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A NEW FIELD ORIENTED CONTROLLER UTILIZING SPATIAL POSITION MEASUREMENT OF ROTOR END RING CURRENT

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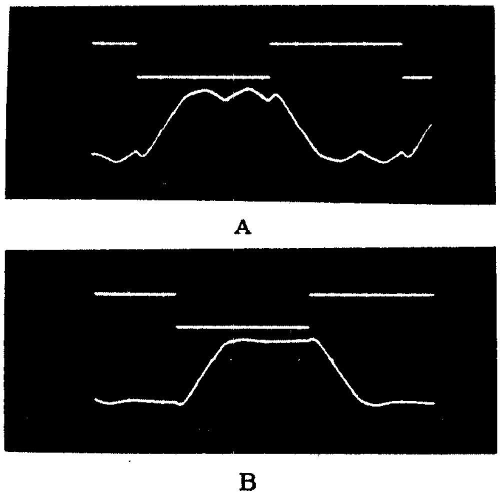
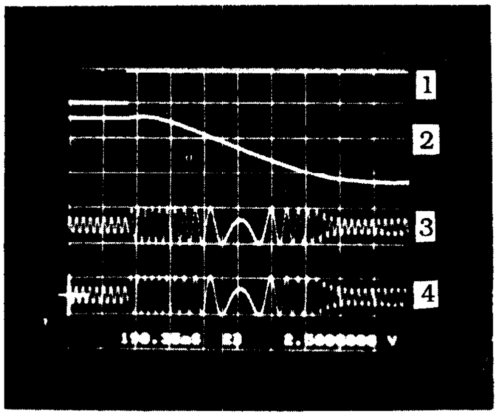
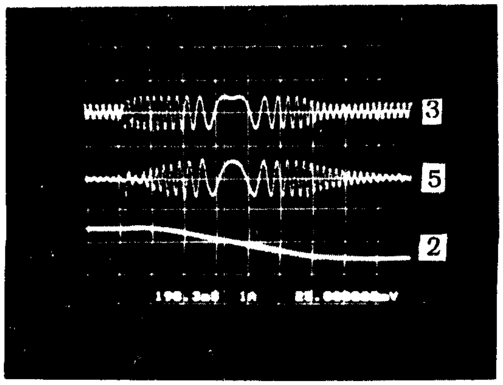


Fig. 10 Waveforms of Speed Command and Actual Speed for Step Reversal in Speed Command. Rotor Time Constant Assumed to be in Error by a Factor of Two. A) With Conventional Field Oriented Control, B) with F.O.C. and the Angle Correction Signal of Fig. 4. Top Trace: Speed Command, Bottom Trace Speed Response from -700 RPM to 700 RPM. Time Scale 793.4 ms/div.





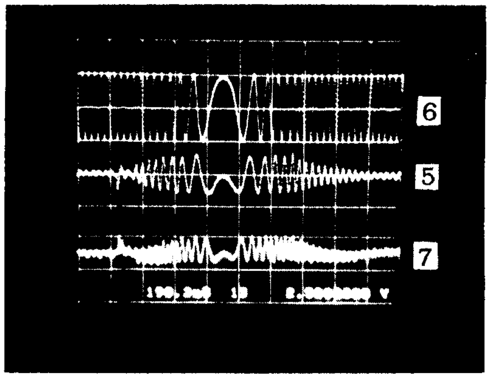


Fig. 11 Detailed Waveforms for Step Reversal in Speed Command. Same Conditions as Fig. 12 B). Trace #1: Speed Reference, Trace #2: Actual Speed, Trace #3: Stator Current, Scale 50A/div., #4: Stator Current Reference, Scale 25V/div., #5 Rotor Current, Unscaled 2.5 V/div, Scaled 50A/div, #6 Cosine Reference Signal, Scale 10 V/div, #7 Output of Multiplier Multiplying (5) and (6), Scale 25 V/div, Time Scale 198.3ms/div.

CONCLUSION

In this paper several new types field oriented controllers have been presented. The control concept utilizes the measurement of the rotor end ring current phase position but not the measurement of the current amplitude. The primary advantage over previous controllers is the elimination of the inaccuracies in the hall probes produced by temperature variations. In this manner the field oriented controller remains robust in a machine for internal air temperature environments reaching 150 degrees celsius.

