

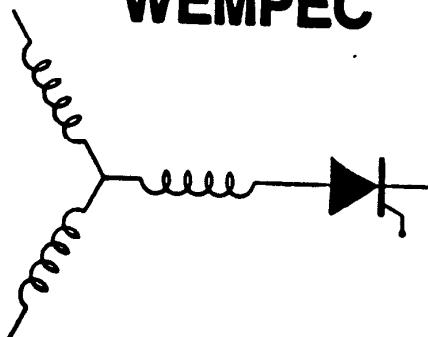
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A New Direct Field Oriented Controller
Employing Rotor End Ring Current Detection

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ABSTRACT

The usual method of induction motor torque control uses the indirect field orientation principle in which the rotor speed is sensed and slip frequency is added to form the stator impressed frequency. Unfortunately, the rotor resistance varies as the motor heats up under load thereby changing the rotor time constant which has a deleterious effect on the torque response. In this paper a new direct field oriented control scheme is presented which employs the rotor end ring current detection and removes the dependence of the controller accuracy on temperature. This field orientation scheme does not require an incremental encoder for rotor position sensing. The motor torque can be accurately controlled even down to zero frequency operation. The controller is completely independent of rotor time constant variations.

INTRODUCTION

The field oriented control techniques incorporating microprocessors have made possible the application of induction motor drives in high performance applications. In general, two generic types of field oriented control are in use. The first scheme, originally devised by Hasse [1], uses the so-called indirect field orientation principle in which the rotor speed is accurately sensed and slip frequency is added to form the stator impressed frequency. The slip frequency is calculated through a non-linear block which is dependent upon the rotor time constant. Unfortunately, the rotor

resistance varies over a wide range as the motor heats up under load and during low speed operation thereby changing the rotor time constant and having a adverse effect on the torque transient response. Also, the rotor inductance is a function of the flux level in the machine and, hence, varies widely during field weakening operation causing additional difficulties in regulating torque at high speeds.

The second method, developed by Blaschke [2] and termed direct field orientation, is inherently the most desirable induction motor control scheme available. In this scheme, torque is controlled by measuring stator current and air gap flux and, from these measurements, the amplitude and position of the rotor flux is estimated. Torque is controlled by direct regulation of the stator current amplitude and phase relative to the rotor flux. This approach is rarely used since the controller is unable to operate reliably to zero speed because of the inaccuracies involved in the flux measurement below several hertz.

Recently, another method of direct field orientation has been proposed by Maguraneau [3,4] and Yamamura [5]. In this approach, the end ring current is measured by means of hall sensors and the rotor bar current is calculated. The torque is then controlled by adjusting the stator current having the correct phase and amplitude relationship with respect to the rotor current. In these implementations, however, the rotor current must be accurately measured in both amplitude and phase. Unfortunately, the hall sensors are sensitive to temperature variations so that an accurate measurement of rotor current is very difficult.

The paper [6] proposed an indirect field oriented control scheme which utilizes the measurement of rotor end ring current to remove the dependence of the control

accuracy on temperature. The resulting control scheme is independent of temperature variations of the Hall sensors.

In this paper a new direct field oriented control scheme which employs rotor end ring current detection is presented. The rotor flux vector is formed from the stator current vector and the rotor current vector which is obtained from the rotor end ring current vector. This scheme does not require an incremental encoder for rotor position sensing for field orientation. Moreover, the motor torque can be accurately controlled even down to zero frequency operation. The method proposed here is essentially insensitive to variations in rotor time constant.

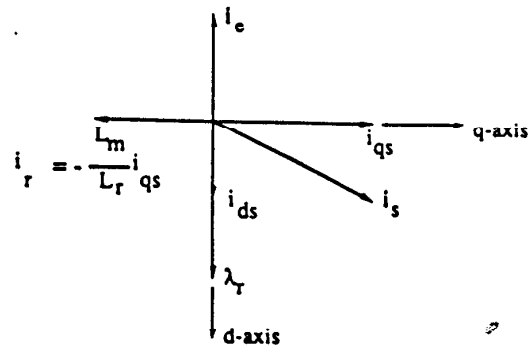


Fig. 1 d-q Representation of Spatial Position of Machine Variables in Steady State.

