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ABSTRACT

The purpose of this work is to investigate and implement a new adaptive controller for correction of the rotor time constant necessary for the calculation of the slip frequency in Indirect Field Oriented Control (IFOC) of Induction Machines. The implementation of the controller is based on the machine airgap field flux which is measured by detecting the third harmonic component of the stator phase voltages. The proposed adaptive controller depends only on a single, easily measurable machine parameter estimate, namely the magnetizing inductance. Moreover, a correction strategy to compensate for changes of the magnetizing inductance when changes in the airgap flux level occur is also proposed in this work. Such strategy is based on a function which relates the value of this inductance to the amplitude of the third harmonic stator voltage component. This new controller does not require any sensors in the airgap of the machine nor does it require complex computations of machine parameters. Only access to the stator neutral connection is necessary to measure the airgap flux. Verification of the validity and feasibility of the technique is obtained from simulation and preliminary experimental results.

INTRODUCTION

Many methods presented in the recent literature have been proposed to circumvent the problem of detuning of the slip calculator gain when employing Indirect Field Oriented Control (IFOC) of induction machines [1-7]. Identification, estimation and adaptation schemes have been employed in these works with the sole intent to correct the rotor time constant used as a reference value in the calculation of the slip frequency. In the majority of these studies, the rotor time constant is corrected by means of schemes which depend upon a multitude of other machine parameters such as the magnetizing inductance, stator and/or rotor leakage inductances and even on the stator winding resistance. Dependance of a reference model adaptive controller on machine parameters can be minimized when a convenient machine variable is chosen to be the reference model. In this sense, the rotor flux would be the ideal variable to measure and utilize in the correction for variations of the rotor time constant without the need of any machine parameter. Such a procedure, however, requires the installation of Hall-Effect sensors to measure the rotor flux which would preclude the utilization of the indirect type of field orientation here proposed since it would then be more desirable to simply implement a Direct Field Orientation controller. The next variable closest to the ideal case represented by the choice of the rotor flux, is the airgap flux. With the airgap flux one needs only the knowledge of the magnetizing inductance of the machine to establish an adaptive controller for the rotor time constant.

It is shown in this paper that a third harmonic airgap flux component exists due to the saturation of the stator magnetic material when zero sequence stator currents are not allowed to circulate. This harmonic flux component induces a third harmonic zero sequence voltage component in the stator phases which is a function of the amplitude of the airgap flux and the winding configuration of the stator phases. When the three phase voltages are summed, the fundamental and characteristic harmonics are cancelled and the resultant wave form contains mainly a third harmonic together with higher frequency components due to the rotor slots [8].

The method described in this work proposes an original approach to measure the airgap flux from the third harmonic contents of the stator voltages. An adaptive scheme is implemented which will at the same time adapt for rotor time constant as well as magnetizing inductance estimates. The airgap flux measured from the third harmonic contents of the stator phase voltages is resolved into its d and q components, with the d component being utilized in the adaption scheme for the rotor time constant while the magnitude of the flux adapts the magnetizing inductance estimate.

MEASUREMENT OF AIRGAP FLUX FROM THE THIRD HARMONIC CONTENTS OF MACHINE PHASE VOLTAGE

The adaptive controller proposed in this paper is

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based on the estimation of the d-axis rotor flux component from the airgap flux which is obtained, in turn, from the third harmonic content of the stator phase voltages. A brief discussion of the machine operating principles introducing the method of measuring the airgap flux devised in this research is presented in [8]. Therein, the authors demonstrate that a dominant third harmonic airgap flux component is produced in the airgap as a consequence that the stator teeth of the machine are normally (as a machine design option) operating in a saturated condition. As the stator teeth begin to saturate, the teeth with the highest flux density will saturate first so that the flux distribution around the airgap will assume a flattened sinusoidal form with peak value B_{sat} as shown in Fig. 1.

