Air-Gap Flux Position Estimation of Inaccessible Neutral Induction Machines by Zero Sequence Voltage

Alfio Consoli°, Giuseppe Scarcella°, Antonio Testa*, Thomas A. Lipo§

° *DEES - University of Catania - Viale A. Doria, 6 - 95125 Catania, Italy* - e-mail: aconsoli@dees.unict.it

* *DFMTFA - University of Messina - Salita Sperone, 31- 98166 Sant'Agata, Messina, Italy* - e-mail: atesta@ieee.org

§ *ECE Dep.- University of Wisconsin – 1415 Engineering Drive, Madison, WI 53706 1691, USA* - e-mail: lipo@engr.wisc.edu

Abstract

The paper describes a new and straightforward approach to estimate the air-gap flux position in induction machines. The proposed scheme is based on the injection of a high frequency oscillating stator voltage, instead of a three phase high frequency voltage, thus allowing a reduction in audible noises and torque ripple. The main feature of the proposed approach, is that a simple air-gap flux tracking algorithm is developed using the amplitude variation of the high frequency component of the zero sequence voltage. Moreover, the zero sequence voltage is sensed at the output of the inverter, rather than at motor terminals. The estimated position is not influenced by load and parameter variation and can be performed at any frequency including low and zero frequency. An experimental prototype has been implemented showing the performance of the proposed approach.

1. INTRODUCTION

Field Oriented Control (FOC) allows independent control of torque and flux in induction motor drives using a reference frame synchronous with the rotor flux and decoupling the stator current in two d,q components. According to the Direct Field Oriented Control (DFOC) approach, the position of the rotor flux is computed from the air-gap flux vector position, that can be directly measured by suitable flux sensing devices. A direct measurement of the flux is in its nature insensitive to motor parameter variations, but such a scheme has been always regarded as less practical because of the presence of the flux sensors. By comparison, Indirect Field Oriented Control (IFOC) offers a relatively simpler hardware approach because such a control utilizes machine parameter values (the rotor time constant and the magnetizing inductance) to implement an on line

incremental encoder) to measure the rotor speed (position), is more easily accepted than the presence of flux sensing devices inside the machine, the cost and size of the drive using a position or speed transducer is increased. Academic and industrial researchers in recent years have been constantly interested in the development of sensorless drives. In sensorless FOC drives an algorithm allows one to measure or calculate the flux position without flux, position or speed transducers. Sensorless FOC algorithms can be classified according to flux position detection technique. A first class of sensorless methods obtain the flux position directly from voltage and current measurements and calculations; a second class, the flux tracking methods, requires monitoring variables proportional to the error between the estimated and the correct flux positions, while the voltage and current measurements or calculations are aimed only at reducing this error. In general the some critical working conditions like low or zero stator frequency. Recently, it has been demonstrated that, by using high frequency injection, algorithms belonging to the first and the second class can be developed, able to work even at zero frequency. Most of them are based on evaluation of the saturation induced saliency [1], [2], [3], [4]. A new method was proposed in [5] based on injecting a three phase high frequency stator voltage component and considering the effects of the high frequency field on saturation of the main field. The present paper describes a new scheme, based on the effects outlined in [5] and belonging to the flux tracking class.

All previously presented flux tracking methods based on high frequency injection and saturation induced saliency, show some drawback that this paper tries to overcome. The method proposed by Blaschke et al. [6] requires the knowledge of rotor currents, not always available in induction machines. A modified version proposed by the authors uses only stator currents, but the approach is still difficult to implement. In [7] a high frequency oscillating voltage is injected on the estimated d axis in the d, q synchronous reference frame for tracking the flux position. Assuming that when the algorithm starts an arbitrary position is the correct position, the effect of the high frequency is evaluated into two orthogonal axes, 45 degrees shifted from the pre-assumed estimated axis. The monitoring variable is the difference between the two high frequency impedances, respectively of the rotor flux axis and quadrature axis, that according to the explanation given in the paper are different because of the large variation of the rotor resistance due to skin effect. The authors have recently proposed a more detailed and convincing explanation of the difference in the two high frequency impedances which is due to saturation induced saliency, as it is clear from Finite Element Analysis [8].

