XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22-27, 2003, Dubrovnik, Croatia

SLIP FREQUENCY MEASUREMENT OF ASYNCHRONOUS MOTORS

R. Micheletti, R. Pieri

Department of Electrical Systems and Automation, University of Pisa
Via Diotisalvi, 2 I-56126 Pisa, Italy

Abstract - The paper deals with the accurate slip measurement of induction motors. The proposed procedure uses a non-invasive slip measurement scheme based on digital filtering and dynamic parameter estimation. The slip measurement is carried out without speed sensor and is deduced analyzing the magnetic field harmonics spectrum in proximity of the induction motor. First the emf induced waveform, taken from a searching coil, is filtered using algorithms based on the discrete Fourier transform. Then the stator frequency and rotor frequency are obtained by comparing the filtered voltage with a mathematical model using an optimization procedure. The model's parameters are varied until an adequate match is obtained with the filtered voltage. Experimental results are presented to validate this method.

Keywords: Induction motors, Slip measurement, Digital filtering.

1. INTRODUCTION

Induction motor drives are now being more and more in process industry because of the application of the field oriented control strategy. However, the performance of such control method depends strongly on the accuracy of the motor parameters used in the vector controller. It is well known that the variation of the rotor resistance and rotor constant time has a most dominant effect on the control performance. Unfortunately the rotor resistance depends widely on the rotor temperature and on the slip frequency, resulting in the destruction of the coupled condition of the flux and torque.

In recent years many studies are then carried out to overcome this situation. Estimation methods to get rotor parameters use extended Kalman filter approach [1], observer technical [2] and adaptive system [3].

It is actively proceeding to research for speed-sensorless vector control which estimates rotor speed and slip frequency without speed sensor. The slip frequency detection is carried out utilizing rotor slot harmonics [4], [5] or sensing and exploiting the stator current [6].

This paper presents an algorithm for the accurate measurement of the slip frequency based on digital filtering and dynamic parameter estimation method [7]-[10]. The slip frequency measurement is carried out without speed sensor and is deduced analyzing the magnetic field harmonics spectrum in proximity of the induction motor. First the emf induced waveform, taken from a searching coil, is filtered using algorithms based on the discrete Fourier transform. Then the stator frequency, rotor frequency and consequentially the slip frequency are obtained by comparing the filtered voltage with a mathematical model using an optimization procedure. The model's parameters are varied until an adequate match is obtained with the filtered voltage.

The parameters that affect the performance of the algorithm are essentially the data window size, the sampling rate and the characteristics of the filter.

The effect of the quantization error of the input voltage introduced by a 12-bit A/D converter has been included in the analysis. The influence on the slip measurement accuracy of other motors running in the closeness is also analyzed and it is mapped the response of the measuring system at several positions of the searching coil.

Mathematical development of the algorithm is presented and the effects of key parameters that affect the performance of the algorithm are discussed. A representative set of experimental test results are presented.

The proposed method can be reliably applied in rotor parameter identification in steady state conditions and running test.

2. ESTIMATION ALGORITHM OF STATOR AND ROTOR FREQUENCY

The stator frequency f_s and rotor frequency f_r are obtained with the same procedure by comparing the respective filtered voltages with a mathematical model using an optimization method.

After filtering operation, we obtain a set of "n" samples of the stator (rotor) voltage. The filtered voltage can be approximated by a sinusoid

$$v(t) = V \sin(\omega t + \theta) \tag{1}$$

where V and θ are amplitude and phase, respectively.

By rewriting the voltage in terms of quadrature components

$$v(t) = A \sin \omega t + B \cos \omega t = v(A, B, \omega, t) \tag{2}$$

with

$$V = \sqrt{A^{2} + B^{2}}$$
$$q = \tan^{-1}(B/A) \qquad (3)$$

Expanding v(t) in a Taylor series in the neighborhood of given values A_0, B_0, ω_0 of parameters A, B, ω gives

$$v(t) = v(t)_a + \left[\frac{\partial v(t)}{\partial A}\right]_a \Delta A + \left[\frac{\partial v(t)}{\partial B}\right]_a \Delta B + \left[\frac{\partial v(t)}{\partial w}\right]_a \Delta w \qquad (4)$$

where the higher order terms of the expansion are ignored and $\alpha = (A_0, B_0, \omega_0)$.