PRINCIPLE OF FIELD ORIENTATION

A d-q axis diagram illustrating the principle of field orientation is shown in Fig. 1. In general, the instantaneous position of the maximum rotor flux density must be located within the machine. In a d-q axis representation of the machine, the rotor flux linkage vector forms the circuit equivalent of the rotor flux density and the position of the rotor flux linkage vector must be located upon the d-q plane. This spatial position is usually taken to be the d-axis as shown in Fig. 1. The excitation of the machine is controlled by the component of stator MMF that is co-linear with the peak rotor flux density. The torque of the machine is controlled by maintaining the excitation component of stator MMF constant while injecting a varying and proportional amount of stator MMF spatially at a right angles to the peak rotor flux density (in electrical degrees). The d-q circuit equivalent approach is to properly adjust the in-phase (d-axis excitation component) and out-of-phase (q-axis torque component) spatial components of stator current relative to the rotor flux linkage vector as shown in Fig. 1.

It is important to note that the rotor end ring current produces an MMF distribution that is spatially at right angles with the rotor bar current when expressed in electrical degrees. Hence, the rotor current vector can be obtained from the rotor end ring current vector with proper transformation and then the rotor flux linkage vector can be formed by adding the stator current vector and the transformed rotor current vector with proper amplitude ratio.

ROTOR FLUX VECTOR CALCULATION FOR FIELD ORIENTATION

While measurement of the rotor current is generally impractical with a squirrel cage machine, the rotor end ring leakage flux can, however, be easily measured by placing Hall sensors in the vicinity of the rotor end ring. Since the path of the end ring leakage flux is essentially through air, such a flux measurement is effectively proportional to the rotor end ring current and, with the proper transformation and correction factor, to the rotor bar current itself. This signal can now be used as a feedback signal to produce field oriented control. In previous papers, the sensing signal was used as a feedback signal to directly control the rotor currents of the machine [3,4]. Unfortunately, the characteristics of Hall sensors are dependent on temperature and an accurate measurement of rotor current over a wide operating condition becomes difficult. Hence, previous direct field oriented controllers utilizing rotor current measurement suffer a deterioration in performance due to temperature changes as, in the same manner, does the indirect field oriented controller.

The direct field oriented control scheme, which is proposed here, is shown in Fig. 2. In this example, two Hall sensors, located near to the rotor end ring and spaced by 90 electrical degrees, sense the rotor end ring leakage flux and therefore the bar currents at these two points. Rotor flux is related stator and rotor currents by:

