the feasibility of the proposed approach .

Introduction

In any alternating current machine, the active power measured at the terminals of the machine is related to its electromagnetic torque while the reactive power is associated with the energy stored in the windings of the motor. In modern control of induction machines it has been shown that it is useful to affix a synchronously rotating d-q axes to the vector representing the rotor flux. When the rotor flux linkage vector λ_r defining the physical orientation of the rotor flux of the rotor flux density is aligned with the d-axis, any perturbation in the stator current i_{qs} orthogonal (electrically in phase quadrature) with λ_r, and will not affect the value of λ_r. Therefore the energy associated with λ_r will not be changed. However, if there exists an error between actual rotor time constant T_r* and estimated T_r, the rotor flux linkage λ_r will deviate from d-axis. In this case a perturbation in i_{qs} will cause a change in λ_r, which is reflected by a change in the reactive power associated with the rotor flux. If this change in reactive power can be minimized by modifying the estimated T_r, a better alignment of λ_r with the d-axis can be achieved. Based on this principle, an investigation has been made, based on the measurement of the reactive power of an induction machine and determination of the rotor flux relationship relative to the reactive power. A new method for making modifications in the rotor time constant T_r to determine the rotor flux position can then be developed. This new means for adapting to rotor time constant changes is presented in this paper.

Reactive Power Associated with Rotor Flux

From the basic equations of the induction machine, in synchronous frame assuming steady state, the following equations can be obtained.

$$Q = \frac{3}{2}\{V_{qs}I_{ds} - V_{ds}I_{qs}\}$$
$$= \frac{3}{2}\Omega_e\left(L_s' I_1^2 + \frac{L_m}{L_r}\Lambda_{dr}I_{ds} + \frac{L_m}{L_r}\Lambda_{qr}I_{qs}\right) \qquad (1)$$

where Ω_e: synchronous angular velocity;
Q: steady state reactive power
I_1: stator current amplitude

$$I_1^2 = I_{ds}^2 + I_{qs}^2$$
$$L_s' = L_s\sigma;$$
$$\sigma = 1 - \frac{L_m^2}{L_sL_r}$$

and where capital letters are used to denote steady state quantities.

Increment of Reactive Power Caused by Rotor Flux

From (1), it is observed that the reactive power is a function of I_{ds}, I_{qs}, Ω_e, Λ_{dr} and Λ_{qr}. If there exists an increment Δi_{qs}, this component can produce an increment of $\Delta\omega_e$ and $\Delta\lambda_{qr}$ when Λ_{dr} is not aligned with the d-axis. Hence, an approximate increment of reactive power can be obtained by taking total differential of (1)

$$\Delta q = \frac{\partial q}{\partial i_{qs}}\Big|_0 \Delta i_{qs} + \frac{\partial q}{\partial \omega_e}\Big|_0 \Delta\omega_e + \frac{\partial q}{\partial \lambda_{qr}}\Big|_0 \Delta\lambda_{qr}$$

where

$$\frac{\partial q}{\partial i_{qs}}\Big|_0 = 3\Omega_e L_s' I_{qs} + \frac{3}{2}\Omega_e\frac{L_m}{L_r}\Lambda_{qr}$$

$$\frac{\partial q}{\partial \omega_e}\Big|_0 = \frac{Q}{\Omega_e}$$

$$\frac{\partial q}{\partial \lambda_{qr}}\Big|_0 = \frac{3}{2}\Omega_e\frac{L_m}{L_r}I_{qs}$$

when λ_r is aligned with the d-axis, and $\Lambda_{qr}=0$. For the purpose of making modifications in T_r, define a modifed reactive power such that

$$\Delta q_r = \Delta q - (3\Omega_e L_s' I_{qs} \Delta i_{qs} + \frac{Q_0}{\Omega_e} \Delta\omega_e)$$

in which case

$$\Delta q_r = \frac{3}{2}\Omega_e \frac{L_m}{L_r}(\Lambda_{qr}\Delta i_{qs} + I_{qs}\Delta\lambda_{qr}) \qquad (2)$$

This term is caused by the variation of λ_r due to the deviation of λ_r from d-axis due to the difference between T_r and T_r^*. From (2) it is clear that if $\Lambda_{qr}=0$ and $\Delta\lambda_{qr}=0$, then $\Delta Q_r=0$, which indicates that Λ_r is aligned with d-axis.