The principle of operation of the estimation technique is based on the comparison between the real values of the filtered voltage and the estimation values of the model. Thus the problem consists in determining the parameters A, B, ω able to minimize the error between sampled values and estimation values. The total square error, at instant t_S, is expressed as

$$E = \sum_{s=1}^{n} \left[v_r(t_s) - v(t_s) \right]^2 \qquad (5)$$

where $v_r(t_S)$ and $v(t_S)$ represent the sampled outputs of the real system after filtering and the model reference at time t_S, respectively.

Substitution of (4) into (5) yields

$$E = \sum_{s=1}^{n} \left\{ v_r(t_s) - v(t_s)_a - \left[\frac{\partial v(t_s)}{\partial A}\right]_a \Delta A - \left[\frac{\partial v(t_s)}{\partial B}\right]_a \Delta B - \left[\frac{\partial v(t_s)}{\partial w}\right]_a \Delta w \right\}^2 \qquad (6)$$

The total square error is minimized by solving the partial derivatives of (6) relative to A, B, ω evaluated at A_0, B_0, ω_0

$$\frac{\partial E}{\partial A} = 0; \quad \frac{\partial E}{\partial B} = 0; \quad \frac{\partial E}{\partial \omega} = 0 \qquad (7)$$

There results after rearrangement

$$\sum_{s=1}^{n} \left[\frac{\partial v(t_s)}{\partial A}\right]_a \left\{ v_r(t_s) - v(t_s)_a \right\} = \sum_{s=1}^{n} \left[\frac{\partial v(t_s)}{\partial A}\right]_a \left\{ \left[\frac{\partial v(t_s)}{\partial A}\right]_a \Delta A + \left[\frac{\partial v(t_s)}{\partial B}\right]_a \Delta B + \left[\frac{\partial v(t_s)}{\partial w}\right]_a \Delta w \right\}$$

$$(8)$$

$$\sum_{s=1}^{n} \left[\frac{\partial v(t_s)}{\partial w}\right]_a \left\{ v_r(t_s) - v(t_s)_a \right\} = \sum_{s=1}^{n} \left[\frac{\partial v(t_s)}{\partial w}\right]_a \left\{ \left[\frac{\partial v(t_s)}{\partial A}\right]_a \Delta A + \left[\frac{\partial v(t_s)}{\partial B}\right]_a \Delta B + \left[\frac{\partial v(t_s)}{\partial w}\right]_a \Delta w \right\}$$

$$\sum_{s=1}^{n} \left[\frac{\partial v(t_s)}{\partial w}\right]_a \left\{ v_r(t_s) - v(t_s)_a \right\} = \sum_{s=1}^{n} \left[\frac{\partial v(t_s)}{\partial w}\right]_a \left\{ \left[\frac{\partial v(t_s)}{\partial A}\right]_a \Delta A + \left[\frac{\partial v(t_s)}{\partial B}\right]_a \Delta B + \left[\frac{\partial v(t_s)}{\partial w}\right]_a \Delta w \right\}$$

Solution of (8) gives the corrections ΔA, ΔB and Δω necessary for updating parameters A, B and ω for each iteration step. This recursive technique permits to obtain the unknown stator and rotor frequency with good accuracy.

Finally the slip frequency is given by

$$s = f_r/f_s \qquad (9)$$

Iterative methods are well known for their sensitivity to the initially guessed values of the unknowns. The initial values used for the model reference are determined as follows. The initial value of ω_0 is obtained using the first five samples of the input voltage

$$?_0 = \frac{1}{T_s} \sqrt{\frac{3\left[2v(t_1+2T_s) - v(t_1) - v(t_1+4T_s)\right]}{2\left[v(t_1+T_s) + 4v(t_1+2T_s) + v(t_1+3T_s)\right]}} \qquad (10)$$

The initial values of A_0 and B_0 are determined solving the system:

$$v(t_1) = A_0 \sin \omega_0 t_1 + B_0 \cos \omega_0 t_1$$
$$v(t_1 + T_S) = A_0 \sin[\omega_0 (t_1 + T_S)] + B_0 \cos[\omega_0 (t_1 + T_S)] \qquad (11)$$

3. RESULTS

The measurement algorithm has been verified to investigate the validity of this technique.

