

Direct Field Orientation Control Using the Third Harmonic Component of the Stator Voltage

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ABSTRACT

A new direct field orientation controller for induction machines based on determination of the spatial position of the air gap flux from the third harmonic component of the stator phase voltages is presented in this paper. The control utilizes spatial saturation harmonic components rotating at synchronous frequency which are generated in the air gap flux when the machine operates in a saturated condition. When the machine is wye connected, the sum of the three phase voltages results in a signal dominated by the third harmonic and a high frequency component due to the rotor slot ripple. Two methods of locating the rotor flux from the third harmonic voltage signal for the purpose of rotor field orientation are discussed and proposed. It is also demonstrated that the rotor speed can be obtained as well from the third harmonic voltage signal, which makes the implementation of this direct field orientation strategy very attractive in terms of cost, simplicity and performance. Experimental results showing the nature of the third harmonic voltage signal are presented.

1. INTRODUCTION

The advantages of direct field orientation over the indirect type in overcoming sensitivity of the control to changes in machine parameters has been discussed very thoroughly in the literature [1-4]. However, implementation of the direct type of field orientation has been regarded as being difficult in practice by virtue of the sensors (e.g. search coils or Hall effect sensors) needed for the control. These sensors, besides contributing a considerable amount to the total cost of the controller, often impose limitations on the range of machine operation.

A new direct field orientation controller which uses a minimum number of sensors is proposed in this paper. In particular, the controller proposed requires only access to the neutral point connection of the stator windings so that measurement of the phase voltage can be realized. This neutral connection does not carry machine currents. It is shown that when the machine is in a saturated condition, which is the invariably the case over most of the range of induction machine operation, a third harmonic stator voltage signal is obtained from the summation of the three phase voltages. The air gap flux and the rotor speed are then obtained from this third harmonic voltage signal in a

very reliable manner since the useful signal is large and practically noise free.

2. SATURATION HARMONIC AIR GAP FLUX COMPONENTS

The direct field orientation strategies proposed in this paper are based on the measurement of the air gap flux linkage via the third harmonic voltage component of the stator phase voltages. A discussion of the induction machine principles of operation under saturation and the consequent generation of harmonic components in the air gap flux is presented in [5] and [6]. In these works the authors show that the resultant component of the air gap flux density when the machine is under a saturation condition includes the all odd harmonic components, including the triplens 3rd, 9th, and so forth. These spatial harmonic components are synchronously rotating with the fundamental air gap flux component. Furthermore, it is shown that the third harmonic is the dominant harmonic component and that it is responsible for the induction of a third harmonic zero sequence voltage component in the stator phase voltages.

The concept of synchronously rotating saturation harmonics is illustrated in Figure 1 which depicts the air gap flux components for a condition of saturation occurring in both the stator and rotor teeth. As the stator and rotor teeth begin to saturate, the teeth with the highest flux density will saturate first so that the flux distribution around the air gap will assume a flattened sinusoidal form with peak value B_{sat} as shown in the figure. In addition, for most machines the air gap flux density is also modulated by a high frequency component due to the existence of stator and rotor slots as illustrated in Fig. 1-b. This high frequency component is proportional to the rotor mechanical speed and can be utilized as a means to measure the speed, thereby eliminating the need for a tachometer or an encoder [4].

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 air gap mmf, will contain only the so called characteristic harmonics (5th, 7th, 11th, and so on), while the air gap flux and, consequently, the phase voltages contain the predominant third harmonic and higher frequency slot components.

