A NEW MOTOR SPEED MEASUREMENT ALGORITHM BASED ON ACCURATE SLOT HARMONIC SPECTRAL ANALYSIS

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Abstract – *In this paper a new induction motor speed method based on Chirp-Z Transform and zero padding of the supply current is presented. The algorithm has been implemented on a microprocessor. A virtual instrument has been built to control and to monitor on line motor speed. The motor speed method has been tested on a 7.5 kW induction motor driven by a pulse width modulation voltage source inverter for different load and supply frequency conditions. The proposed method has been compared to a FFT based one implemented on the same microprocessor. Thanks to a shorter sampling time window errors related to not stationary current signal are reduced. Then the achieved goal is an increased accuracy due to shorter sampling time window and better spectral resolution. Moreover the processing time has been reduced increasing algorithm speed response.*

Keywords – Speed measurement, encoderless, rotor slot harmonics, Chirp-Z Transform, virtual instrument.

1. INTRODUCTION

Thanks to the development of power semiconductor devices, microelectronics and control techniques induction motor drives are widely spread in industrial applications. During the last two decades, a lot of attempts have been made to replace the conventional speed transducers, as tachometer generators or encoders, in adjustable speed drives and servo drives, by measuring speed indirectly by means of motor electrical quantities. In fact speed detectors attached to motor shafts imply an extra cost and impose restrictions on the mechanicalness, the maintenance, the robustness, the reliability and the layout of the drive. Different methods have been already presented in literature that can be summarized as follows:

- methods based on both voltage and current measurements;
- methods based on voltage or current measurement;

The firsts calculate motor speed by means of observer and adaptive scheme deduced by motor mathematical models [1]. They have the advantage of low processing time and to be already tailored for control applications. On the other hand they depend on time variations of electromagnetic motor parameters due to heat, flux saturation, etc. Moreover voltage measurements imply an extra cost of dedicated sensors and filters due to the extremely distorted voltage waveforms of the inverter supplying the induction motor.

The seconds are based on frequency estimation of rotor slot harmonic present in the supply voltage or current [1]. They do not depend on electromagnetic motor parameters but require longer processing times.

Methods based on supply current harmonic analysis are easier to be implemented thanks to the filtering behavior of the motor stator winding and remembering that a current sensor is always present into the supplying inverter.

In literature authors' attention have been mainly focused on the optimization of the rotor slot harmonics research algorithm instead of the spectral analysis technique [2-4].
It can be observed that the features of speed measurement methods based on rotor slot harmonic are strictly dependent on the spectral analysis technique used. In a previous work Authors have developed a detailed comparison of different spectral analysis methods [6]. The aim has been to determine which is the most suitable method to analyze signal's spectral harmonic content in a very close frequency band in the case of periodic non-stationary signals. Chirp – Z Transform has shown to be the most suitable.

In this paper an induction motor speed measurement method is presented. The algorithm is based on Chirp-Z analysis of the supply current [7], with an increased spectral resolution obtained with zero padding technique. Next, on line algorithm implementation on a microprocessor and the virtual instrument built to control and to monitor the running experiment are described. Finally the comparison of the proposed method with a FFT based one implemented on the same microprocessor by means of experimental results is carried out.

2. MOTOR SPEED MEASUREMENT ALGORITHM: THEORETICAL CONSIDERATIONS

In order to explain how the algorithm has been developed, theoretical consideration are presented in the following.

2.1 Speed measurement based on rotor slot harmonics

Air-gap flux of an induction motor fed by a sinusoidal voltage supply waveform comprise a wide range of different harmonics (space harmonics) due to stator winding

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distribution on stator surface, stator slots, air-gap eccentricity, rotor slots.

Only air-gap eccentricity and rotor slot harmonics depend on motor slip and therefore can be useful to detect motor speed. These harmonics are detectable either on supply voltage or on current. Anyway, filtering behavior of the stator winding and the possibility to utilize inverter current sensors (no extra cost needed) suggest spectral supply current analysis to detect them.

Air-gap eccentricity harmonics are very difficult to be detected due to the fact that they are very close to fundamental supply component and with smaller amplitude. [3,4].