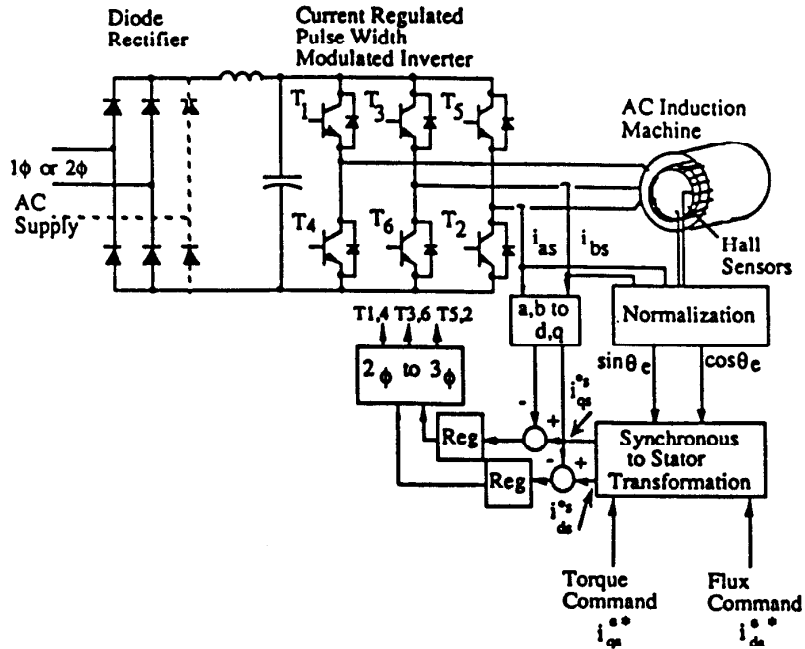


Fig. 2 Direct Field Oriented Controller Employing End Ring Current Detection

$$\lambda_{qr}^s = L_m i_{qs}^s + L_r i_{qr}^s \quad (1)$$

$$\lambda_{dr}^s = L_m i_{ds}^s + L_r i_{dr}^s \quad (2)$$

Normalizing these signals by their amplitude, the sine and cosine of the rotor flux position can be formed.

$$\cos\theta_e = \lambda_{qr}^s / \lambda_{dqr}^s \quad (3)$$

$$\sin\theta_e = \lambda_{dr}^s / \lambda_{dqr}^s \quad (4)$$

where,

$$\lambda_{dqr}^s = \sqrt{\lambda_{qr}^{s2} + \lambda_{dr}^{s2}} \quad (5)$$

These two sinusoidal variations can be used to transform the stator current for torque command, i_{qs}^{e*} , and flux command, i_{ds}^{e*} , expressed in the synchronous frame, to equivalent command currents, i_{qs}^{s*} and i_{ds}^{s*} , in the stationary reference frame. The resulting command currents, i_{qs}^{s*} and i_{ds}^{s*} , are summed with the actual measured currents in d,q form and regulated with a pulse width modulated inverter. Hence, stator currents of desired amplitude and phase with respect to the rotor flux linkage are produced.

The terms related to rotor current in Eqs. (1) and (2) are, however, affected by changes of temperature of the Hall sensors. To overcome this problem a rotor flux position calculator utilizing adaptive gain of the rotor current can be introduced as shown in Fig. 3. Adaptation is based on an Index of performance which requires the d axis component of rotor current in synchronous reference frame to be maintained at zero. The d axis component of rotor current in synchronous reference frame can then be written as,

$$i_{dr}^e = i_{qr}^s \sin\theta_e + i_{dr}^s \cos\theta_e \quad (6)$$

which tends to zero, provided that the commanded and real rotor flux vectors are equal. The adaptive loop in Fig. 3 can be viewed as an additional servo drive that keeps the brushes of an equivalent DC machine in the neutral zone resulting in no interaction between the armature and the field circuit. Note that in the proposed scheme the rotor flux position is directly sensed. No incremental encoder or other device for sensing rotor position is necessary.