The flattening of fundamental component of the airgap density is produced primarily by a third harmonic component which has its origin in the non-linear magnetic characteristic B-H curve of the magnetic material utilized in the machine. The airgap flux will have, at any instant of time, the same spatial distribution around the airgap provided that the machine is balanced and operating in a normal balanced condition. Therefore, the third harmonic flux component rotates with the fundamental component, both at synchronous speed [9].

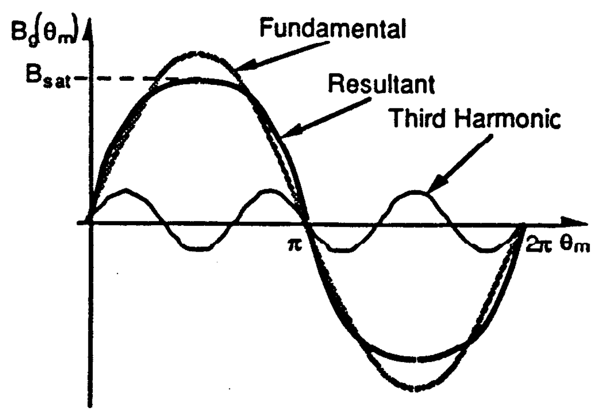


Fig. 1 - Actual Flux Density Distribution Around the Airgap of an Induction Machine (Heavy Line). Its Fundamental Component and Third Harmonic Components are also Shown.

This synchronously rotating third harmonic flux density component will link the stator windings and a third harmonic voltage will be induced in each one of the phases. The third harmonic induced voltages are all in phase forming a zero sequence set and consequently the line voltages will be free of these components.

The amplitude of the induced third harmonic phase voltages is a function of the saturation level which is dictated by the amplitude of the fundamental component of the airgap flux. In addition, the amplitude of these harmonics is also a function of the stator winding configuration and the third harmonic airgap flux will link the stator windings only if a corresponding third harmonic winding function exists. In other words, in order to have induced third harmonic voltages the winding harmonic distribution and/or harmonic pitch factors for the third harmonic of the winding distribution function must be different from zero [10], [11].

If the machine phases are connected in wye without a neutral connection, no zero sequence components (triplen harmonics in a three phase system) will exist in the current. Also, if the rotor cage is assumed to be equivalent to a delta winding connection, the induction machine can be viewed as an ungrounded three phase wye-delta transformer where no circulation of zero sequence current is possible in the wye side. Therefore, the stator currents, and consequently the airgap mmf, will contain only the so called characteristic harmonics (5^{th}, 7^{th}, 11^{th}, and so on), while the airgap flux and, consequently, the phase voltages contain the triplens and higher frequency slot components.

It can be shown that the rotating third harmonic flux component will also induce a complete polyphase set of currents in the rotor circuit of the machine, which will contribute to the rotor losses and torque production. However, the induced third harmonic currents in the rotor are very small compared to the fundamental component and consequently the airgap third harmonic flux component is not disturbed in any practical way by the load condition of the machine.

A more detailed analysis of the generation of the third harmonic stator voltage for a saturated machine is appropriate at this point. Taking into account only the fundamental and third harmonic components for the airgap flux density when the machine is under the saturation condition, and neglecting the influence of the rotor third harmonic currents, the resultant air gap field flux density, $\mathbf{B}_{st}$, is expressed by the vectorial sum of the three phase flux components according to:

$$\mathbf{B}_{st} = \mathbf{B}_{as} + \mathbf{B}_{bs} + \mathbf{B}_{cs}\,, \tag{1}$$

or,

$$\mathbf{B}_{st} = \frac{3}{2}\mu_0\, k_e\, N_{s1} I_s \cos(\theta - \theta_e) + -\frac{3}{4}\mu_0\, k_m\, N_{s1} I_s \left[\cos(\theta - \theta_e) + \cos(3\theta - 3\theta_e)\right] \tag{2}$$