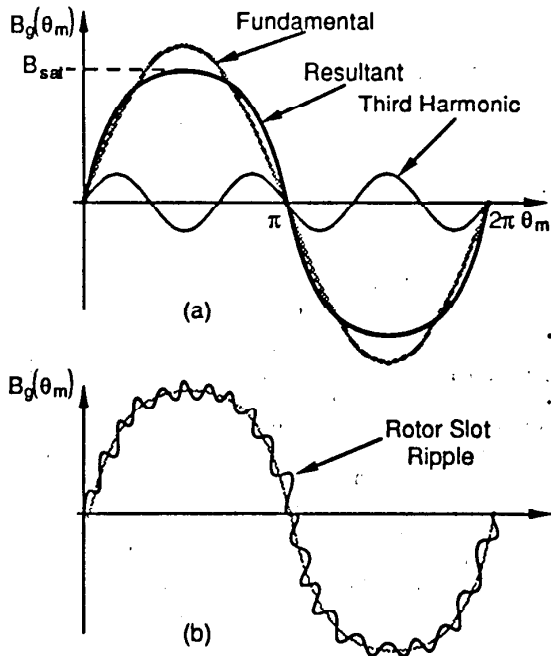


Fig. 1: Air gap Flux Density under Stator and Rotor Teeth Saturation Condition. (a) Fundamental and Third Harmonic Components, and (b) Slot Ripple Modulating the Resultant Air gap Flux.

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 [5], [6]. The amplitude of the induced third harmonic phase voltage is a function of the saturation level which is dictated by the amplitude of the fundamental component of the air gap flux. Therefore, a function relating the third harmonic stator voltage and the air gap voltage exists and it is used to determine the fundamental air gap flux linkage of the machine, λ_{m1} .

3. LOCATING THE AIR GAP AND ROTOR FLUXES FROM THE THIRD HARMONIC SIGNAL

3.1 AIR GAP FLUX ORIENTATION

With the fundamental of the air gap flux linkage located from the third harmonic voltage signal, a direct air gap field orientation strategy can be implemented as a first

intuitive option. In this control scheme, the air gap flux is aligned with the d -axis of the d - q plane with the stator current components i_{qs} and i_{ds} being the command variables for the torque and flux respectively. Unfortunately, this type of field orientation scheme does not allow a complete decoupling between the command variables i_{qs} and i_{ds} , which is only achieved by the introduction of a decoupling network. This decoupling network, however, brings the disadvantage of being dependent on sensitive machine parameters. It also contributes to an increase in the complexity of the control algorithm. Another potential limitation of this type of controller relates to the static stability of the drive which will present a limited pull out torque if a current command is used as the flux control [7].

3.2 ROTOR FLUX ORIENTATION

After eliminating the possibility of air gap flux orientation, the rotor flux orientation strategy becomes as the next best candidate. However, an additional computation is necessary in order to obtain the rotor flux from the air gap flux, as described by Eqs. 1 and 2.

$$\lambda_{qr}^s = \frac{L_r}{L_m} \lambda_{qm}^s - L_{lr} i_{qs}^s \quad (1)$$

$$\lambda_{dr}^s = \frac{L_r}{L_m} \lambda_{dm}^s - L_{lr} i_{ds}^s \quad (2)$$

Although dependent on machine parameters, the rotor flux can be obtained with reasonable accuracy since the rotor leakage inductance, L_{lr} , and the ratio of total rotor inductance to air gap inductance, L_r/L_m , are only moderately dependent on the saturation level.

3.3 LOCATING THE ABSOLUTE POSITION OF THE ROTOR FLUX

A practical problem which arises when implementing the rotor flux orientation control scheme comes from the fact that the air gap flux is not absolutely located by the third harmonic voltage signal which comprises information concerning only the sine or cosine component of the air gap flux (d or q component). Therefore, it is necessary to extend the control methodology to obtain the two quadrature components of the air gap flux.

Figure 2 shows the air gap flux fundamental and third harmonic components together with one of the stator line currents for a loaded machine. Clearly point B in the third harmonic wave locates the maximum of the fundamental component of the air gap flux (point A) which can then be referred to the stator current maximum value (point C) by the angle displacement γ_{im} . Hence, by detecting point A and measuring the angle γ_{im} the absolute position of fundamental air gap flux component can be known. A quadrature oscillator can then be built and synchronized to

the point B in the third harmonic voltage signal and the angle γ_{im} . Therefore, from the third harmonic signal we obtain a sine and cosine signals which argument, θ_f , corresponds to the position of the air gap flux. The rotor flux is then determined as in Eqs. 1 and 2 and the rotor field orientation scheme, Fig. 3, can be implemented.