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ABSTRACT

The preferred method of fast response induction motor control 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. However, the rotor resistance varies over a wide range as the motor heats up operation thereby changing the rotor time constant and having a detrimental effect on the torque transient response. In this paper a new approach to induction motor field oriented control is proposed which utilizes measurement of the spatial position but not amplitude of the rotor end ring currents. Since drift problems cause significant errors in the amplitude measurement inherent in previous schemes the new method is therefore considerably more robust than previously reported controllers. The motor torque can be accurately controlled even down to zero frequency operation. The controller is also completely independent of rotor time constant variations.

INTRODUCTION

The principle of field oriented control is now well established as the standard upon which all induction motor torque controllers are compared, if not, in fact, based. The preferred method of control 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 [1]. The slip frequency is calculated through a non-linear block which is dependant 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 deleterious 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.

Another method of control, termed direct field orientation, is possible [2]. In this scheme, torque is controlled by measuring stator current and air gap flux and, from these measurements, estimating the amplitude and position of the rotor flux. 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 difficult.

In this paper a new approach to induction motor field oriented control is proposed which removes the dependance of the controller accuracy on temperature. The system is therefore considerably more robust than previously reported controllers. The motor torque can be accurately controlled even down to zero frequency operation. The controller is also completely independent of rotor time constant variations.

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 is to properly adjust the in-phase (d-axis excitation component) and out-of-phase (q-axis torque

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component) spatial components of stator current relative to the rotor flux linkage vector as shown in Fig. 1.

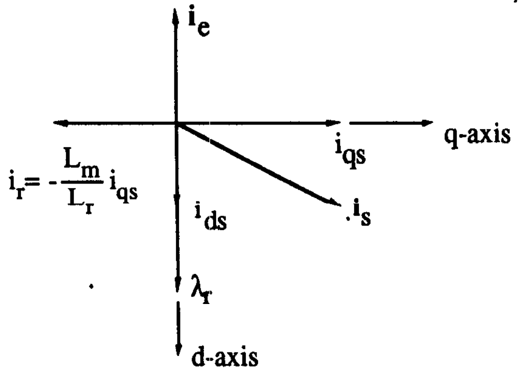


Fig.1. d-q Representation of Spatial Position of Machine Variables.

It is interesting and important to note from Fig. 1 that the rotor flux linkage vector is always precisely 90 degrees out of phase with the rotor current vector. This result is inherently due to the fact that the voltage across the rotor resistance is equal to the time rate of change of rotor flux linkages. In addition, it is well known that the rotor end ring current produces an MMF distribution whose amplitude is spatially at right angles with the amplitude of the rotor bar current when expressed in electrical degrees. Hence, the current vector representing the rotor end ring current becomes co-linear with the rotor flux linkage vector as illustrated in Fig. 1.

CONCEPT OF ROTOR END RING CURRENT VECTOR AND UTILITY FOR MOTOR CONTROL

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 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, hall sensors are very susceptible to drift so that an accurate measurement of rotor current over a wide operating condition is difficult. Hence, previous direct controllers utilizing rotor current measurement suffer deterioration in performance due to temperature changes in much the same manner as the indirect field controller.

This problem can be overcome by using the sensed signal to determine only the position of the rotor end ring current and, consequently, the position of the rotor flux density (rotor flux linkage). Hence, the controller becomes unaffected by the changes of the characteristics of the hall sensors with temperature. A practical control scheme utilizing this concept is shown in Fig. 2. In this example, two hall sensors located near the rotor bars and spaced by 90 electrical degrees sense the rotor leakage flux and therefore the bar currents at these two points. The signals are normalized by their amplitude to form the sine and cosine of the rotor flux position as shown in detail in Fig. 3(a). These two sinusoidal variations can be used to transform