Equation 2 above shows that the airgap field constitutes of two travelling waves: the fundamental component traveling in the airgap at synchronous frequency, ω_e, and the third harmonic which travels at three times the synchronous frequency. The flux linking the stator phase a, for instance, is obtained from the integral of the product of expression above for the air gap flux density, and the stator phase-a winding function, $N_{as}(\theta)$.

$$\lambda_{as} = \frac{3}{2}\mu_0 rl\left[k_e N_{s1}^2 I_s \cos\theta_e - \frac{1}{2}k_m N_{s1}^2 I_s \cos\theta_e - \frac{1}{2}k_m N_{s1} N_{s3} I_s \cos 3\theta_e\right] \quad (3)$$

Moreover, the phase voltage is given by

$$v_{as} = \frac{3}{2}\mu_0 rl\left[-\omega_e k_e N_{s1}^2 I_s \sin\theta_e + \frac{1}{2}\omega_e k_m N_{s1}^2 I_s \sin\theta_e + \frac{3}{2}\omega_e k_m N_{s1} N_{s3} I_s \sin 3\theta_e\right] \quad (4)$$

where the following symbols are defined:

- k_e constant related to the air gap length,
- k_m constant related to the saturation level,
- r air gap mean radius,
- l equivalent machine stack length,
- N_{s1} winding factor for the fundamental component of the winding function,
- N_{s3} winding factor for the third harmonic component of the winding function,
- I_s stator current amplitude,
- ω_e synchronous speed,
- θ_e electrical angle,
- θ angular position around the airgap.

It is evident from the expression above that the third harmonic voltage component of the stator phase voltage has a fixed phase relationship with the fundamental air gap flux and that its amplitude is a function of the amplitude of the fundamental flux component.

ADAPTIVE CONTROLLER FOR THE ROTOR TIME CONSTANT BASED ON THE STATOR VOLTAGE THIRD HARMONIC CONTENTS

When the three stator phase voltages are summed, the fundamental and characteristic harmonics are cancelled and the resultant wave form contains mainly a third harmonic together with high frequency components due to the rotor slots. This resultant term is produced by the third harmonic of the airgap flux which clearly maintains a constant position in respect to the fundamental flux component. Therefore, the third harmonic component of the zero sequence voltage can be used to locate the instantaneous position of the airgap flux as well as to estimate its fundamental amplitude. The signal is a sine wave, practically free from the noise and fast transitions that characterize the line (or phase) voltage signals.

The amplitude of the fundamental of the airgap flux component, $|\lambda_m|$, is obtained from the third harmonic component of the stator flux linkage which is obtained by integrating the third harmonic stator voltage v_3. The amplitude then of the fundamental component of the flux linkage is expressed in terms of the third harmonic flux component via a non-linear function, f_λ.

$$|\lambda_m| = f_\lambda(|\lambda_3|) \quad (5)$$

Figure 2 shows the relationship between the airgap fundamental flux component, $|\lambda_m|$, and the third harmonic flux component, $|\lambda_3|$, obtained from the stator third harmonic voltage, plotted here for a 3-hp induction machine described in the Appendix at the end of this paper.

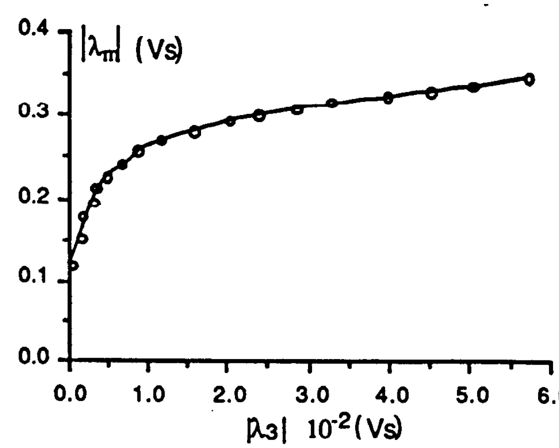


Fig. 2: Function Relating the Fundamental Component of the Airgap Flux with the Amplitude of the Third Harmonic Flux Component for a 3-hp Induction Machine Described in the Appendix.