The rated values of the induction motor used in the experiments are given in Table 1.

Table 1 Rated values of a tested induction motor

Power	11 kW
Voltage (Y)	400 V
Current (Y)	21.5 A
Frequency	50 Hz
Revolution per minute (r/min)	1450
cos φ	0.85

The slip frequency measurement is carried out analyzing the waveform of the induced emf, taken from a searching coil, due to the magnetic field in proximity of the induction motor.

Fig. 1 shows the waveform of the induced emf with motor no-loaded at 1498 rpm (s=0,13%). Obviously this condition is the most severe because the weak value of the emf at rotor frequency component may decrease the measurement accuracy; moreover it requires a longer acquisition interval.

With more realistic working conditions, the slip frequency is about s=3,33%, corresponding to a rotor frequency of 1.66 Hz; therefore the acquisition interval decreases considerably to a time that, in some cases, could be compatible with control purposes.

The searching coil is put on the frame of the induction motor.

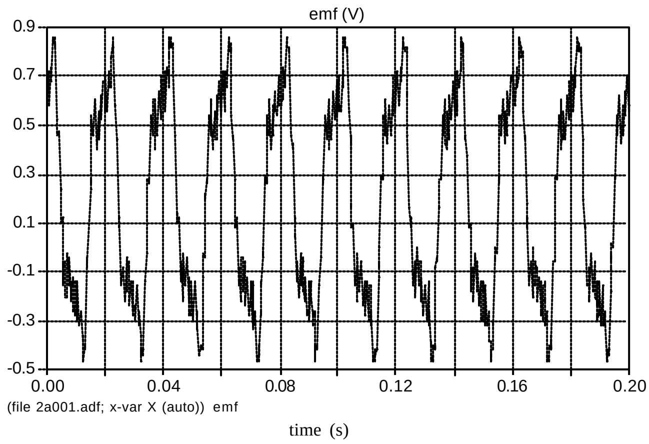

Fig. 1. Waveform of the induced emf with searching coil put on the frame of the induction motor.

Then this waveform is filtered using algorithms based on the discrete Fourier transform.

The filtering operation is obtained with two eighth order IIR filters. The first one is a bandpass filter with a center frequency of 50 Hz and bandwidth 4 Hz, whose output is the emf component at the stator frequency (emf at stator frequency component). The second one is a lowpass filter with variable cutoff frequency from 1 Hz to 3 Hz; in the test illustrated in next picture we selected a cutoff frequency of 1 Hz. The output of the lowpass filter is the emf component at the rotor frequency (emf at rotor frequency component).

The emf at stator and rotor frequency components for no-load conditions and searching coil put on the frame of the induction motor are shown in Fig. 2.

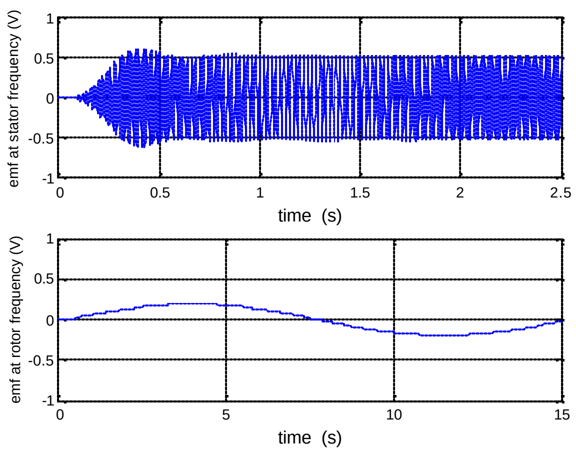

Fig. 2. Emf at stator and rotor frequency components with searching coil put on the frame of the induction motor.

Fig. 3 shows the waveform of the induced emf with motor no-loaded at 1498 rpm (s=0,13%) but searching coil leaned against one side of the induction motor.