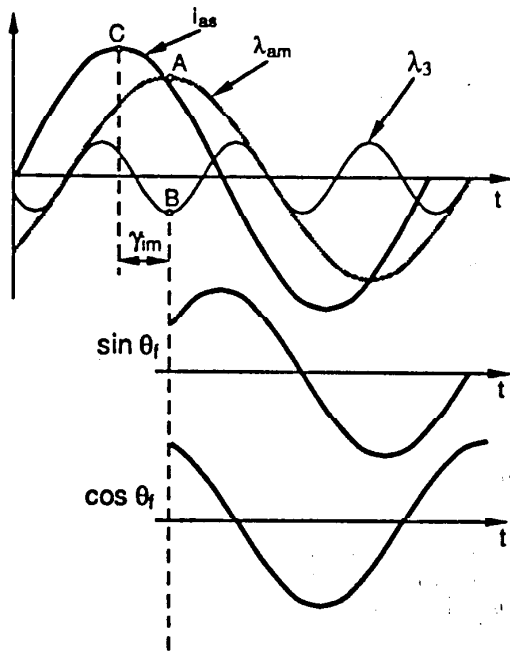


Fig. 2: Air gap Flux and its Third Harmonic Component in Reference to one of the Line Currents. The Sine and Cosine Signals Generated are also Shown.

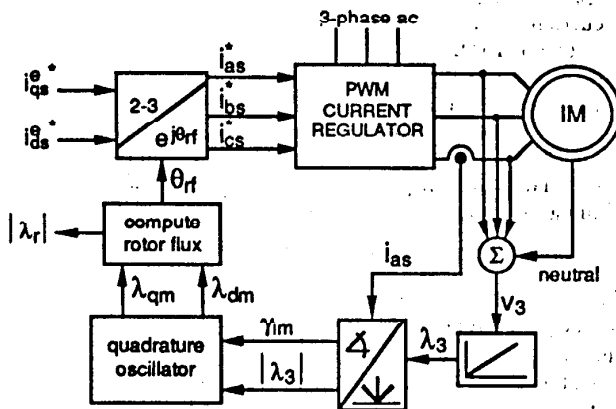


Fig. 3: Implementation of the Direct Rotor Field Orientation Controller by Locating the Position of the Rotor Flux from the Third Harmonic Voltage Signal.

3.4 MEANS OF DRIVING ROTOR FLUX ANGLE TO ZERO

Another solution proposed for the problem of locating the rotor flux from the third harmonic is now proposed. Figure 4 shows the relative positions for the stator current and air gap and rotor flux vectors which when in the synchronous reference frame can be interpreted as phasor quantities. Given the current commands i_{qs}^{e*} and i_{ds}^{e*} the current vector amplitude and angle θ_{is} are computed. The amplitude of the fundamental component of the air gap flux is obtained from the third harmonic flux component via a non-linear function, $f(\lambda)$. This function is obtained experimentally from the no-load test data [6]. The third harmonic flux is derived by a simple integration process of the stator third harmonic voltage, so that the air gap fundamental flux amplitude is expressed as,

$$|\lambda_{amd}| = f_{\lambda}(|\lambda_3|) = f_{\lambda} \left(\left| \int v_3 dt \right| \right) \quad (3)$$

With the angle γ_{im} measured as indicated in Fig. 2, the air gap flux d and q components are determined and the rotor flux is obtained from Eqs. 1 and 2.