The relative position of the fundamental component of the airgap flux with respect to the stator current is obtained by measuring the phase displacement between two fixed points in the third harmonic flux and line current. Figure 3 shows this phase displacement represented by the symbol γ_{im}, with the two reference points in the line current and third harmonic signal taken so that γ_{im} corresponds to the phase displacement between the maximum values of current and airgap flux fundamental components.

The fundamental and third harmonic components airgap flux, and the stator current are depicted in Fig. 4 in a synchronously rotating reference frame representation for a condition of field orientation. It is clear from this vector arrangement that the airgap flux can be resolved into its d and q components with the knowledge of its magnitude and the angles γ_{im} and θ_{is}.

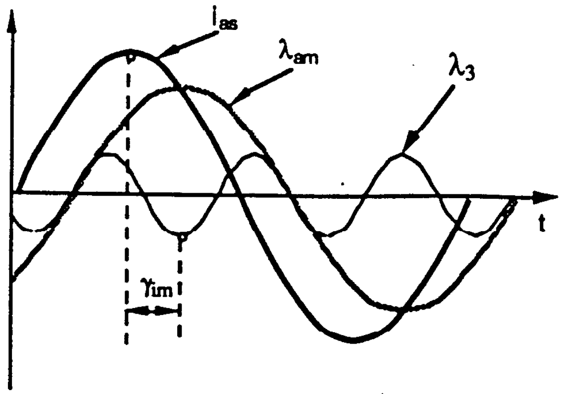


Fig. 3: Fundamental Components of Stator Line Current, i_{as} , and Airgap Flux Fundamental (λ_{am}) and Third Harmonic (λ_3) Components. The Phase Displacement for the Stator Current and Airgap Flux is Represented by the Angle, γ_{im}.

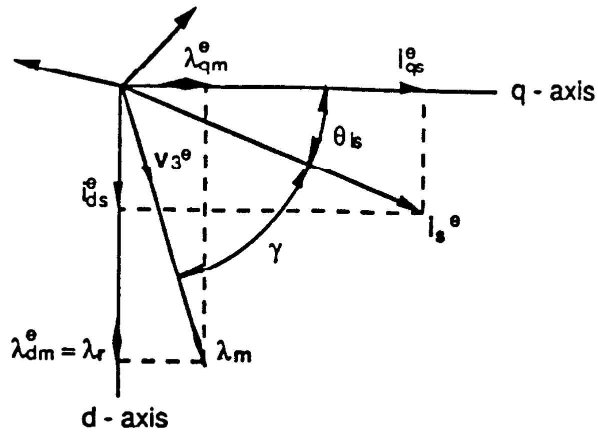


Fig. 4: Stator Current, Airgap Flux, and Third Harmonic Voltage Vectors for a Field Orientation Condition in the Synchronous Reference Frame.