Rotor slot harmonics (rsh) frequencies depend on motor speed, number of rotor slots, Z, the supply harmonic order, α, pole pair, p, the fundamental supply harmonic. Then for each supply component it is found on the spectrum a couple of rotor slot harmonics whose frequencies can be expressed as follows:

$$f_{sh} = \frac{Z}{p} \cdot f_r \pm \alpha \cdot f_0 \qquad (1)$$

where f_{sh} are the rotor slot harmonics frequencies in Hz and f_r is the rotor speed expressed in Hz and f_0 is the frequency of the supply component in Hz [8]. In a no load operation condition rsh frequencies are expressed as follows:

$$f_{sh0} = \left(\frac{Z}{p} \pm \alpha \right) \cdot f_0 \qquad (2)$$

Due to the fact that Z and p are normalized, f_{sh0} are integer multiples of the supply frequency and then not noticeable on the current spectrum. With common Z and p values the most noticeable rsh frequencies are positioned on the spectrum near the 11th/13th supply harmonic and then near signal harmonics with comparable amplitudes [2,3,7]. Loading the motor, rsh frequencies will move on the left of the spectrum, as shown from (5), and will increase their amplitudes, Fig.1.

$$f_{sh} = f_{sh0} - \frac{Z}{p}\left(f_0 - f_r\right) \qquad (3)$$

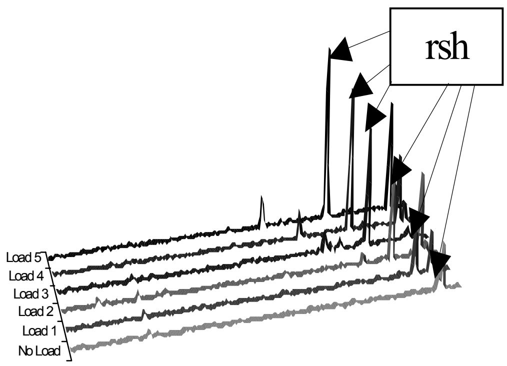

Fig.1 – Different current spectra for different load conditions, zoomed on rsh frequencies.

Therefore motor speed can be evaluated in rpm as follows:

$$n = \frac{60}{Z} \cdot \left(f_{sh} \pm \alpha \cdot f_0\right) \qquad (4)$$

As can be observed from (3), rsh moves only into a narrow frequency band limited by the maximum slip frequency and therefore it would be not necessary to analyze the entire signal spectrum. On the other hand it is necessary to evaluate fundamental supply frequency. Therefore the requirements for a rotor slot speed detection algorithm are the followings:

- low uncertainty spectrum in two different narrow frequency bands;
- short sampling time window.

The first requirement implies a reduced frequency distance between two next spectral lines in a narrow frequency band, i.e improved spectral resolution. The second allows to reduce errors due to not stationary current signals and to increase speed response thanks to a reduced processing time. These requirements are not in agreement each other in the case of Fast Fourier Transform (FFT), that is commonly used for speed detection. In fact, this algorithm is not suitable when a not stationary signal has to be analyzed in a narrow frequency band, because of good spectral resolution clashes with short sampling time window [5,6,9].

So it has been looked for a spectral analysis method able to evaluate rsh frequencies with a shorter sampling time window (lower number of sampled points) without increasing spectral resolution.

2.2 Spectral analysis method

In [5,6,9] it has been shown how Chirp Z Transform (CZT) allows to reduce resolution utilizing all sampled data to reconstruct signal in a fixed and limited frequency window. Setting appropriately different parameters, CZT algorithm evaluates Discrete Fourier Transform (DFT) only in a fixed frequency interval f_w. Spectral resolution is then equal to [5-9]:

$$\Delta f_{CZT} = \frac{f_w}{N} \qquad (5)$$

where N is the number of samples.

Therefore this algorithm can be used to obtain a limited spectral analysis with a considerably better resolution, i.e. lower, than other methods. Moreover using CZT algorithm it is possible to decrease spectral resolution both reducing frequency interval f_w and number of samples. On the other hand there are some limitations on both frequency interval (related to the maximum slip) and processed samples.

2.3 Number of processed samples and sampling frequency

Rotor slot harmonics frequencies depend on motor working conditions. For this reason it is not possible to obtain a synchronized sampling and then signal spectrum is anywhere affected by leakage error. This means that the energy of any harmonic component is distributed in a lobe instead of to be concentrated in a spectral line. It can be demonstrated that the width lobe of any spectral component is equal to $2/T_w$ [9], where T_w is the length of the sampling time window. Then a short sampling window implies an increase of the limit of reliability (the minimum distance between two different harmonics both noticeable on the signal spectrum) due to tonal interference between closed harmonics.

Therefore two opposite requirements must be fulfilled to choose sampling time window:

- reduction of the errors due to not stationary current signals and improvement of the algorithm speed response;
- reduction lobes width and improvement of the spectral resolution.

The sampling time window depends on both the sampling frequency and the number of acquired samples.