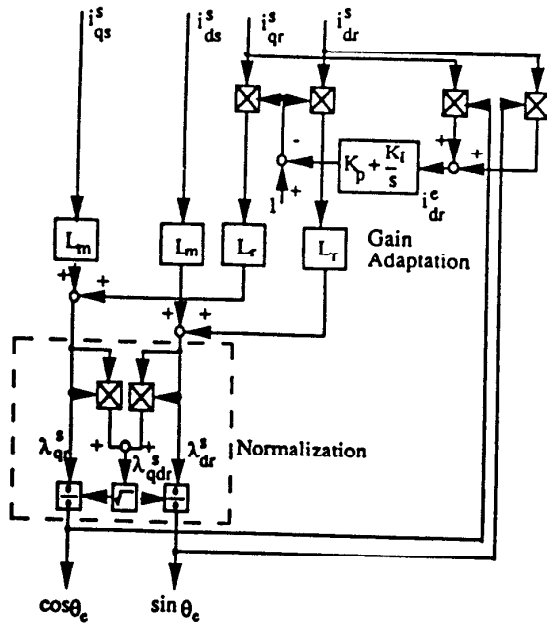


Fig 3 Rotor Flux Position Calculator With Adaptive Rotor Current Referral Ratio

EXPERIMENTAL AND COMPUTED RESULTS

Figure 4 illustrates a cross-sectional view of the stator and rotor end parts, showing the arrangement of the two Hall-Effect sensors which were fixed to a ferrite bar. Three of these sets were mounted around the end ring bar and displaced by 120 electrical degrees with respect to each other. These sensors were installed in a 7.5 HP, 4-Pole, 230V induction machine, the rotor of which is shown in Fig. 5, together with the two disks used to install the Hall sensors. Note that this arrangement of the Hall sensors does not require any extensive mechanical adaptation or change in the rotor geometry.

Experimental results have demonstrated that the signals from Hall sensors 1 and 2 in Fig. 4 are respectively 75% and 62% larger than the signals obtained when no ferrite is used. The ratio between signals from sensors 1 and 2 (v_{s1}/v_{s2}), is 0.75 when the machine is operating under rated conditions. The ratio between the signal produced by the end ring current and the signal produced by the stator current is 4.0 for sensor 1, and 1.8 for sensor 2 at the rated conditions. Although the signal from sensor 2 is larger, the signal from sensor 1 was found to be less influenced by the stator end

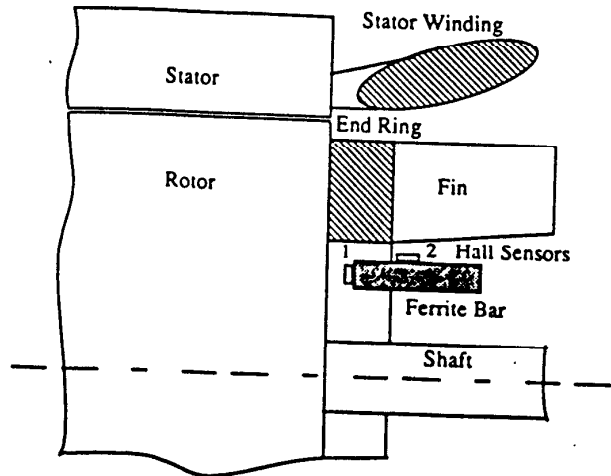


Fig. 4 Cross Sectional View of the Induction Machine Showing Location of One of the Sets of Hall Sensors.

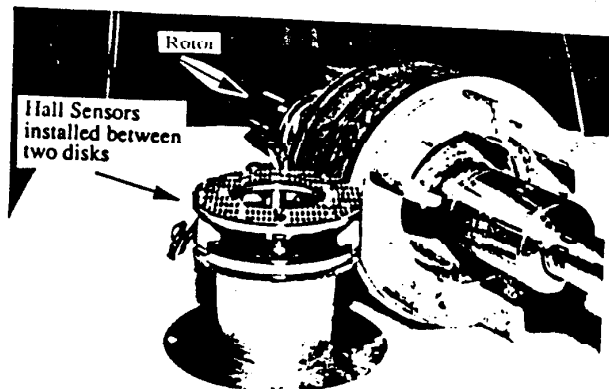


Fig. 5 Rotor and Hall Sensor Arrangement Before Installation in Induction Machine

winding flux leakage and thus the position occupied by the sensor 1 was determined to provide better results. Hence, the position of sensor 1 is suggested for future research work.

The signals from the three hall sensors of position 1 are plotted in Fig. 6 for a motor starting transient at 50% of rated voltage. Note that the traces are at line frequency since the hall probes do not rotate with the rotor. Hence, it can be said that the hall probes essentially accomplish a transformation of variables from a rotating to a stationary reference frame. This trace is virtually identical in form to

the simulation traces for rotor currents obtained in the stationary reference frame for this same machine [8].