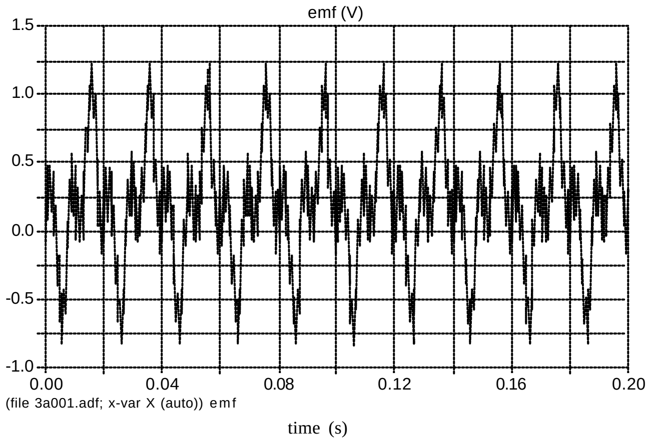

Fig. 3. Waveform of the induced emf with searching coil leaned against one side of the induction motor.

The emf at stator and rotor frequency components for no-load conditions and searching coil leaned against one side of the induction motor are shown in Fig. 4.

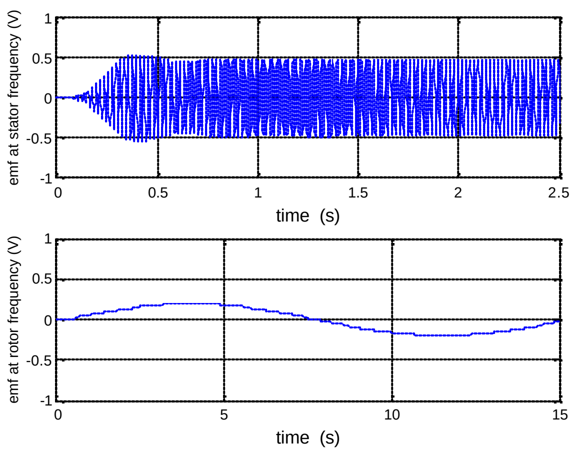

Fig. 4. Emf at stator and rotor frequency components with searching coil leaned against one side of the induction motor.

Next pictures show the waveforms of the induced emf and the emf at stator and rotor frequency components for no-load conditions (1498 rpm; s=0,13%) with searching coil at one side of the induction motor at distance 10 cm and 20 cm, respectively.

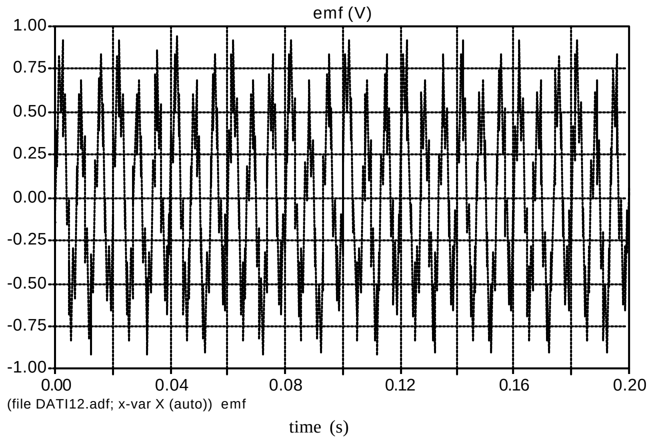

Fig. 5. Waveform of the induced emf with searching coil at one side of the induction motor at distance 10 cm.

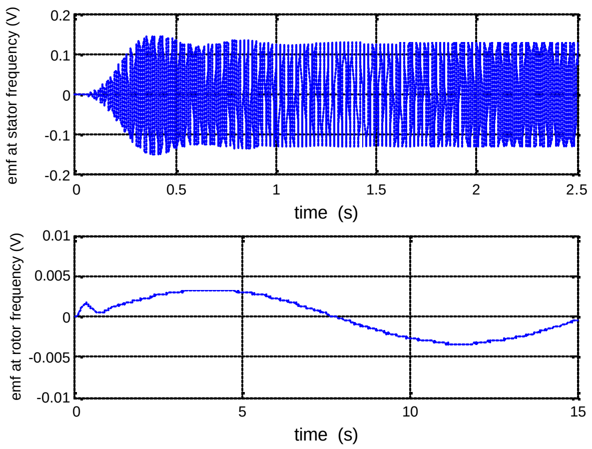

Fig. 6. Emf at stator and rotor frequency components with searching coil at one side of the induction motor at distance 10 cm.