Hence, if one can measure Δq, Δi_{qs} and $\Delta\omega$, the perturbation in reactive power Δq_r can be calculated by (2). Subsequently by using Δq_r, correction of the rotor time constant T_r is possible.

Relation Between Δq_r and $\Delta\tau_r^*$

From [2] we have the results: In indirect field orientation control of induction motor, in steady state:

1) when $\tau_r > \tau_r^*$, $\Delta\tau_r^* < 0$, $(\Delta\tau_r^* = \tau_r^* - \tau_r)$, ω_s^* becomes smaller than the desired value, which causes λ_r to lead the d-axis and thus $\lambda_{qr}>0$. If a step change $\Delta i_{qs}>0$ is applied, then $\Delta\lambda_{qr}>0$ causes λ_{qr} to increase, which in turn will produce $\Delta Q_r>0$. Fig.1. shows this situation.

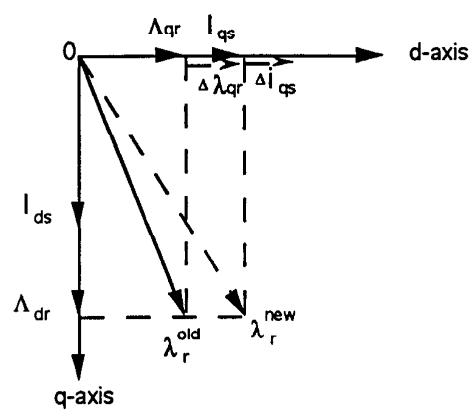

Fig. 1 $\tau_s^* < \tau_r$ (λ_r leads the d-axis)

2) when $\tau_r < \tau_r^*$, $\Delta\tau_r^* > 0$ ω_s^* then is greater than the desired value, which causes λ_r to lag the d-axis in which case $\lambda_{qr}<0$ as shown in Fig.2. When a step change $\Delta i_{qs}>0$ is applied, $\Delta\lambda_{qr}>0$ causes λ_{qr} to decrease, which in turn will produce a negative Δq_r. This situation is shown in Fig. 2.

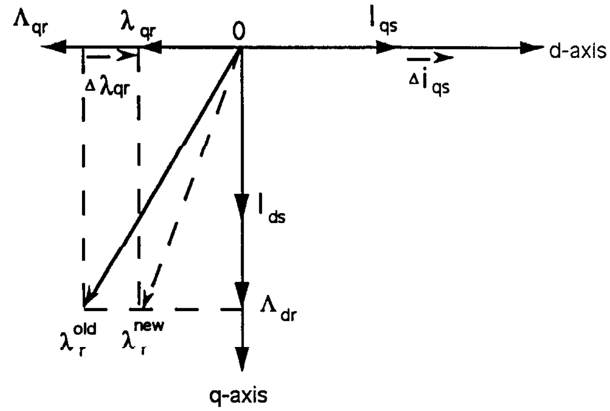

Fig. 2 $\tau_r^* > \tau_r$ (λ_r lags the d-axis).

From 1) and 2) we can deduce that for a positive $\Delta i_{qs}>0$, negative $\Delta\tau_r^*<0$ will cause a positive increment in Δq_r, while positive $\Delta\tau_r^*>0$ will cause a negative Δq_r. Thus we can use following equations to make a correction in τ_r.

$$\Delta\tau_r^* = -K\,\Delta q_r \qquad ; \qquad K>0$$

$$\tau_r = \tau_{ro} + \Delta\tau_r^*$$

where τ_{ro} is the initial estimation of time constant.