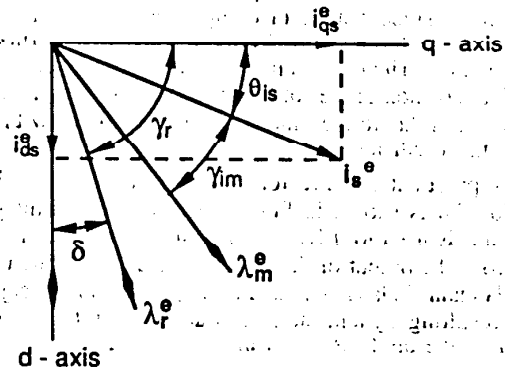


Fig. 4: Stator Current, Air gap Flux and Rotor Flux Vectors Represented in a Synchronous Reference Frame.

In rotor field orientation condition the rotor flux is aligned with the d -axis when the q -axis rotor flux component and the rotor flux angle δ in Fig. 4 becomes zero. The rotor flux orientation can then be achieved by driving, for instance, the rotor flux angle δ to zero by controlling the synchronous frequency, ω_e , applied to the transformation of the stator reference currents from the synchronous to the stationary reference frame. Changes in this frequency will accelerate or decelerate the current vector such that the angle δ is driven to zero. Moreover, since the d and q -axis are fixed with respect to the current components, driving the angle δ to zero has the same effect as orienting the rotor flux with respect to the d -axis, which is clearly the final objective to achieve rotor field

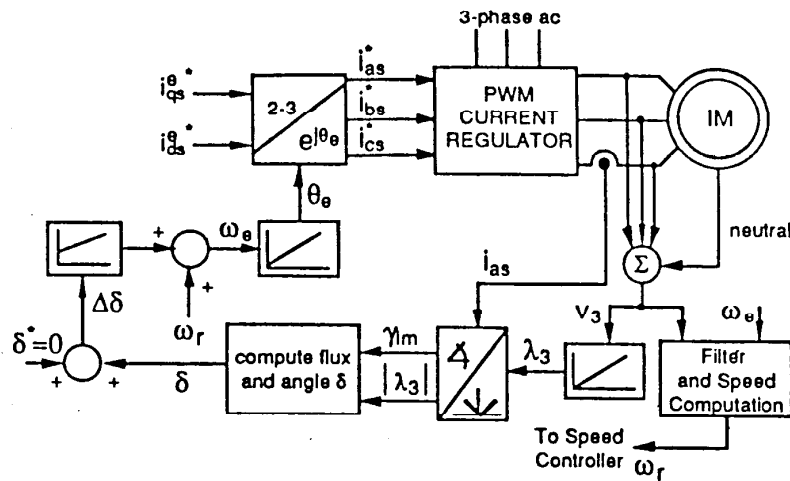


Fig. 5: Direct Rotor Field Orientation Control Implementation by Driving the Rotor Flux Angle δ to Zero.

orientation. As an alternative, the q-axis component of rotor flux can be driven to zero which achieves the same result in, perhaps, a more direct fashion.

A non-ideal torque response is expected for both controllers since delays in computing the air gap flux amplitude and the angle between current and flux is unavoidable. The method proposed for the location of the absolute position of the rotor flux vector will present even more delays due to the time constants associated with the quadrature oscillator.

A practical scheme for the controller proposed in Section 3.4 is shown in Fig. 5. A proportional-integral regulator is used to drive the error in the rotor angle, $\Delta\delta$ to zero. The output of the regulator is added to the rotor speed obtained also from the third harmonic voltage signal. The resulting synchronous frequency is integrated to generate the angle θ_e used in the transformation of the stator current references.