Figure 7 shows an expanded trace of the rotor end ring current measured for the rated load condition. Note that the three phase signals are nearly balanced and are properly phase displaced by 120 degrees. The measured and calculated angles between stator and rotor currents are provided in Figs. 8a and 8b for the arrangement as shown in Fig. 4 with and without the ferrite bar, respectively. Note the good agreement between calculated and measured values obtained in both cases. These results confirm the feasibility of rotor current vector detection in a simple and low cost manner.

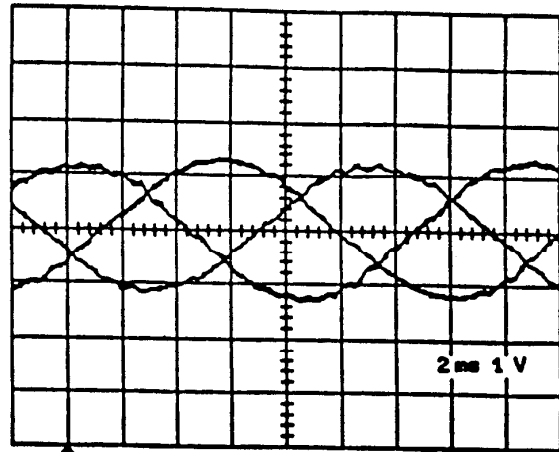


Fig. 7 Three Phase End Ring Currents During Rated Load Condition Operating at Rated Speed

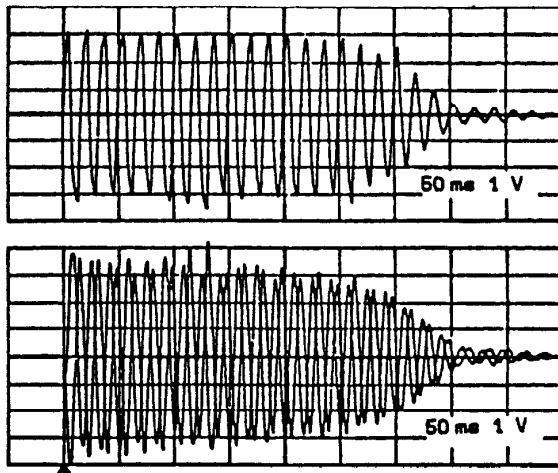


Fig. 6. Experimental Results of Three Phase Rotor End Ring Currents During Starting Transient of Induction Machine at 50% of Rated Voltage.

Typical simulation traces of the direct field oriented controller are shown in Figs. 9 and 10. Figure 9 shows the acceleration and speed reversal from 1000 rpm to -1000 rpm for a 7.5 HP, 60 Hz, 4 pole IM loaded with additional inertia equal to the inertia of rotor. A speed controller is included as part of the simulation, which is not shown in Fig. 2. The power converter used as a part of this simulation is a high frequency ac link converter [9].

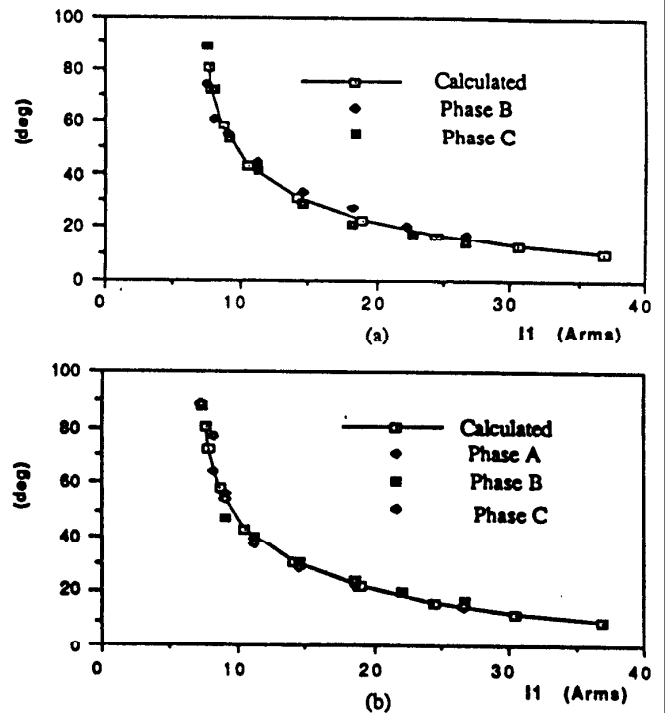


Fig. 8 Calculated and Measured Angles Between Stator and Rotor Currents for Arrangement With Ferrite Core (a) and Without it (b), for the Arrangement shown in Fig. 4