Simulation

As we are only interested in long term steady state behavior of the induction motor for the purpose of rotor time constant, τ_r, correction, the time rate of change of the stator flux terms in the model are neglected, which results in the following model.

Machine model:

$$\frac{d}{dt} i_{qr} = -\frac{1}{\tau_r} i_{qr} - \omega_s i_{dr} - \omega_s \frac{L_m}{L_r} i_{ds}$$

$$\frac{d}{dt} i_{dr} = -\frac{1}{\tau_r} i_{dr} + \omega_s i_{qr} + \omega_s \frac{L_m}{L_r} i_{qs}$$

$$v_{qs} = r_s i_{qs} + \omega_e \lambda_{ds}$$

$$v_{ds} = r_s i_{ds} - \omega_e \lambda_{qs}$$

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

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

The control model (with i_{qs}^* and λ_{dr}^* as commands) is

$$i_{ds}^* = \frac{\lambda_{dr}^*}{L_m}$$

$$\omega_s^* = \frac{L_m i_{qs}^*}{\tau_r \lambda_{dr}^*}$$

In this study it is assumed that an ideal current source excites the induction motor. This can be considered as a reasonable approximation of a current regulated pulse width modulated inverter excitation of the machine Simulation of the system used the simulation languae ACSL utilizing an APOLLO workstation.

Figures 3 through 6 show the simulation results. In all cases the actual rotor time constant τ_r^* is 0.21377 seconds. The traces in all four of these figures are, from top to bottom: IQS= i_{qs} - q-axis stator current (A.), WR=ω_r - rotor speed (radians per second), Q=q - (quasi)reactive power (volt-ampers), DQ=Δq - change in reactive power (volt-amperes), LAMDR=λ_{dr} - d-axis component of rotor flux linkage (webers), LAMQR=λ_{qr} - q-axis component of rotor flux linkage (webers), TR=τ_r - rotor time constant estimate (seconds).

In Figs. 3 and 4 the initial estimate of the rotor time constant τ_{ro} was set at 0.5 seconds. The two figures can be used to compare the effects of feedback gain on the adaption algorithm. Note that for a gain of K=0.0001 (Fig. 3) the solution converges to the correct time constant asymtotically while a gain of K = 0.0004 produces a slightly underdamped but more rapidly converging solution. Note that the scales of many of the variables expanded over a narrow range. The spikes in q, λ_{dr} and λ_{qr} curves are produced by the step increase of i_{qs} from the ideal current source and by the simplified machine model. In Figs. 5 and 6 the estimate for the rotor time constant begins at τ_{ro} = 0.1. Again gains of K = 0.001 and 0.004 are examined. Again both solutions converge rapidly.

In practice, the rotor resistance will never vary by more than a factor of two from its coldest to hottest temperature. Figures 3 to 6 demonstrate that the algorithm remains rapidly convergent over a five to one variation and four to one variation in controller gains suggesting a good convergence property. Figure 7 shows the flow chart for the τ_r correction algorithm. However, it is apparent from the curves that different values of gain K has significant influence on the correction process so that if K is too large, the excess gain can cause instability. At present, K is estimated in the same manner the technique used to determine the integral (K_I) and proportional (K_P) parameters in a PI regulator.

Conclusion:

It has been shown that the difference between estimated and real rotor time constants τ_r and τ_r^* will cause a deviation of λ_r from d-axis and consequently a loss of field orientation. If one applies a small stator q-axis current perturbation, this deviation will cause an extra reactive power increment which is related to the change of λ_{qr} and reflects the error in the rotor time constant $\Delta\tau_r^*$. Making use of this information and minimizing the perturbation of Δq_r, it has been shown that it is possible to correct τ_r and thus minimize the deviation of λ_r from d-axis. Indirect field orientation control of the induction machine is thereby achieved despite possible wide variations in the rotor time constant.