Since the feedback signal contains not only a third harmonic component but also a high frequency ripple component due the rotor slots, speed control can be implemented without the need of an external speed sensor as shown in the scheme in Fig. 5. Since an additional speed sensor becomes unnecessary, this approach could contribute markedly to a reduction in the overall controller cost. In Fig. 5 the rotor slot ripple signal, v_{slot} , which modulates the third harmonic voltage signal, is isolated by means of a band pass filter having a variable center frequency. A switched capacitor filter controlled by the synchronous frequency ω_e is utilized for this end as in [4] and [5]. The rotor speed is derived from,

$$\omega_r = \frac{\omega_{slot} - \omega_e}{n_r} \quad (4)$$

where,

ω_r rotor speed in electrical rad/s

ω_{slot} slot ripple frequency in rad/s

n_r number of rotor bars.

The accuracy for the speed signal is strictly a function of the number of rotor bars. The amount of skewing for the rotor bars and the type of rotor slot (open or enclosed) are factors determining the amplitude of the rotor slot ripple. Experimental results have shown that the speed can be predicted with reasonably good accuracy for the test motors used in this research.

4. SIMULATION RESULTS

Simulation and some experimental results are obtained for 3 HP, 230 Volts, 4 poles induction machine. Figure 6 shows the third harmonic voltage signal and one of the motor line currents obtained when the machine is driven by a current regulated pwm converter. The spectrum components for the third harmonic stator voltage signal is also shown. As described above, this signal is the result of the summation of the three stator phase voltages. As predicted, the third harmonic is the dominating component followed by the inverter switching frequency and rotor slot ripple. Note that all polyphase spectrum components are eliminated by the summation process.

Figure 7 presents simulation results for the direct rotor field orientation controller proposed in Section 3.4. Variables shown in the Fig. 7 represent the reference for the torque current component i_{qs}^* , torque, rotor q-axis flux component and the rotor angle δ . Rated values for flux and torque current component commands are used. The system transient behavior is very good, especially regarding to the torque transient response. A complete field orientation condition is achieved after approximately 300 mS from the change in the torque command. A practical implementation of this controller is under way and experimental results will soon become available.

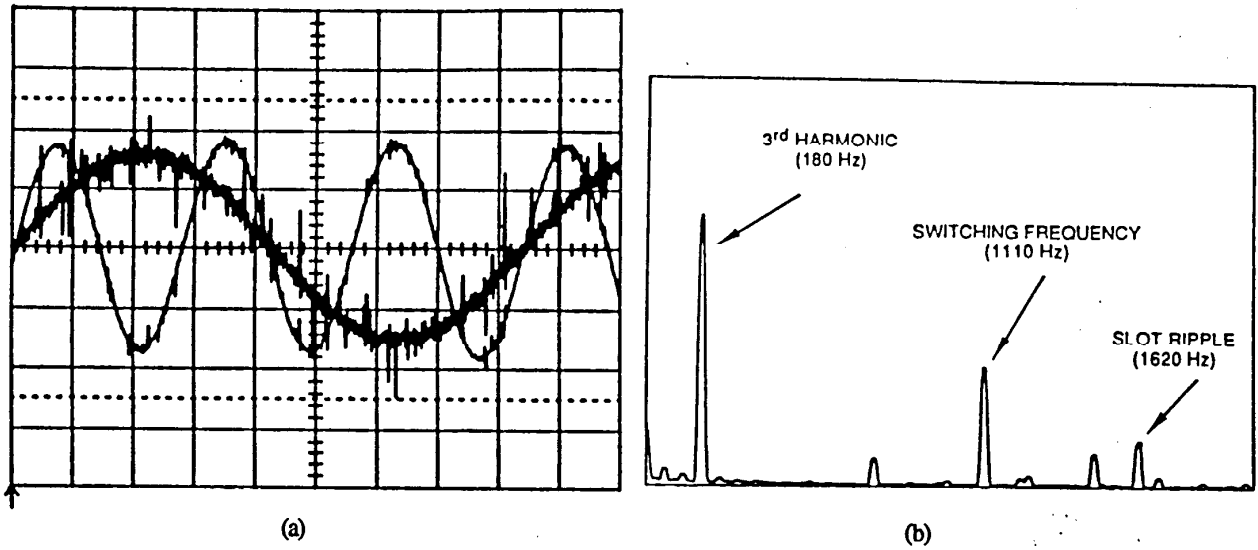


Fig. 6: (a) Third Harmonic Voltage Signal and Line Current, (b) Spectrum of the Third Harmonic Stator Voltage Signal. Data Obtained for a 3HP, 230V, 4 Poles Induction Machine Driven by a PWM Inverter.