On the contrary, the main feature of the proposed approach is that the monitored variable is the amplitude of the high frequency component of the zero sequence voltage, that is directly correlated with the flux position. The zero sequence voltage is sensed at the output of the windings are required. An experimental prototype is implemented showing the performance of the proposed approach.

2. FLUX TRACKING BY ZERO SEQUENCE VOLTAGE

In this paper the flux tracking algorithm is obtained in a simpler way, than in previous approaches. Rather than a complex impedance measurement, the proposed technique uses the amplitude of the high frequency component of the zero sequence voltage. Induction machines during normal operations usually show zero sequence phase voltages as a consequence of saturation phenomena. Saturation of stator and rotor iron causes the air-gap flux to assume a flattened waveform as shown in Fig. 1, with harmonic content highly dominated by the third harmonic component that depends, through a non linear function, on the amplitude of the fundamental air-gap flux.

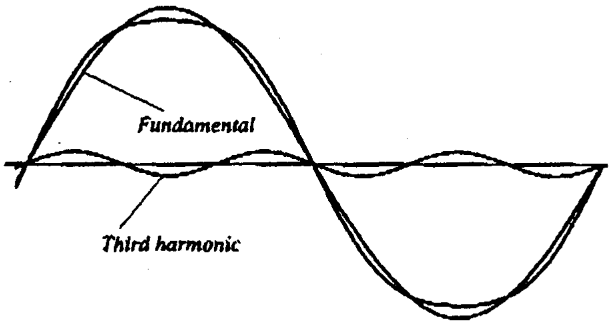


Fig. 1 - Air-gap flux components.

An additional fluctuating high frequency voltage is injected in order to produce a high frequency oscillating field $\mathbf{F}_{hf}$, along the estimated d axis, as shown in Fig. 2. This field according to the position of the estimated d axis with respect to the main field axis $\mathbf{F}_m$, generates a variation of saturation level that modulates the amplitude of the zero sequence high frequency flux and consequently of the high frequency zero sequence voltage. If the estimated d axis is in phase with the correct d axis, the variation of the saturation level is frequency component of the zero sequence voltage has a minimum. By following the maximum of such voltage signal a simple but effective flux tracking can be performed.

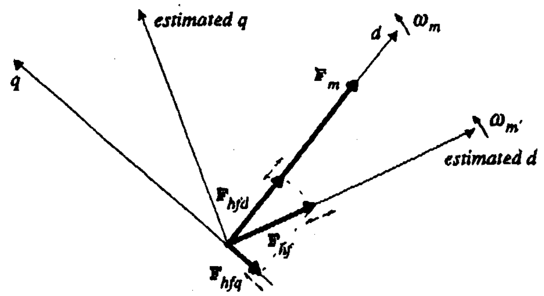


Fig.2 – Rotating and Oscillating fields in the proposed approach.

Compared to previous flux tracking sensorless approaches the proposed technique represents a great simplification because the fluctuating additional stator voltage V_{hf} is introduced to generate an amplitude variation of the zero sequence voltage that can be easily measured. Moreover, during a perfect tracking, the high frequency voltage V_{hf} produces a negligible torque ripple that is due only to the flux ripple. In fact, in such conditions there is no high frequency current component on the torque axis, but only a high frequency current component on the d axis, according to the field oriented expression of the torque:

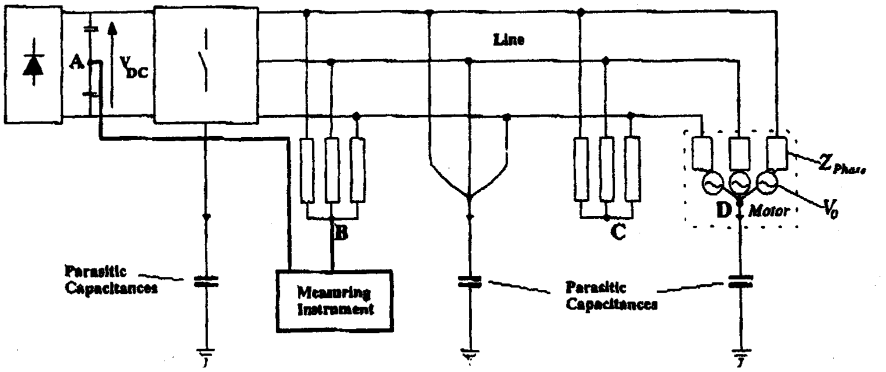
$$T_e = k\lambda_{dr} i_{qs}$$

3. ZERO SEQUENCE CURRENT PATHS

The proposed approach requires measurement of the zero sequence voltage. Normally this can be achieved inserting a voltage probe between a stable point as the mid point of the two capacitors in the DC bus and the neutral of the stator windings. In this paper is proposed a new approach able to measure the zero sequence voltage of the motor using alternative points to the neutral of the machine and not so close to the motor terminals. In this way, application of the proposed flux tracking method can be extended to those drives in which the neutral of the stator winding is not accessible or an additional cable between the inverter and the machine is not allowed. The zero sequence current paths in an industrial drive are shown in Fig. 3, where A is the mid point of the two capacitors of the DC bus that almost coincides with the mid point of the three-phase supply, B is the mid point of a three-phase star-connected balanced load at the inverter output, C is the mid point of a three-phase star connected balanced load at the end of the cable line, D is the neutral point of the stator winding.

The zero sequence equivalent circuit is shown in Fig. 4, where the zero sequence voltage created by saturation, is indicated by the voltage generator V_0. In the figure are also indicated the zero sequence impedances of the inverter, the cable line and the motor. In the ideal case of no parasitic capacitances the zero sequence currents cannot circulate and consequently all the points A, B, C, and D go oscillate as a result of the presence of the zero sequence generator.

When a current flows in the zero sequence circuit, the



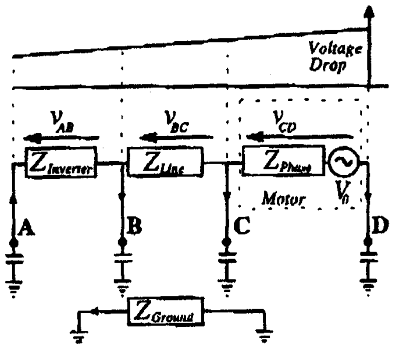


Fig. 4 -Zero sequence equivalent circuit of the drive.

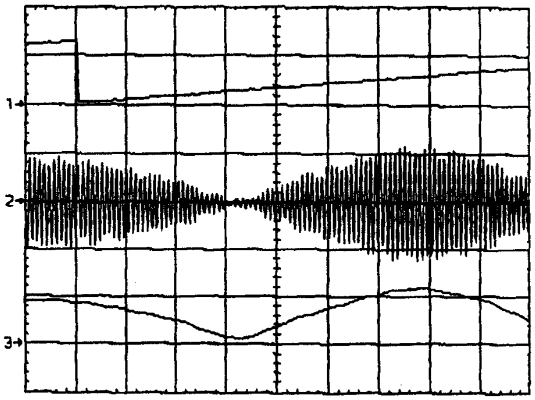
potential of all the points, will follow the potential of D assuming a different value that depends on the zero sequence impedances as in a sort of voltage divider and on the currents flowing in parasitic capacitance. In Fig. 4 is shown an ideal potential drop obtained by considering the current flowing only through the points A and D and in the ground connection, and assuming an equal zero sequence impedance for length unit of all the circuit components, such as the inverter, the cable and the motor phase. According to this theory, the zero sequence voltage in the neutral point of the stator winding influences the zero sequence voltage in every point of the connection between the motor and the three phase supply. Therefore, points for zero sequence voltage measurements can be created anywhere in the circuit by using a three-phase star-connected impedance. In theory, the measurement result would be inversely proportional to the distance between the measurement point and the motor terminals. In practice, the zero sequence impedances are quite different and the parasitic currents in the capacitances cannot be neglected, so that the voltage drop does not follow the ideal line but a more complex behavior that strongly depends on the experimental system. It has been experienced that the voltage drop is almost independent from the cable length, and the zero sequence voltage at the output of the inverter with a long cable is almost the same than the zero sequence voltage at motor terminals, thus advantaging the application of the proposed approach.