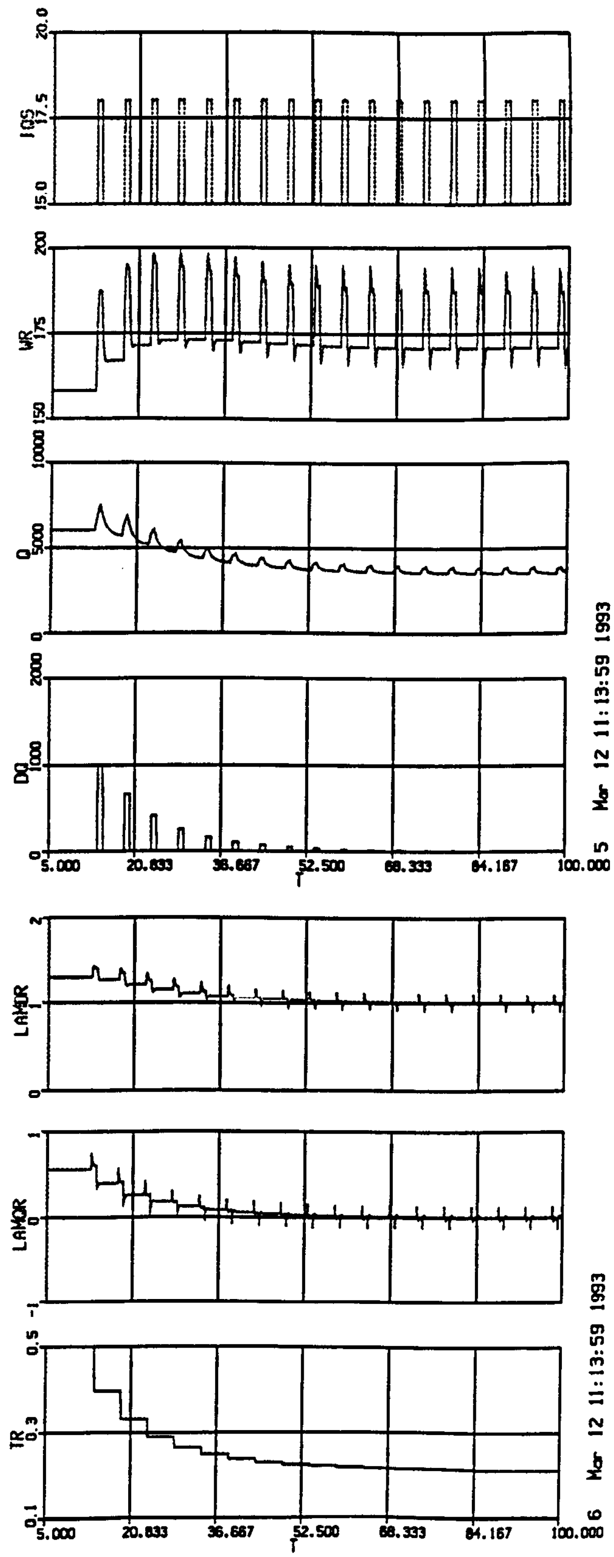

Fig. 3 Simulation results for τ_{ro}=0.05 (>τ_r=0.21377) seconds and K = 0.001.