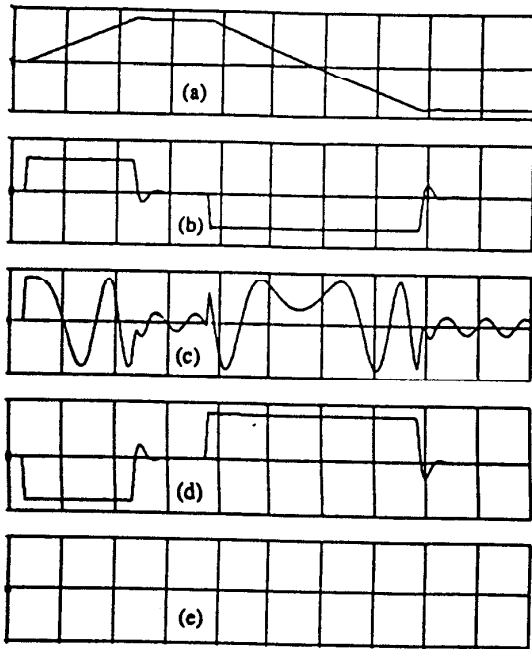


Fig. 9 Acceleration and Speed Reversal of 7.5 HP Induction Motor with Direct Field Oriented Control Scheme According to Fig. 2. (a) Speed, 1200rpm/div. (b) Torque, 100N-m/div. (c) Stator Current, 60A/div. (d) q-Axis Rotor Current, 60A/div. (e) d-Axis Rotor Current, 60A/div., and Time Scale is 0.04Sec./div.

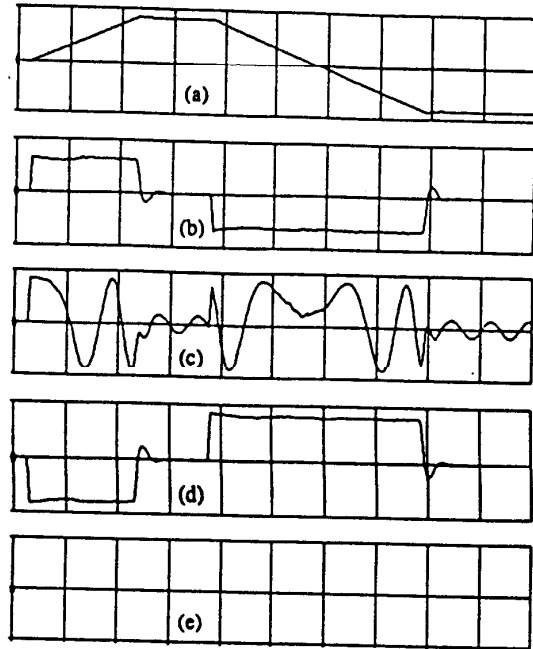


Fig. 10 Acceleration and Speed Reversal of 7.5 HP Induction Motor with Direct Field Oriented Control Scheme According to Fig. 2. With Rotor Current Signal Assumed to be in Error of -6%. (a) Speed, 1200rpm/div. (b) Torque, 100N-m/div. (c) Stator Current, 60A/div. (d) q-Axis Rotor Current, 60A/div. (e) d-Axis Rotor Current, 60A/div., and Time Scale is 0.04Sec./div.