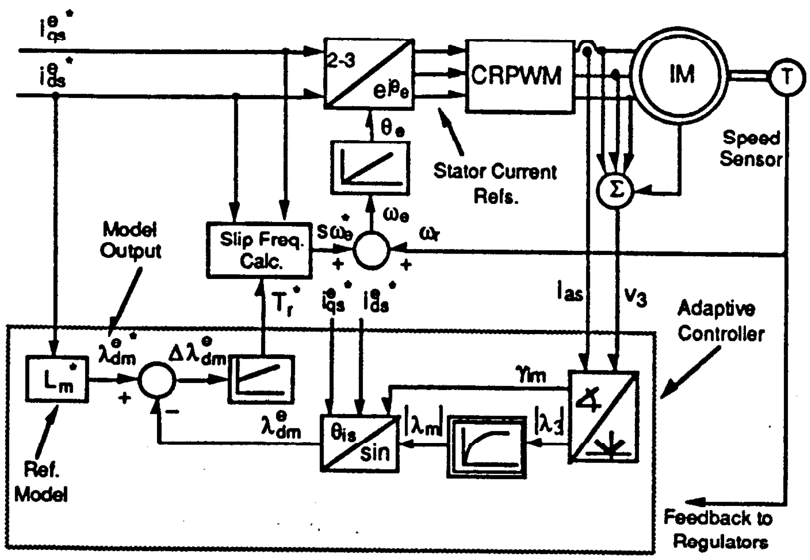


Fig. 5: Configuration for Implementation of the Rotor Time Constant Correction Scheme.

The d -axis component of the airgap flux, which corresponds to the rotor flux when the machine is field oriented, is then computed as,

$$\lambda_{dm}^e = -|\lambda_m^e| \sin(\theta_{is} + \gamma_{im}) = -f_\lambda (|\lambda_3^e|) \sin(\theta_{is} + \gamma_{im}) \qquad (6)$$

with θ_{is} computed from the reference values for the stator currents, i_{qs}^{e*} and i_{ds}^{e*} as indicated by Eq. 7,

$$\theta_{is} = -\tan^{-1}\left(\frac{i_{ds}^{e*}}{i_{qs}^{e*}}\right) \qquad (7)$$

The airgap flux d -axis component computed from

Eqn. (6) above is utilized by the adaptive controller which can be viewed as a Model Reference Adaptive Controller (MRAC) approach [2, 4, and 14]. Figure 5 shows the proposed configuration for implementation of the rotor time constant correction scheme.

The simplicity of the controller reference model is the key point in this implementation. The controller only requires an estimate for the magnetizing inductance, L_m^* in order to set the flux reference which, together with the flux computed as in (6), define the flux error signal, $\Delta\lambda_{dm}^e$. This error is driven to zero by the flux controller as the rotor time constant, T_r^*, is adjusted to its correct value. The simplicity achieved for the reference model in the controller scheme presented in Fig. 5 is possible only due to the choice for the model output chosen, λ_{dm} in this case.

In spite of the simplification obtained, the controller still depends on the magnetizing inductance, a parameter that very likely will change with changes in the machine operation conditions. Changes in the magnetizing inductance are associated with the airgap flux level, which is a function of the stator current d - q components. Therefore, changes in the torque or flux commands will change the airgap flux level and consequently the magnetizing inductance, especially if the machine operates in the non-linear segment of the magnetization characteristic curve.

Fortunately a function relating the actual value of the magnetizing inductance and the magnitude of the third harmonic flux component can be readily obtained from the the function relating the airgap flux amplitude and third harmonic flux amplitude described by f_λ in Eqn. (5). Hence, a function, designated as f_{Lm}, is thus obtained,

$$L_m = f_{L_m}(|\lambda_3|) \tag{8}$$

and Fig. 6 presents this function obtained experimentally for a 3-hp induction machine.

This function relating L_m and $|\lambda_3|$ is easily incorporated in the controller in Fig. 5 and the resulting adaptive control scheme becomes independent of variations of the magnetizing inductance. Figure 7 shows the new controller strategy for correcting the rotor time constant.