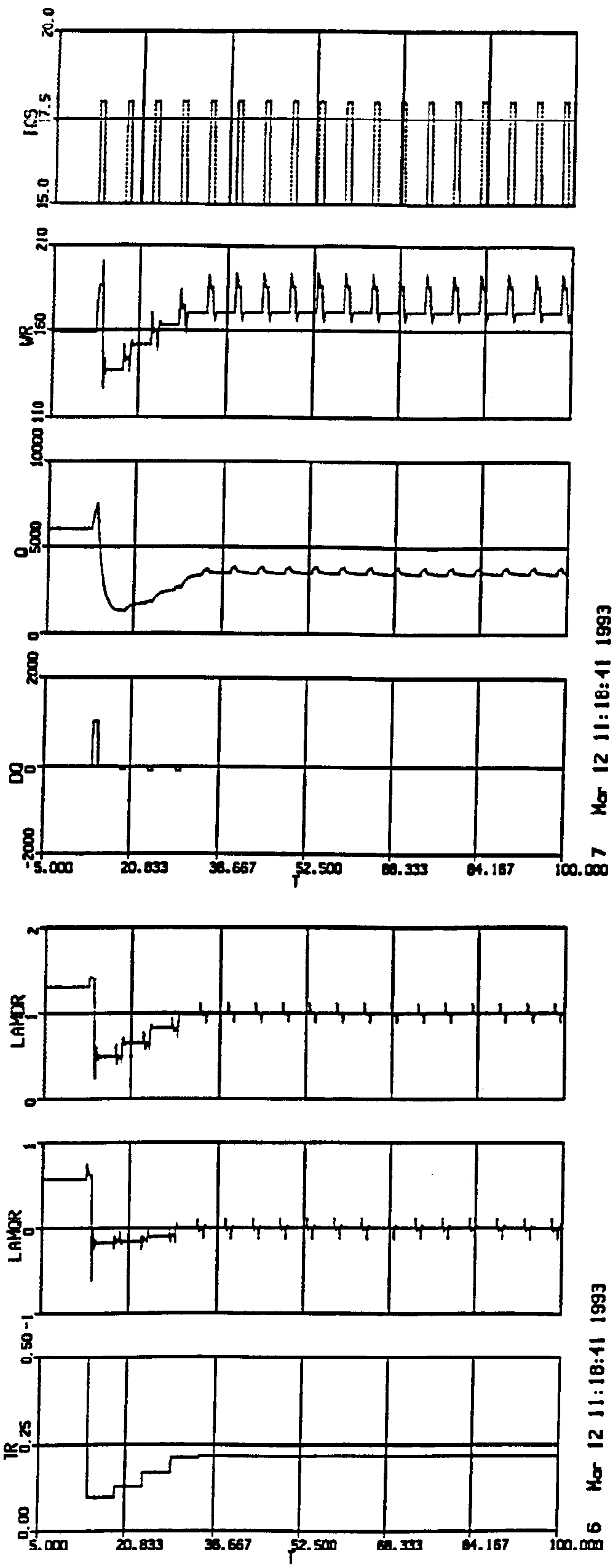

Fig. 4 simulation results for T_{ro}=0.5 (> T_r^*=0.21377) seconds and K=0.0004

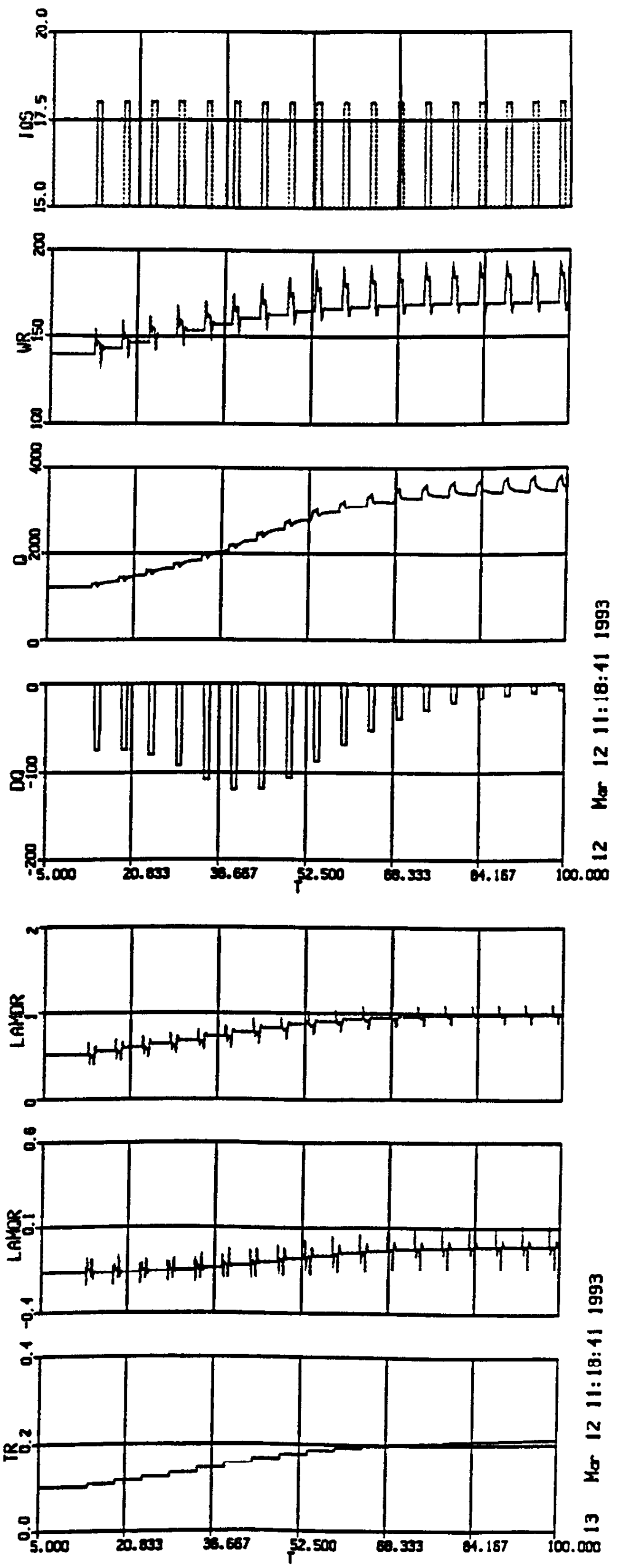

Fig 5 simulation results for T_{ro}=0.1 (< T_r^*=0.21377) seconds and K=0.0001