The sampling frequency is chosen taking into account the Nyquist's criterion and the performance of the microprocessor. Having fixed the sampling frequency samples number is determined trying to find the best compromise between the opposite requirements above mentioned. Thanks to zero padding it is possible to improve spectral resolution without increasing sampling time windows.

2.4 Zero Padding [9].

This spectral analysis technique refers to the operation of extending a sampled points sequence of length N to a length $N_z > N$ by appending N_z-N zero samples to the given sequence. In this way, the density of samples of the spectrum is increased from N to N_z. Hence, the spectrum between the real samples can be interpolated to an arbitrary density by sufficient zero padding.

On the other hand zero padding does not allows to improve the limit of reliability (determined by the amplitude of spectral components lobes, which depend on the length N of sampled points). Moreover, increasing the percent of zeros in the processed buffer, the amplitude of the harmonics in the spectrum decrease, so getting worse the spectrum. Therefore it cannot be reduced indefinitely samples number.

The result of the previous considerations is that zero padding can be used only to improve speed measurement method accuracy.

2.5 Double Chirp Z Transform speed measurement technique [7]

The steps of the algorithm are then the following:

- current signal filtering by means of an anti aliasing filter;
- sampling and buffering;
- windowing with an Hanning function to reduce leakage error [6];
- zero padding in cascade to buffered points;
- searching of fundamental frequency by a CZT of the buffered data applied to a frequency window corresponding to supply frequency range;
- searching of main rsh frequency by a CZT of the same buffered data applied to a frequency window corresponding to the maximum motor slip;
- speed evaluating by (4)

2.5 Method uncertainty.

It can be easily observed by the (4) that the maximum error related to the speed measurement is related to the spectral resolution. Then maximum method uncertainty is evaluable as follows:

$$E_n = \frac{60}{Z} \cdot \frac{\Delta f_z}{2} \cdot (1+\alpha) \qquad (6)$$

where Δf_z is the spectral resolution obtained with the zero padded buffer of samples.

3. MICROPROCESSOR ON LINE IMPLEMENTATION

The speed measurement technique has been implemented on line on a IBM Power PC 604e microprocessor of a DS1103 dSPACE control board. The algorithm has been developed by means of SIMULINK® graphical interface and user code written in C language. A speed detection method based on FFT has been implemented on line too in order to perform a comparison. In Table I the main features of both methods are summarised.

Table I – Comparison between the features of DOUBLE CZT and FFT speed measurement algorithms with a sampling frequency of 2kHz.

Speed measurement technique	Processed points		Processing time [s]	Δf [Hz]	E_n [rpm]
	Samples	Zeros			
DOUBLE CZT	256	256	0,128	0,058	0,17
FFT	1024	1024	0,512	0,976	2,92

Thanks to the better spectral resolution of CTZ, rsh frequencies can be evaluated with higher accuracy than by means FFT. Moreover, errors due to current unstationarity are reduced thanks to a shorter sampling time window. Finally the method uncertainty and the processing time of speed measurement algorithm based on CZT is lower than FFT based one.

4. EXPERIMENTAL RESULTS

Measurements have been carried out by means of a test bench made up by a 7.5 kW three phase induction motor fed by a PWM voltage source inverter and loaded by a dc machine with independent excitation supplied by a four quadrant ac-dc converter. Speed is mechanically measured by a direct current tachometer generator. To calibrate the DC tachometer generator, it has been applied the procedure described by the standard IEEE 251/84 “Test procedures for direct current tachometer generator”. The tachometer generator voltage has been sampled by dSPACE board and filtered with a 2th order Buttherworth low pass filter with 2 Hz cut–off frequency in order to reduce ripple. Current has been sensed by a Hall sensor with an active low pass filter (8th order Buttherworth with 850 Hz cut–off frequency) and then sampled by dSPACE board.

The induction motor can be driven either by the 50 Hz net or by the PWM inverter. The d.c. machine is fed by the four quadrant ac-dc converter. Varying the armature current reference of the current control loop it is possible to obtain any load torque.

A virtual instrument has been built to control and to monitor on line the running experiment. The instrument panel shown in Fig.2.