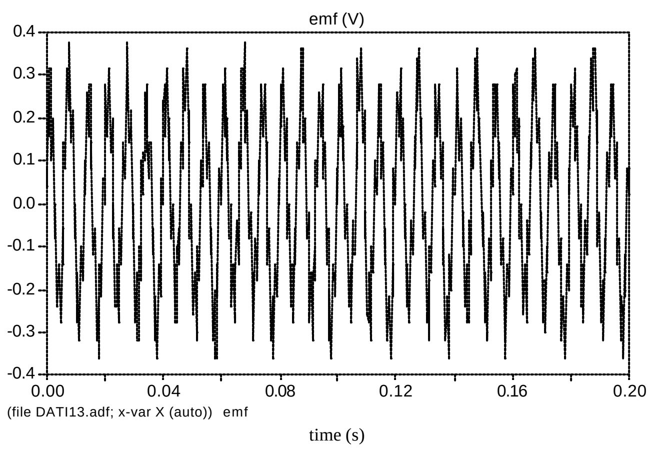

Fig. 7. Waveform of the induced emf with searching coil at one side of the induction motor at distance 20 cm.

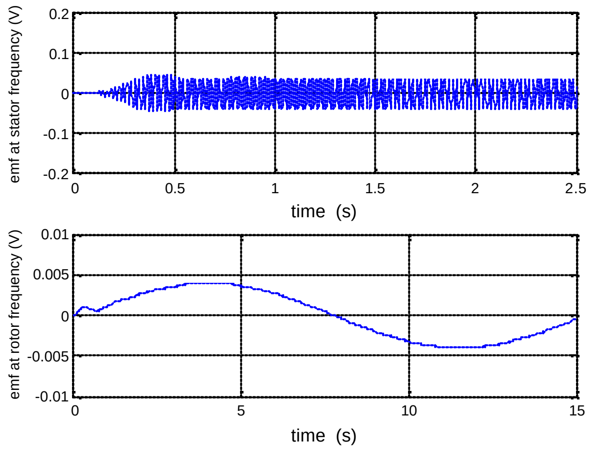

Fig. 8. Emf at stator and rotor frequency components with searching coil at one side of the induction motor at distance 20 cm.

The delay introduced by the filtering operation is approximately 0.5 s.

Tests have been carried out for different values of the slip frequency in the range from s = 0,13% to s = 5% with sampling frequency set to 800 Hz. The elaboration for generating new values of A, B, and ω at each iteration step is carried out on a data window of about 1/4 cycle of the respective filtered voltages; these values of sampling frequency and data window size have been selected in order to increase the speed of convergence and to improve the accuracy.

The initial values of parameters ω_0 , A_0 , B_0 are estimated as mentioned in previous section; only six iteration steps are required to get to the convergence.

The proposed system operated satisfactorily for any value of the slip frequency in the previously mentioned range and for any position of the searching coil at distance less than 10 cm; the error was always within ±0,08%.

With searching coil at distance 20 cm, the accuracy of the slip estimate deteriorates slightly because of the weak value of the emf at stator and rotor frequency components; the error was in any case within ±0,2%.

Thus the influence on the slip measurement accuracy of other motors used in our tests, running at distance greater than 40 cm is practically negligible.

4. CONCLUSION

A new digital approach for the accurate measurement of the slip frequency of induction motors has been presented.

The non invasive procedure based on digital filtering and dynamic parameter estimation has been shown to work effectively over a nearly wide range of speed and loading conditions.