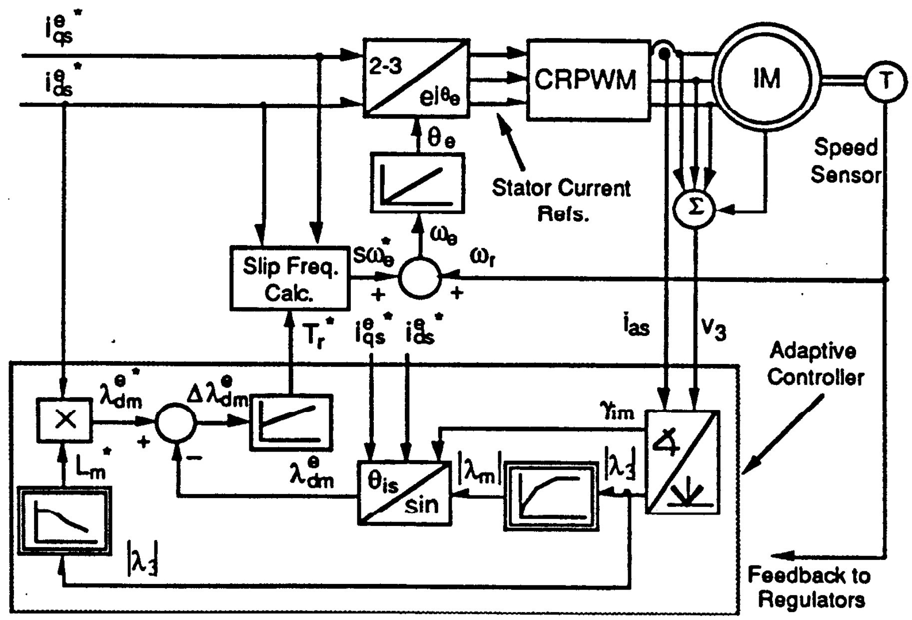


Fig. 7: Implementation for the Rotor Time Constant Correction Scheme with Correction for the Magnetizing Inductance Estimate Based on the Amplitude of the Third Harmonic Voltage Signal.

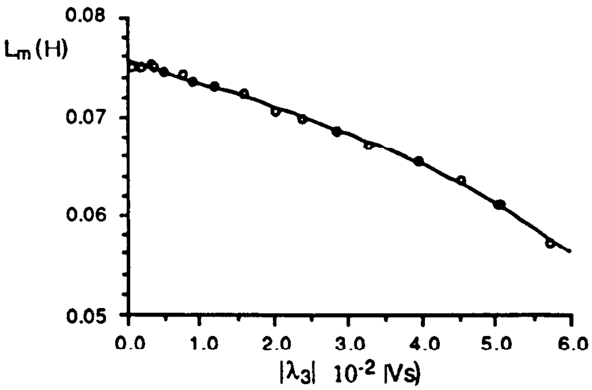


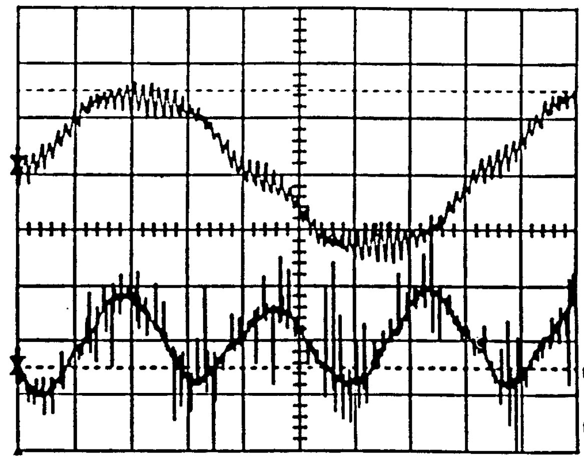
Fig. 6: Magnetizing Inductance for a 3-hp Induction Machine as a Function of the Amplitude of the Third Harmonic Flux Signal.

SIMULATION AND EXPERIMENTAL RESULTS

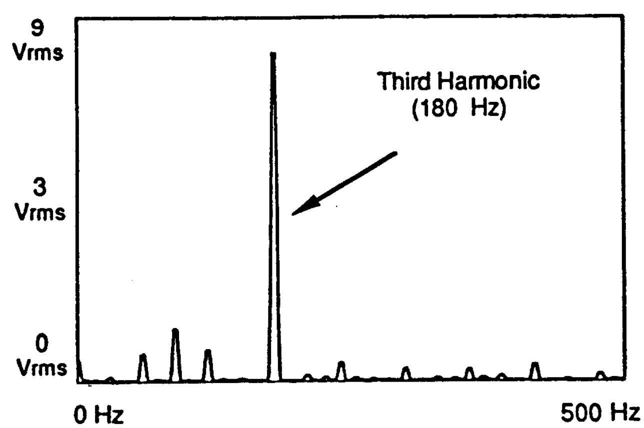
Preliminary experimental results demonstrating the feasibility of the idea of locating the airgap flux via third harmonic stator voltage have been obtained in the laboratory. A 3-hp induction machine described in the Appendix has been chosen for these tests and the simulation procedure described later.