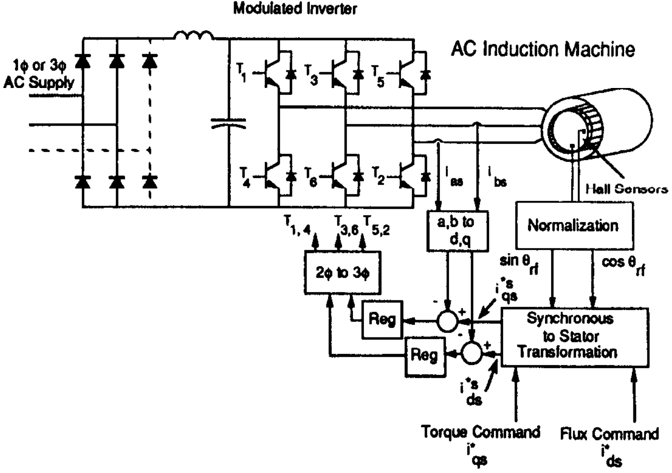


Fig. 2 Direct Field Oriented Controller Using End Ring Current Position Sensing

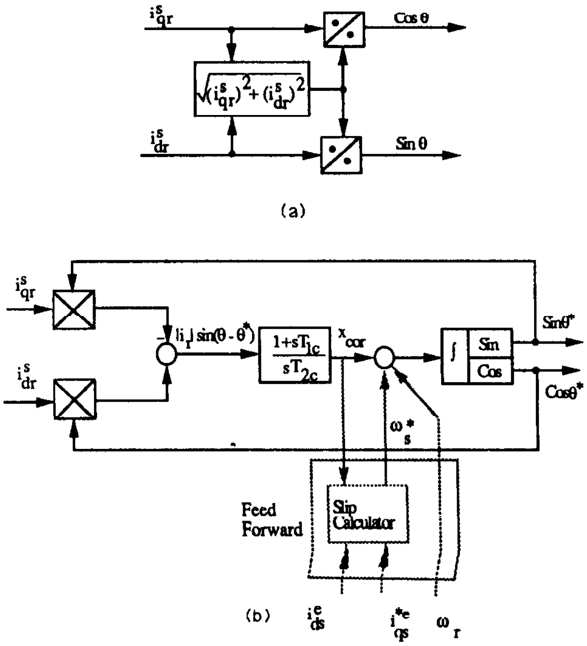
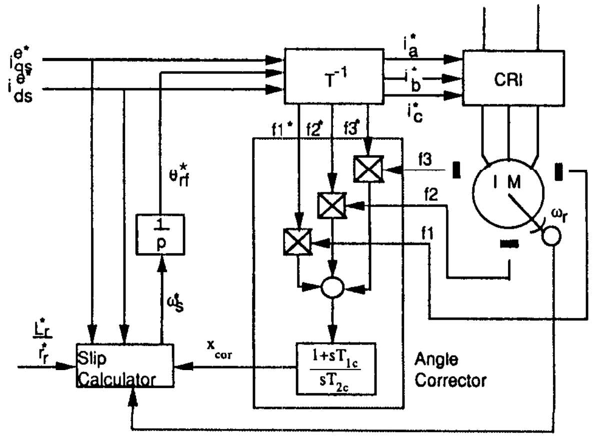


Fig. 3 Methods for forming sine and cosine of the rotor flux position, A) Direct Method, B) Method utilizing PLL.

the stator current for torque command and flux command expressed in the synchronous frame to equivalent command currents in the stationary reference frame. The resulting command currents are summed with the actual measured currents in d,q form and regulated with a pulse width modulated inverter in the usual manner to form a stator current source of the desired amplitude and phase with respect to the rotor flux linkage.

An alternate scheme for obtaining sine and cosine of rotor flux position is shown in Fig. 3(b). This scheme has good filtering capabilities of the high frequency components [6] and has constant and stable amplitude of the output signals. In this approach hall sensor signals are multiplied by the sine and cosine of the commanded rotor flux angle. A signal is thus obtained which, when fed through a PI controller, zeros any error between the commanded and the real rotor flux position. By feeding forward the computed rotor flux position angle, the dynamics of the PLL scheme in Fig. 3(a) can be improved. As in indirect feed forward orientation control this angle can be calculated on the basis of calculated slip frequency and rotor speed. Therefore, the output signal from the PI controller in Fig. 3(a) can be considered as a correction signal which for a properly adjusted feed forward slip controller tends to zero. The correction signal can also be used for a slip calculator gain adjustment. Thus, changes of the slip controller gain due to temperature variations are compensated.

Although the PLL scheme in Fig. 3.(a) has good filtering properties, additional measures can be used to eliminate the presence of non-fundamental components in sine and cosine signals. Probably most severe is the third harmonic and its multiples which arise due to saturation of the machine. This problem can, however, be eliminated by utilizing three hall sensors in a three phase arrangement as shown in Fig. 4. In this case, third harmonic and other triple components are nulled out when the three product terms are summed.