4. EXPERIMENTAL RESULTS

kW four poles induction machine. In Fig. 5 are shown the absolute position of the rotor flux θ_r calculated with an IFOC approach, and the high frequency zero sequence voltage V_{0hf} measured at the neutral of the stator winding, while the motor is fed by a low frequency (3 Hz) voltage, and an additional single phase high frequency (500 Hz) voltage is superimposed on a fixed d axis. The amplitude of the second waveform is clearly correlated to the absolute position of the air-gap flux θ_m. In Figs. 6, 7 and 8 are shown the same waveforms of Fig. 5 with the zero sequence voltage measured by a three-phase star-connected load respectively at the motor terminals, at the output of the inverter with 0.5 m and 100 m line cable length. It is possible to notice in all the measurements the presence of a useful variation of the amplitude of the zero sequence voltage with the absolute position of the air-gap flux θ_m.

In Figs. 9, 10, 11 are shown some experimental tests with the zero sequence voltage measured by the neutral point of stator windings. In Fig. 9 is performed a steady state flux tracking at 0.5 rad/s, in Fig 10 a speed reversal between 0.5 and -0.5 rad/s and in Fig. 11 a speed transient from 0.5 to 0 and back to 0.5 rad/s, with a zero frequency steady state.

In Figs. 12, 13 and 14 are shown the same waveforms of Figs. 9, 10 and 11 with the zero sequence voltage measured by a three phase star connected balanced load at the inverter output with a line length of 100 meters between the inverter and the motor.



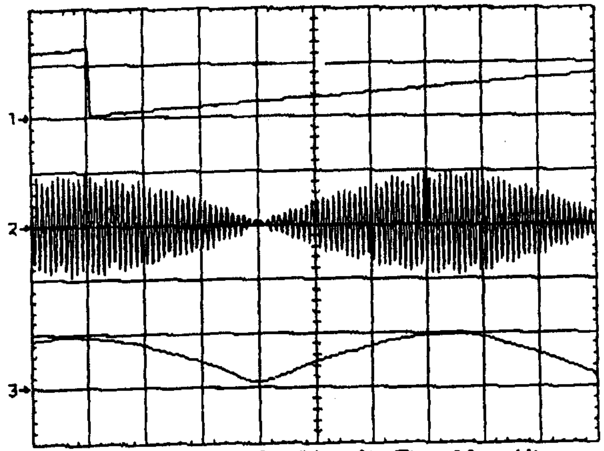


Fig. 6 - *Motor Speed = 10 rad/s, Time 20 ms/div; Position 5 rad/div.* 1) IFOC estimated θ_r, 2) V_{0hf} *500 mV/div*, 3) $|V_{0hf}|$ *500 mV/div* (motor terminals).