Figure 8 shows the third harmonic stator voltage signal obtained from the summation of the three phase voltages for a no-load operation condition at rated frequency, using a current regulated PWM inverter to supply the induction machine. Figure 8-a shows the third harmonic voltage and one of the line currents. The switching frequency noise in the third harmonic voltage can be easily eliminated by an low pass filter (LPF). Another LPF is used for the current so that the phase displacement between the current and third harmonic voltage is kept at its original value. It can be verified that the two points shown in the figure correspond to the maximum values for the airgap flux and current, since the zero crossing for the voltage wave form corresponds to the maximum value for the flux linkage.

As is expected for a no-load condition, the phase shift between these two points, which represents the phase shift between the fundamental components of airgap flux and stator mmf, is very small since the mechanical output power developed is only to overcome the windage and friction losses. As the machine is loaded this phase shift increases in order to respond to the mechanical torque required by the load. As mentioned before, the relatively small content of high frequency components in the third harmonic signal can be easily eliminated by a simple filter making this signal very convenient for an analog or digital manipulation.



(a)



(b)

Fig. 8: Experimental Results Obtained for a 3-hp, 230 Volts, 4 Poles, 60 Hz Induction Machine. (a) Line Current (Upper Trace: 5 Amps/Div.) and Stator Third Harmonic Voltage (Bottom Trace: 5 Volt/Div.). (b) Third Harmonic Voltage Spectrum (Full Scale of 9.0 Volts-rms).

The spectrum contents for the third harmonic signal is analyzed and shown in Fig. 8-b. As predicted, after the summation of the three phase voltages all the polyphase components (fundamental, 5^{th}, 7^{th}, 11^{th}, and so forth) are eliminated and the third harmonic is clearly the dominant component at the lower side of the frequency spectrum. The PWM inverter utilized for these measurements has a switching frequency around 7.0 kHz and the harmonic content amplitudes around that frequency is comparable with the third harmonic signal and needs therefore to be filtered.

The low frequency spectrum components observed in Fig. 8-b are due to an unbalance in the inverter output voltages and do not represent a fact of concern since their amplitudes are small compared to the third harmonic at all range of the inverter/machine operation.

A digital simulation of the adaptive controller shown in Fig. 7 has been carried out to verify the validity of the rotor time constant adaption method. In particular, a Delta-Current Regulated PWM inverter associated with an indirect field orientation controller has been implemented. The induction machine model includes effects of saturation and also makes provision for the existence of third harmonic stator voltages. Neither speed nor position feedback control is assumed so that the effects of detuning in the torque response can be fully investigated.

The simulation results in Fig. 9 show the evolution for T_r^* , λ_{dm}^e , $\Delta\lambda_{dm}^e$, λ_{qr}^e , T_e , which are respectively the rotor time constant reference value, airgap d -axis component, error in the airgap flux d -axis component, rotor q -axis component, and electromagnetic torque. The trace shows the transient which occurs for an increase of 100% in the rotor resistance at an instant 1.0 seconds after the machine starts from rest at rated flux. These results show that the machine is working essentially under field orientation condition up to the instant when the disturbance occurs in the rotor resistance. As soon as the disturbance occurs the rotor and the airgap flux increase as a consequence of the over excitation produced by the increase in the rotor resistance. The adaptive controller starts then to command the rotor time constant to its new value while driving the airgap flux error to zero. After approximately 1.7 seconds the machine regains the condition of field orientation when the rotor time constant reaches its correct value, while the q -axis component of the rotor flux becomes zero.