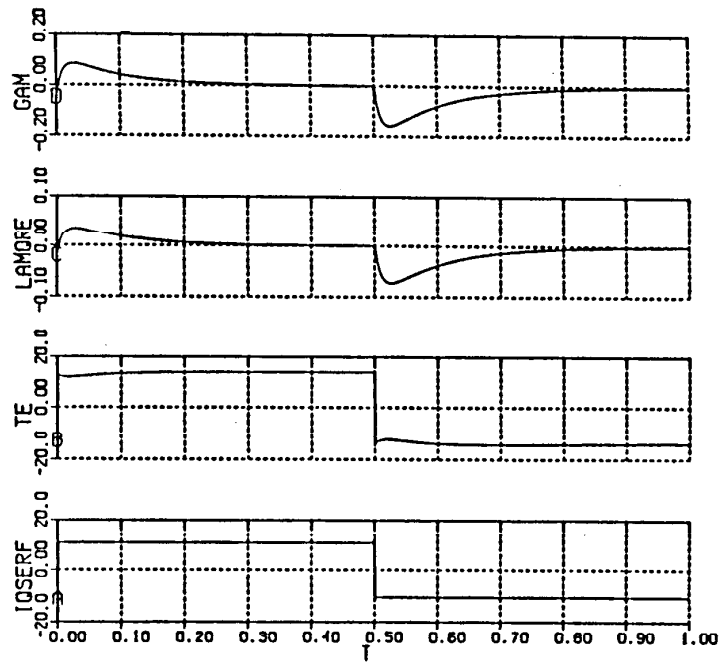


Fig. 7: Simulation Results Showing Implementation of Rotor Flux Field Orientation Control Strategy by Driving the Rotor Flux Angle to Zero. From the Bottom to the Top Traces: i_{qs}^{e*} , T_e , λ_{qr}^{e*} , and δ .

5. CONCLUSIONS

A simple and low cost alternative scheme for induction machine field orientation control has been proposed. It is based on the concept of locating the fundamental component of air gap flux from the third harmonic voltage component induced in the stator phase voltages when the machine is in saturated condition. When the stator phase voltages are summed, the resultant signal contains a dominant third harmonic component followed by the rotor slot ripple which can be used for purposes of speed control. Utilization of this controller requires the stator be star connected and access to the neutral connection.

Two strategies of utilizing the third harmonic voltage signal are discussed. The first uses the third harmonic signal to locate the air gap flux position in absolute terms, which is somewhat difficult to achieve due to the fact no quadrature signal is directly obtainable from the third harmonic signal. The second technique avoids the problem of finding the absolute rotor flux position by driving the rotor flux angle with respect to the d -axis to zero, thereby achieving the desired rotor field orientation condition. Limitations in the torque transient response exist, however, due to the delays introduced by the computation of the flux amplitude and angle measurement.

The second strategy is chosen for practical implementation and simulation evaluation for its simplicity and small delay. The results obtained are encouraging, showing that a very good transient and steady state torque responses are possible with minimal cost.

6. INDUCTION MOTOR PARAMETERS

Quantity	Symbol	Value
Line Voltage	V_l	230 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. magnet. reactance	X_m	22.09 Ω
Rotor Inertia	J_m	0.0104 Kg-m ²
Number of rotor slots	n_r	46
Number of stator slots	n_s	36
Rotor skew	-	1 slot
Stator pole pitch	τ_s	7/9
Load Inertia	J_L	0.0200 Kg-m ²

7. REFERENCES

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