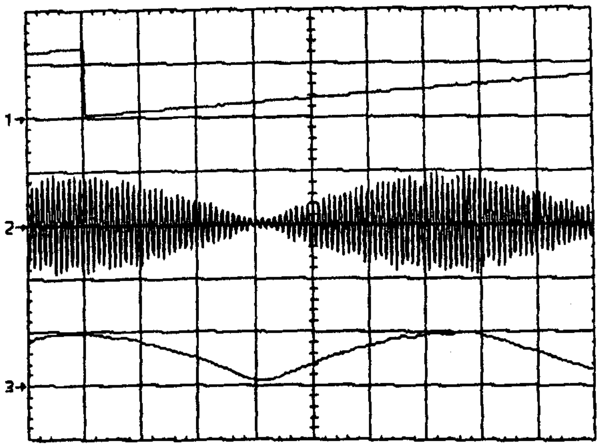
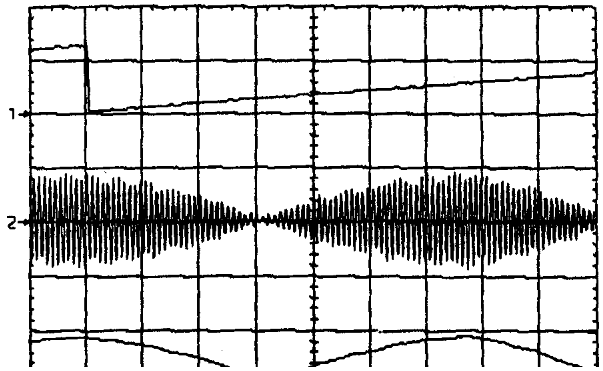


Fig. 7 - *Motor Speed = 10 rad/s, Time 20 ms/div; Position 5 rad/div.* 1) IFOC estimated θ_r, 2) V_{0hf} *500 mV/div*, 3) $|V_{0hf}|$ *500 mV/div* (inverter output with 0.5 m of cable line).



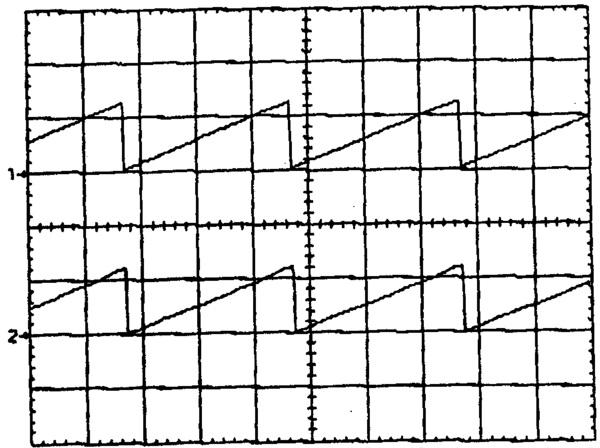


Fig. 9 - *Motor Speed = 0.5 rad/s, Time 2s/div, Position 5 rad/div.* 1) IFOC estimated θ_r, 2) estimated θ_m (neutral point of stator winding).

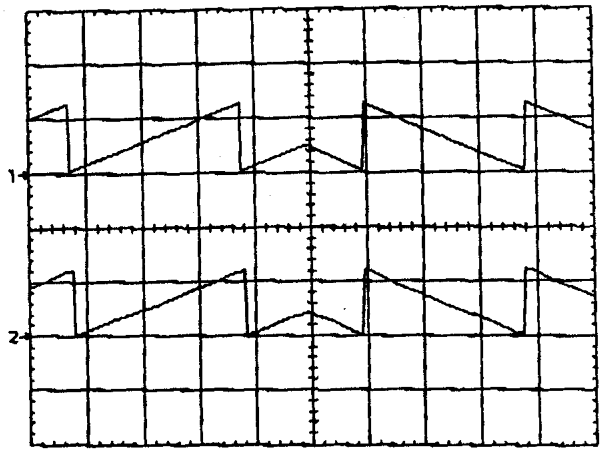
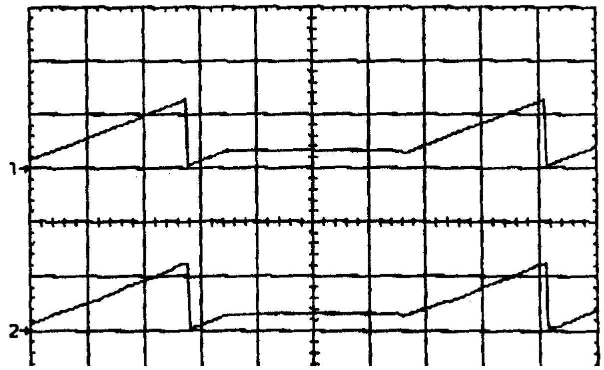


Fig. 10 - *Motor speed change from 0.5 to -0.5 rad/s, Time 2 s/div, Position 5 rad/div.* 1) IFOC estimated θ_r, 2) estimated θ_m (neutral point of stator winding).



