Induction Motor Speed Estimator Using Rotor Slot Harmonics

Gabriela RAȚĂ[1] , Mihai RAȚĂ[1], Iulian GRAUR[2], Dan L. MILICI[1]
[1] *Stefan cel Mare University of Suceava*
str.Universitatii nr.13, RO-720229 Suceava
[2] *Gh. Asachi University of Iasi*
Bd. Profesor Dimitrie Mangeron,nr. 51- 53,RO-70050 Iaşi
gabrielar@eed.usv.ro

Abstract—This paper presents a solution for the estimation of induction machine rotor speed utilizing harmonic saliencies created by rotor and stator slotting. This solution purposes to add a carrier-signal voltage at the fundamental excitation. We obtain a carrier-signal current that contains the spatial information. The PWM reference voltage is calculated with DSP - ADMC401, from Analog Device.

***Index Terms*—Induction motors, harmonic analysis, speed measurement, pulse width modulated inverters, Fast Fourier transforms**

I. INTRODUCTION

The control of speed in electrical drives is usually obtained with mechanical transducer mounted on the machine shaft. In the recent years considerable efforts have been made to introduce speed- and/or shaft position-sensorless torque-controlled drives. Sensorless drives are becoming more and more important as they can eliminate the speed sensor maintaining accurate response. The concept of this technique is that the rotor speed is estimated from easily available voltages and currents of the induction motors and is used in the feedback loop of the speed controller. So, the electrical drives with AC motors are with speed transducer (close loop e.g. [5]) or without speed transducer (open loop system e.g. [4] or with speed estimation sensorless system).

The main objectives of sensorless drive control are:

- reduction of the cost
- increased mechanical robustness
- reduced size of the machine set
- elimination of the sensor cable
- decreased maintenance requirements
- higher reliability
- increased noise immunity
- unaffected machine inertia
- operation in hostile environments.

The techniques of sensorless control for induction motor drives are [1]:

- open-loop estimators using monitored stator voltages/currents and improved schemes
- estimators using spatial saturation stator-phase third harmonic voltages
- estimator using saliency (geometrical, saturation) effects
- model reference adaptive systems
- observers (Kalman, Luenberger)
- estimators using artificial intelligence.

II. ESTIMATORS USING ROTOR SLOT HARMONICS

It is possible to estimate the rotor speed, rotor position, and various flux linkages of a squirell-cage induction motor by utilizing different types of geometrical effects and saliency effects created by saturation. Thus the rotor speed can also be estimated by utilizing slot harmonics or eccentricity harmonics.

The rotor slot harmonics can be detected by using various techniques:

- ✓ Utilizing monitored stator voltages
- ✓ Utilizing monitored stator currents

In a speed-sensorless high-dynamic performance drive, the second technique is preferred since the monitoring of the stator currents is always required, but the voltage monitoring can be avoided.

In the following we discuss about the slip frequency and speed estimation using monitored stator currents:

The rotor speed can be established with the help of stator line currents monitoring and performing harmonic spectral estimation.

The stator current slot harmonic can be obtained by eqn (1), thus if a stator line current of a PWM inverter-fed induction motor is monitored, then $f_{shk} = N_r f_r \pm kf_1$ holds, where $f_r = f_1(1-s)$.

$$f_{shk} = \begin{cases} N_r f_r \pm kf_1 = 3Nf_1 \pm 6mf_1 - N_r f_{s1} & k = 6m-1 \\ N_r f_r \mp kf_1 = 3Nf_1 \mp 6mf_1 - N_r f_{s1} & k = 6m+1 \end{cases} \quad (1)$$

An example for the measured frequency spectrum of a loaded inverter-fed induction motor which has Z_2 = 28 rotor slots, $2p$ = 4, f_1 = 50 Hz is presented in [1].

The Figure 1 shows this example. Due to the inverter, in the window shown, the harmonics present are: 150 Hz, 250 Hz, 350 Hz, 450 Hz. In agreement with

$$f_{shk} = N_r f_1(1-s) \pm kf_1 = 14x50x(1-s) \pm kx50 \quad (2)$$

the slot-harmonic frequencies 14x50x0.988 – 5x50 = 442 Hz; 14x50x0.988 – 7x50 = 342 Hz, and 14x50x0.988 – 9x50 = 242 Hz are also present.

For the purpose of speed estimation, in a PWM inverter-fed induction motor drive, a line current is monitored,

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scaled, and low-pass filtered (to eliminate high frequency PWM harmonics) and e.g. digital FFT can be used to detect the speed-dependent rotor slot harmonic (f_{sh}). When f_{sh} is known, the rotor speed can be obtained as:

$$\omega_r = 2 \cdot \pi \cdot f_r = 2 \cdot \pi \cdot \frac{(f_{sh} \pm f_1)}{N_r} \quad (3)$$

where:

- f_1 is the fundamental stator frequency
- N_r is the number of rotor slots per pole-pairs ($N_r = Z_r / P$, Z_r = *the number of slots, P = the number of pole-pairs*)

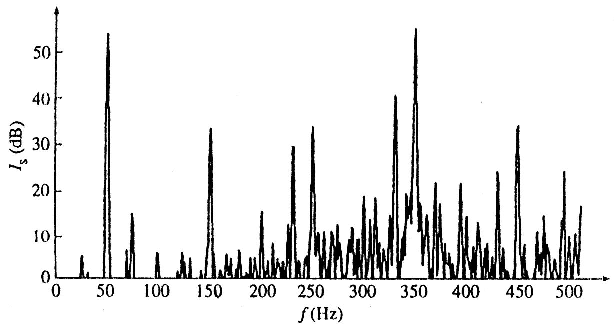


Figure 1. Measured stator-current frequency spectrum of an induction motor [1].