$f1^* = \cos\Theta^*_{rf}$ $\quad f2^* = \cos(\Theta^*_{rf} - 2\pi/3)$ $\quad f3^* = \cos(\Theta^*_{rf} + 2\pi/3)$

$f1 = i_r \sin\Theta_{rf}$ $\quad f2 = i_r \sin(\Theta_{rf} - 2\pi/3)$ $\quad f3 = i_r \sin(\Theta_{rf} + 2\pi/3)$

Fig. 4 Compensation Schematic Eliminating the Effect of Third Harmonic Due to Saturation

EXPERIMENTAL AND COMPUTED RESULTS

Figure 5 shows an experimental trace of the rotor bar current as measured by the hall probes. 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 accomplish a transformation of variables from a rotating to a stationary reference frame. This trace is essentially identical in form to the simulation traces for rotor currents obtained in the stationary reference frame for this machine [9]. Figure 6 shows an experimental x-y trace of the two components of the hall probe measurements plotted one versus the other during the initial starting period of the induction machine. Note that the trace rapidly assumes a circular trace indicating a good phase balance between the two components. Figure 7 shows an expanded trace of the rotor end ring current measurements for a rated load condition. Note that the two signals are very nearly balanced and are phase displaced by 90 degrees.

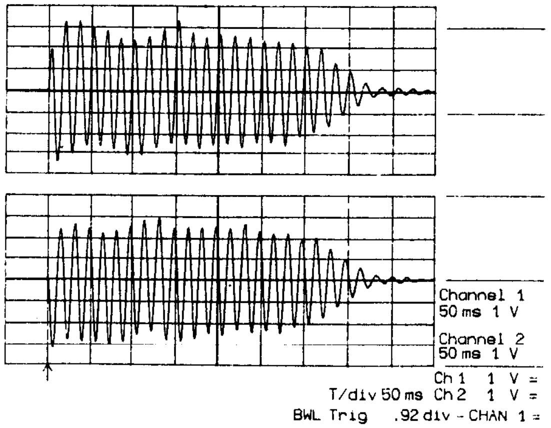


Fig. 5 Experimental Measurement of End Ring Flux using Hall Probe Sensors.

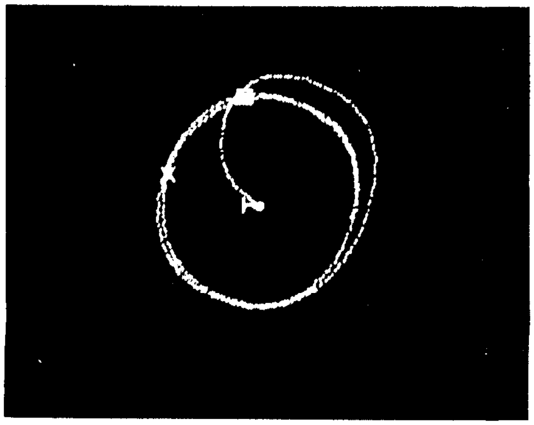


Fig. 6 x-y Plot of the Two Components of End Ring Flux (End Ring Current) During Initial Portion of Starting Transient.

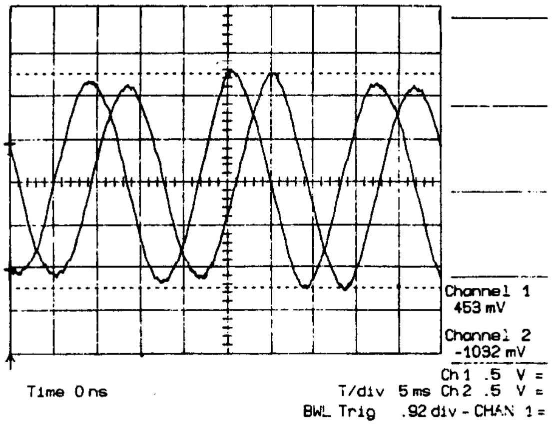


Fig. 7 End Ring Currents During Rated Load Condition at Rated Speed.