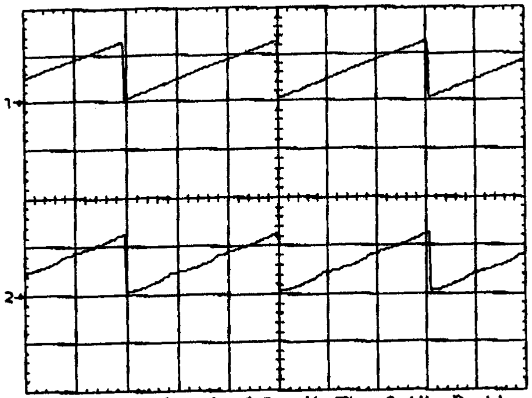


Fig. 12 - *Motor Speed = 0.5 rad/s, Time 2s/div, Position 5 rad/div.* 1) IFOC estimated θ_r, 2) estimated θ_m (inverter output with 100 m of cable line).

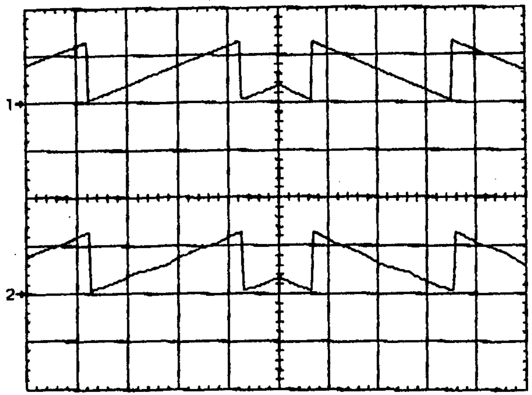


Fig. 13 - *Motor speed change from 0.5 to -0.5 rad/s, Time 2 s/div; Position 5 rad/div.* 1) IFOC estimated θ_r, 2) estimated θ_m (inverter output with 100 m of cable line).

5. CONCLUSIONS

The paper describes a new and straightforward approach to estimate the air-gap flux position in induction machines. The proposed approach is based on the injection of a high frequency oscillating stator voltage and on a flux tracking algorithm where the monitored variable is the amplitude of the high frequency component of the zero sequence voltage. The zero sequence voltage is sensed at the output of the inverter instead than at the motor terminals, thus advantaging the practical implementation of the sensorless control of the required. Experimental results showing the feasibility of the proposed approach are included.

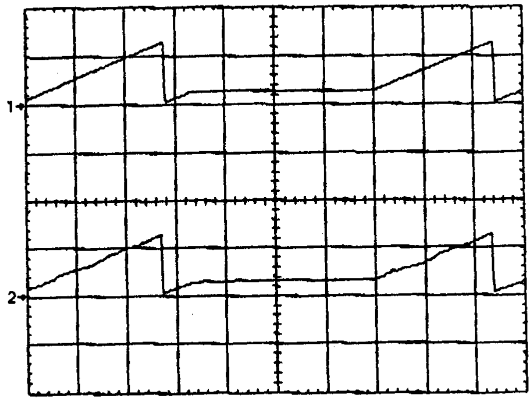


Fig. 14 - Motor speed change from *0.5* to *0* to *-0.5 rad/s. Time 2 s/div; Position 5 rad/div;* 1) IFOC estimated θ_r, 2) estimated θ_m (inverter output with 100 m of cable line)

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