CONCLUSIONS

A new and simple method for correcting the rotor time constant in Indirect Field Oriented Control of induction machines is proposed in this work.

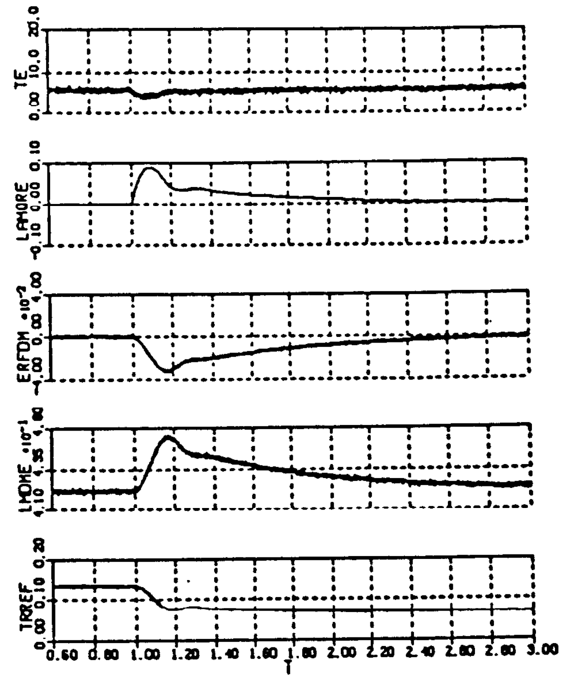


Fig. 9: Simulation Results for the Rotor Time Constant Adaption Scheme as Proposed in Fig. 7. From the Bottom to the Top: Rotor Time Constant, T_r^*, q -axis Component of Airgap Flux, λ_{dm}^e, Airgap Flux Error, $\Delta\lambda_{dm}^e$, d -axis Component of Rotor Flux, λ_{qr}^e, and Torque, T_e , are shown for an Increase of 100% in the Rotor Resistance Occurring at 1.0 second.

The method is based on the measurement of the airgap flux from the third harmonic component of stator voltage. It is shown that due to the machine saturation the airgap flux contains a very strong content of third harmonic which induces a third harmonic voltage in the stator phases. A predominant third harmonic voltage component is obtained when the three stator phase voltages are summed as a consequence of the elimination of the polyphase fundamental and harmonic components. The resulting signal has the advantage of having low levels of noise and high frequency content.

The third harmonic component is then used to determine the resulting instantaneous position of the fundamental component of the airgap flux. The airgap flux is resolved in its d and q -axis components from the third harmonic and line current signals. The d -axis component of the flux is then used as a control signal for the adaptation of the rotor time constant. The controller proposed can be viewed as a Reference Model type where only an estimate of the magnetizing inductance of the machine is necessary for implementation. Furthermore, a correction strategy changes in the magnetizing inductance based on the amplitude of the third harmonic flux signal is also implemented in the controller. This addition is important since the magnetizing inductance is a very sensitive parameter in terms of the airgap flux level, which is a function of load and flux reference conditions.

Preliminary experimental results have proven the feasibility of utilizing the stator third harmonic voltage contents to locate the airgap flux, while simulation results have been used to demonstrate the practicality of the adaption scheme proposed.

APPENDIX

INDUCTION MACHINE PARAMETERS

Quantity	Symbol	Value
Line Voltage	V_l	220 V rms
Output Power	P_o	3.0 HP
Speed	ω_r	1740 rpm
Poles	P	4
Stator Resistance	r_s	1.11 Ω
Rotor Resistance	r_r	0.47 Ω
Stator Leakage Reactance	X_{ls}	1.05 Ω
Rotor Leakage Reactance	X_{lr}	1.05 Ω
Unsat. Magnetizing Reactance	X_m	22.09 Ω
Motor Inertia	J_m	0.0104 Kg-m^2

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