Typical simulation traces of an indirect field oriented controller are shown in Figs. 8 and 9. In Fig. 8 is shown the starting transient, acceleration and subsequent loading of a particular 7.5 HP, 60 Hz, 4 pole induction machine when the slip estimator of the basic indirect field oriented controller of Fig. 4 is incorrectly set to twice the correct slip frequency. The power converter used as a part of this simulation is a high frequency ac link converter [10]. Note that the d-axis current is substantially in error resulting in extended acceleration time and overshoot upon reaching the commanded speed. In Fig. 9 is shown the same starting transient, acceleration and subsequent loading with the compensation signal of Fig. 4 in service. Note that the d-axis rotor current is rapidly zeroed with nearly ideal transient response.

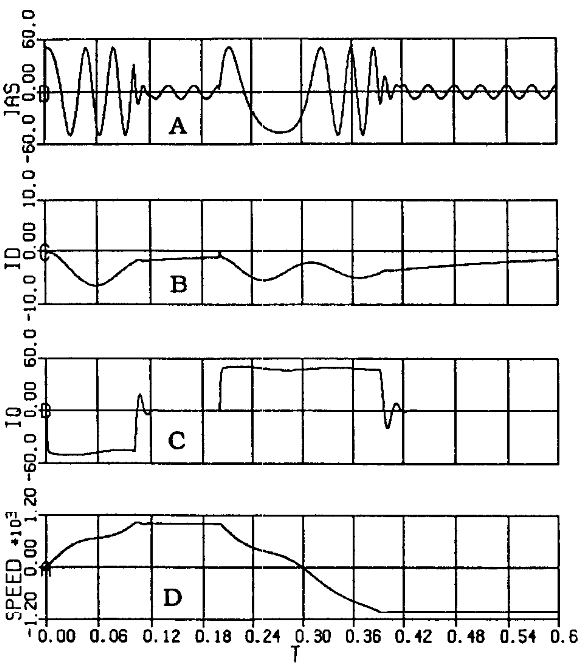


Fig. 8 Energization Transient, Acceleration and Subsequent Loading of a 7.5 HP Induction Motor with Indirect Field Oriented Control. Slip Calculator Assumed to be in Error by a Factor of Two - A) Stator Current, B) q-Axis Rotor Current, C) d-Axis Rotor Current, D) Speed.

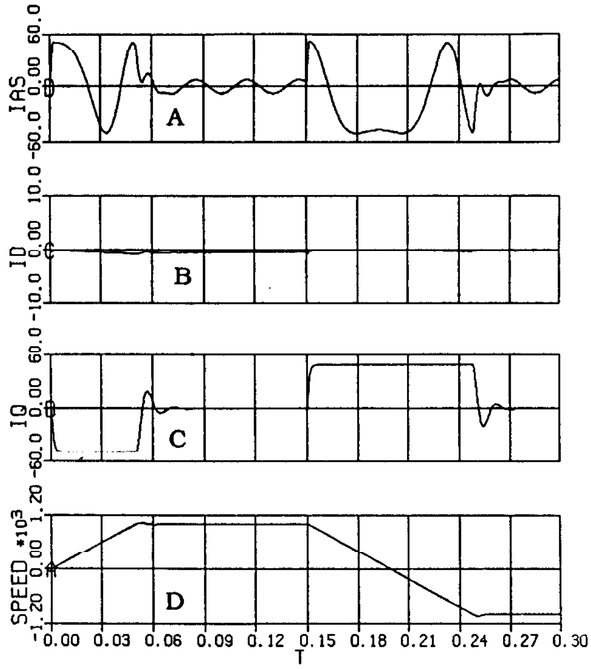


Fig. 9 Energization Transient, Acceleration and Subsequent Loading of a 7.5 HP Induction Motor with Indirect F.O.C. and Feedback Correction Utilizing Hall Sensors - A) Stator Current, B) q-Axis Rotor Current, C) d-Axis Rotor Current, D) Speed.

Figures 10 and 11 show experimental results obtained on actual hardware. In particular, the 7.5 HP, 60 Hz, 4 pole machine simulated in Figs. 8 and 9 was used at the tested motor. Again the feed forward controller was incorrectly set to twice the correct slip frequency. In this case instabilities in operation were actually noticed at light loads during speed reversals as shown in Fig. 10 A). Applying the nonlinear feedback loop with the angle correction signal, see Fig.4, the instabilities disappeared, Fig. 10 B). Traces of important system variables during reversing of the induction machine drive for a step change of speed reference with the rotor angle position feedback signal in service is presented in Figure. 11. Excellent regulation of all variables can be observed.

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