The slip frequency measurement is carried out without speed sensor and is deduced utilizing the magnetic field in proximity of the induction motor. The system apparatus consists of a searching coil, an ADC board and a PC; the measurement system needs only a signal from a searching coil (induced emf) to be digitally filtered using algorithms based on the discrete Fourier transform. Useful estimates of the slip frequency are obtained using about 1/4 cycle of the emf at stator and rotor frequency. Sampling rate, data window size and the characteristics of the filter are critical parameters that affect the performance of the algorithm.

The accuracy of the slip measurement, in the previously mentioned range of the slip frequency, is not affected by the load applied to the motor nor by any consequent changes to the motor parameters.

Moreover the accuracy of the slip estimate is not sensitive to the position of the searching coil if its distance from the induction motor is less than 10 cm; in this range of distance the slip measurement accuracy is good and reliable. The accuracy deteriorates slightly if the distance rises to 20 cm, while the accuracy of the measuring system decreases dramatically with distance greater than 20 cm.

The proposed technique is accurate, simple and low cost; moreover it allows in-field measurement of the slip frequency of induction motor even in hazardous environments and it can be reliably applied in rotor parameter identification in steady state conditions and running test.

Experimental tests confirmed the validity of the proposed procedure.

REFERENCES

[1] Y.R. Kim, S.K.Sul, M.H. Park: Speed sensorless vector control of induction motor using extended Kalman, *IEEE Trans. On Industry Applications*, Sep.-Oct. 1994, pp. 1225-1233.

[2] H. Kubota, K. Matsuse, T. Nakano: DSP-based speed adaptive flux observer of induction motor, *IEEE Trans. On Industry Applications,* Mar.-Apr. 1993, pp. 344-348.

[3] G. Yang, T.H. Chin: Adaptive-speed identification scheme for a vector-controlled speed sensorless inverter-induction motor, *IEEE Trans. On Industry Applications,* Jul.-Aug. 1993, pp. 820-825.

[4] M. Ishida, K. Iwata: A new slip frequqncy detector of an induction motor utilizing rotor slots harmonics, *IEEE Trans. On Industry Applications,* May-June 1984, pp. 575-582.

[5] K.D. Hurst, T.G. Habetler: A comparison of spectrum estimation techniques for sensorless speed detection in induction machines, *IEEE Trans. On Industry Applications,* vol. 33, n. 4, 1997.

[6] R. Beguenane, M.E.H. Benbouzid, G.A. Capolino: On-line identification of induction motor rotor parameters from terminal signals, *Electromotion,* vol.3, no.2, April-June 1996, pp. 51-57.

[7] A. Longo, R. Micheletti, R. Pieri: Fast and Accurate Power System Frequency Measurement by Dynamic Parameter Estimation, *Proceedings of the IMEKO XV World Congress "Measurement to Improve the Quality of Life in the 21st Century – Measurement Helps to Coordinate Nature with Human Activities"*, Osaka, June 13-18, 1999, vol. 4, pp. 63-68.

[8] R. Micheletti: Real time measurement of power system frequency, *Proceedings of the IMEKO XVI World Congress*: *Measurements, support science, improves thechnology, protects environment and provides employment now and in the future*, Vienna, September 25-28, 2000, vol. 3, pp. 425-30.

[9] R. Micheletti, R. Pieri: Non-invasive slip measurement of induction motors, *IEEE Instrumentation and Measurement Technology Conference IMTC 2001*, Budapest, May 21-23, 2001, vol. 1, pp. 1958-61.

[10] R. Micheletti, R. Pieri: Accurate measuring method for the slip of asynchronous motors**,** *12th IMEKO TC4 International Symposium" Electrical Measurement and Instrumentation,* Zagreb, Croatia, September 25-27, 2002.

AUTHORS: Roberto Micheletti, Department of Electrical Systems and Automation, University of Pisa, Via Diotisalvi, 2 I-56126 Pisa, Italy
Tel. (+39 050) 565111, Fax (+39 050) 565333
E-mail: Roberto.Micheletti@dsea.unipi.it

Renzo Pieri, Department of Electrical Systems and Automation, University of Pisa, Via Diotisalvi, 2 I-56126 Pisa, Italy
Tel. (+39 050) 565111, Fax (+39 050) 565333
E-mail: Renzo.Pieri@dsea.unipi.it