In Fig. 10 the same acceleration and speed reversal is shown for the electrical drive according to Fig. 2. It was supposed that because of temperature changes rotor current signal was -6% in error. When driven by the constant current amplifier method the Ga-As Hall sensor output voltage change is $\Delta V_{MAX} -0.06\% / \text{degree Celsius}$. This results in an error in the rotor current readings of -6% when the operating temperature changes +100 degrees Celsius from the temperature at which the gain adjustment was done. Note that the desired torque is actually developed and that the d component of rotor current is kept to be negligibly small.

A digital signal processor based direct field oriented controller has been designed and implemented in the Laboratory. A current regulated pulse width modulated inverter was used to drive the 7.5 HP, 60 Hz, 4 pole induction motor. The results obtained from the experimental system are shown in Figures 11 and 12.

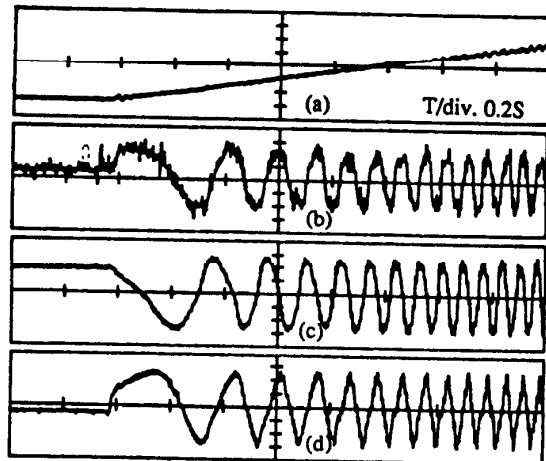


Fig. 11 Waveforms of Motor Speed, Rotor Current and Stator Currents at Constant Torque Operation (Acceleration from 0 rpm to 600 rpm). (a) Motor Speed, 140 rpm/div. (b) Rotor Current Signal Phase A, 0.5V/div. (c) Stator Current Phase A, 5A/div. (d) Stator Current Phase B, 5A/div.

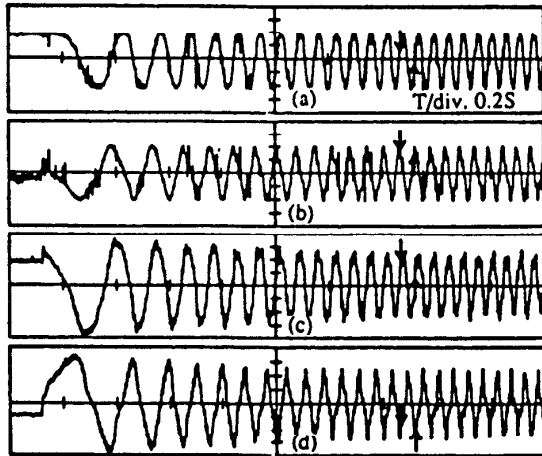


Fig. 12 Waveforms of Rotor Flux Position Signals and Stator Currents at Constant Torque Operation (Acceleration from 0 rpm to 600 rpm). (a) Rotor Flux Position Signal, $\sin\theta_c$, 5V/div. (b) Rotor Flux Position Signal, $\cos\theta_c$, 5V/div. (c) Stator Current Phase A, 5A/div. (d) Stator Current Phase B, 5A/div.

CONCLUSION

A practical implementation and a performance analysis of a new type of direct field oriented controller have been presented in this paper. A low cost and simple solution for rotor current measurement is proposed by measuring the rotor end ring current via Hall-Effect sensors installed as indicated in Fig. 4. An adaptive controller for the rotor current gains is proposed in order to eliminate the error introduced in the measurement due to temperature changes of the Hall sensors. Consequently, the field oriented controller remains robust even for conditions where the machine internal air temperature reaches 100 degrees Celsius. Experimental results for the rotor currents measured from the Hall sensors arrangement and the normalized components of the rotor flux are presented, showing the practical feasibility of the proposed direct field oriented controller. This scheme does not require an incremental encoder for rotor position sensing.

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$$\frac{d\lambda_n}{dt} + \omega_n \lambda_n + i_a r_r = 0$$