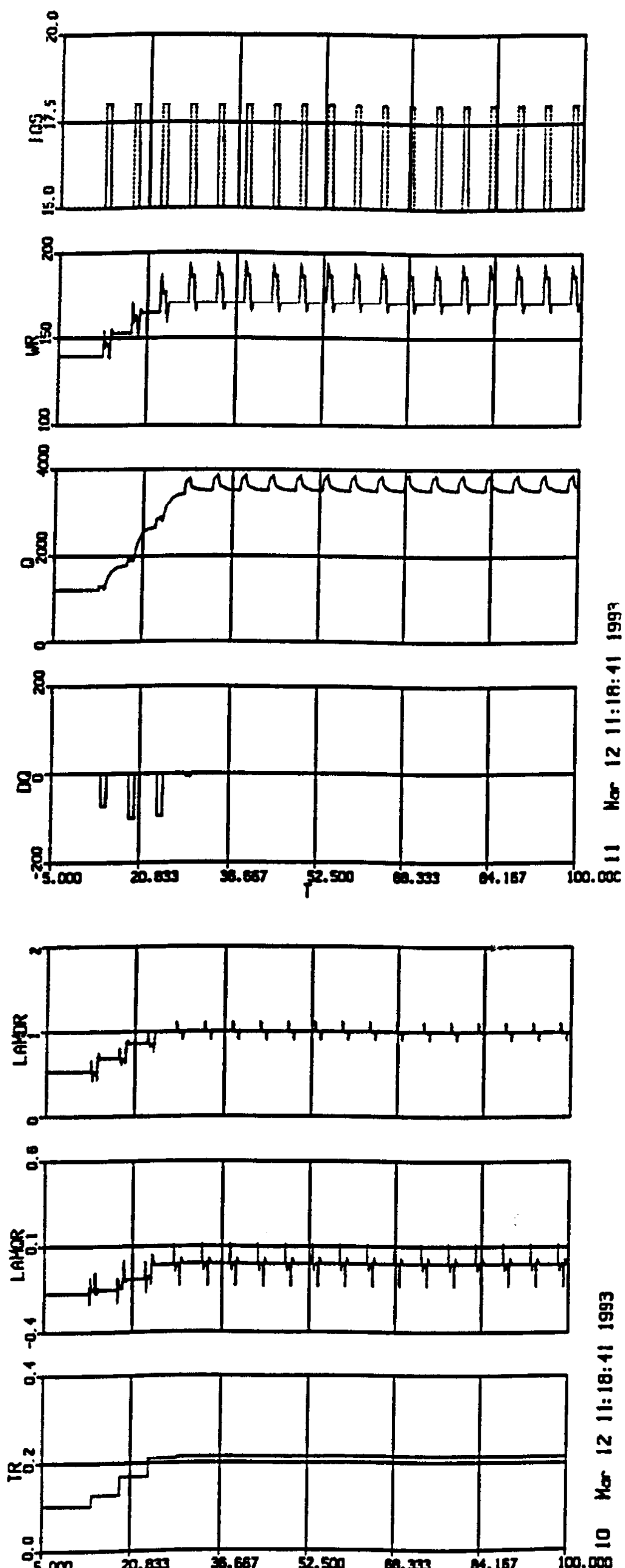

Fig. 6 simulation results for T_{ro}=0.1 (< T_r^*=0.21377) seconds and K=0.0004

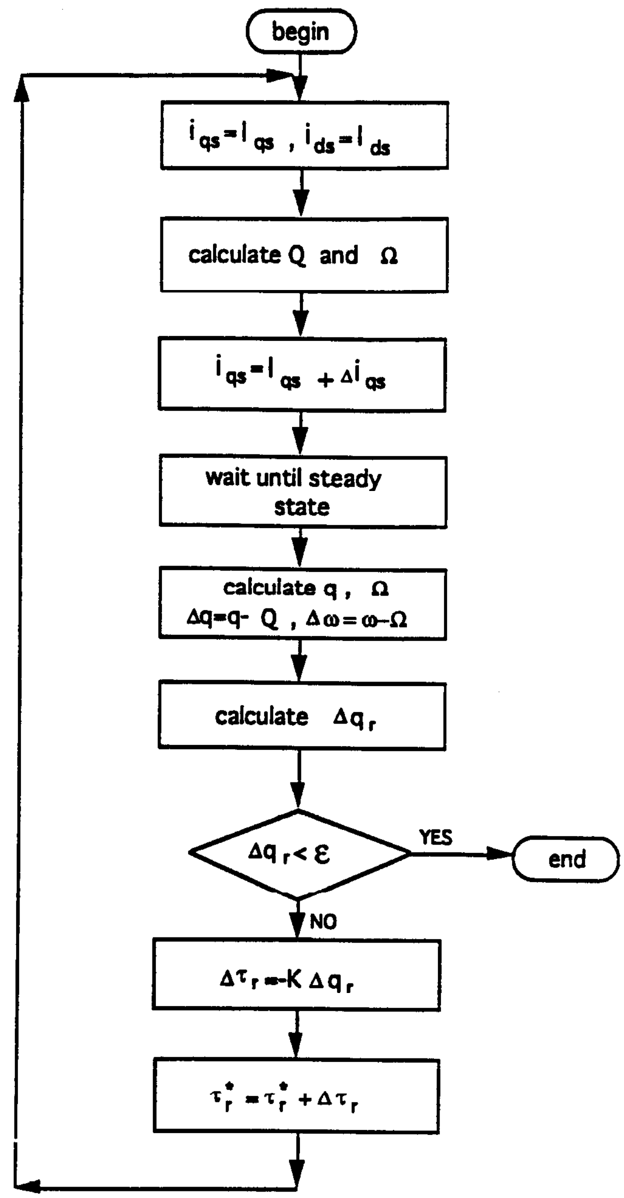

Fig. 7 Flow chart for rotor time constant correction

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Appendix Induction machine parameters

AC 220 Volts, 60 Hz, 5 HP. L_{ls} =2.52 mh, L_{lr} =2.52 mh, L_m =84.7 mh, r_s = 0.531Ω, r_r =0.408Ω, J =0.1 nt·m·sec²/rad