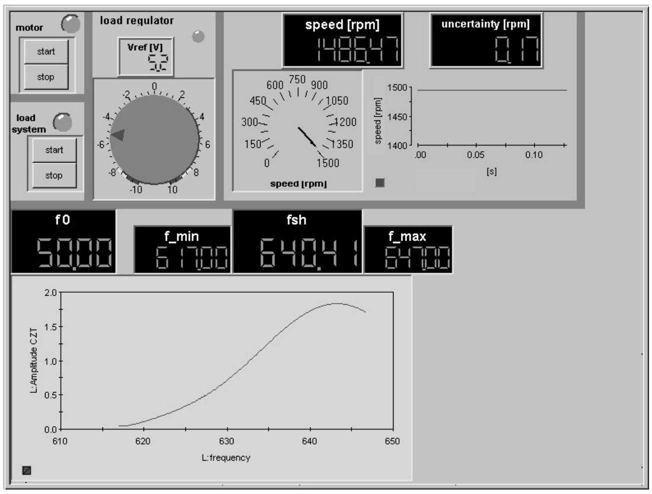

Fig.2 – Virtual instrument panel to control and to monitor the running experiment.

It is more interesting to show the experimental results in the case of the motor fed by the inverter because rotor slot harmonics are more difficult to be detected in the current spectra. In Figg.3 and 4 are shown respectively experimental speed detection by means of tachometer generator, CZT and FFT based methods in two different cases. In Fig. 3 the motor is fed at a constant frequency (50 Hz) and it is differently loaded. In Fig.4 the load is constant and the motor is fed at different frequencies.

The measurement carried out by means of tachometer generator cannot be considered as directly comparable with that obtained by the developed CZT and FFT algorithms; in fact, the first can be considered as a instantaneous voltage (speed) measurement, while the last carries out a speed measurement every 0.128 s, for the CZT, and 0.512 s for the FFT. According to the previous remarks, the reported tachometer generator speed measurement can only to be considered as referring value. From Figg.3 and 4 it is clear how the CZT method is in agreement with tachometer generator speed measurement.

5. CONCLUSIONS

This paper describes the development and the microprocessor implementation of a new induction motor speed method based on Chirp-Z Transform and zero padding of the supply current. To verify the proposed method a comparison has been performed with a method based on FFT spectral analysis. Experimental results have been carried out by means of a 7.5 kW induction motor running at different speeds and driven by a pulse width modulation PWM voltage source inverter. A virtual instrument has been built to control and to monitor on line the running experiment. Finally the advantages can be summarized as follows: increased accuracy due to shorter sampling time window and better spectral resolution; increased algorithm speed response thanks to a reduced processing time.

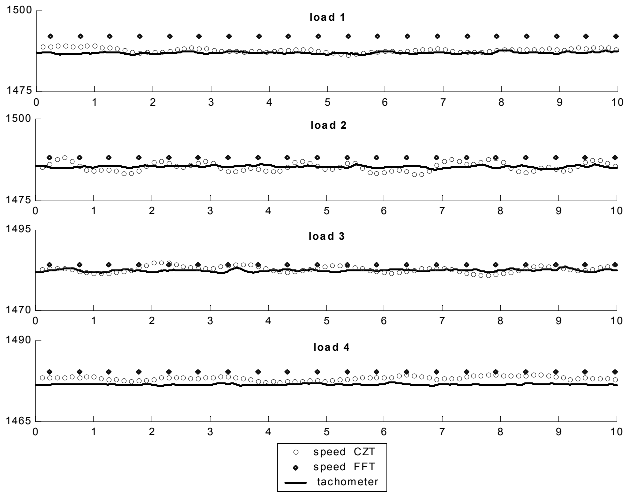

Fig.3 – Speed measurement by means of tachometer generator, CZT and FFT based methods when the motor is fed at a costant frequency (50 Hz) and it is differently loaded.

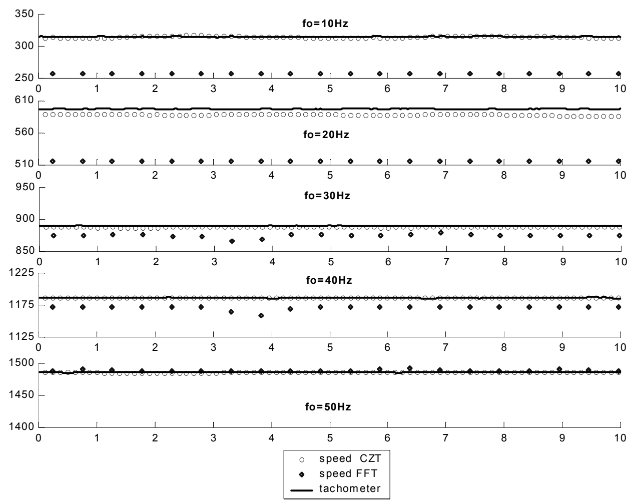

Fig.4 – Speed measurement by means of tachometer generator, CZT and FFT based methods when the motor is constantly loaded and it is fed at different frequencies.

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