It is clear from eqn (1) that the accuracy of the estimated rotor speed depends on the accuracy of f_{sh} and f_1.
For the estimation of f_{sh} it is necessary:

- identification of f_1
- determination of the no-load slot harmonic around a specific stator harmonic
- defining the width of the slot harmonic tracking window
- searching for the highest-amplitude harmonic in the window which is a non-triple harmonic of f_1
- increasing the accuracy of the f_{sh} estimation

III. EXPERIMENTAL RESULTS

This paper presents a solution for the estimation of induction machine rotor speed utilizing harmonic saliencies created by rotor and stator slotting. This solution purposes to add a carrier-signal voltage at the fundamental excitation. We obtain a carrier-signal current that contains the spatial information.

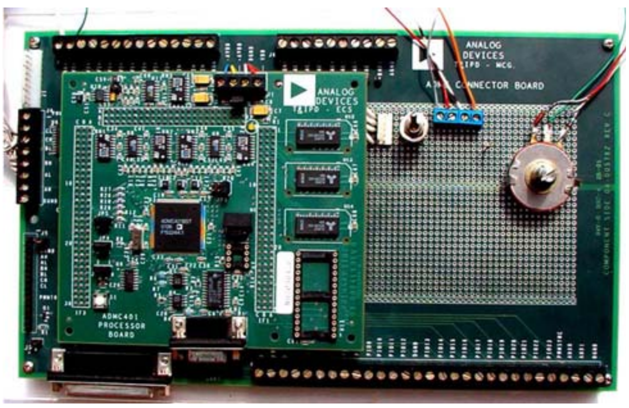


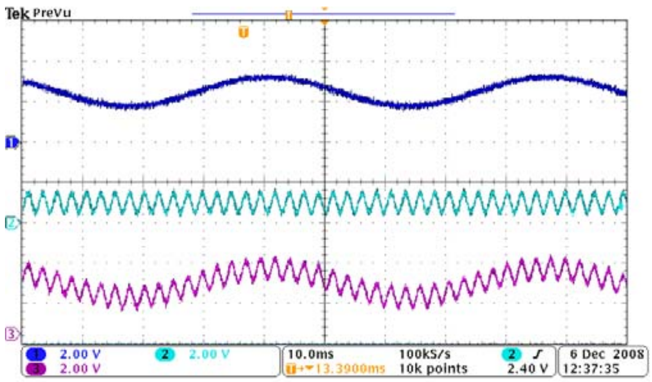
Figure 2. ADMC401 processor board.

The PWM command signals are obtained with an ADMC401 processor board from Analog Device, illustrated in Figure 2. This board is a compact, highly flexible evaluation and development board for the single-chip DSP-based high-performance motor controller, the ADMC401.

The ADMC401 is a single-chip DSP-based controller, suitable for high performance control of ac induction motors (ACIM), permanent magnet synchronous motors (PMSM), brushless dc motors (BDCM) and switched reluctance (SR) motors in industrial applications. The ADMC401 integrates a 26 MIPS, fixedpoint DSP core with a complete set of motor control peripherals that permits fast motor control in a highly integrated environment. [3], [6]

This DSP can be programmed to produce the required PWM signals based on the well-known three-phase sine-triangle PWM techniques. The PWM generation unit is programmed to produce a balanced three-phase set of output signals that have a constant volts/hertz ratio.

As we said before, the induction motor speed estimator is based on the introduction of a constant-frequency carrier signal in the stator currents. For that the PWM reference voltage (the Ch. 3 waveform in Figure 3) is calculated with DSP by adding to the sinusoidal PWM reference voltage (the Ch. 1 waveform in Figure 3) of a fixed frequency carrier signal (the Ch. 2 waveform in Figure 3).



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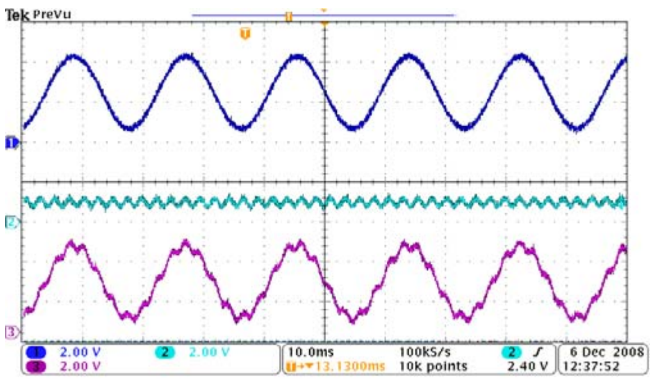


b)

Figure 3. DSP signals with different carrier signal amplitude.

It's possible to adjust the amplitude of carrier signal, as shows Figure 3.a and 3.b with an external analog input by an external potentiometer. These signals are visualized with the oscilloscope through the DAC connector board.

The frequency of carrier signal is 400 Hz, because is far from the main frequency and allows to generate more than one left side band frequency. This frequency neither interfere with the PWM pulsation which, with the actual semiconductor device such as IGBT's, are in the ten kilohertz region (we chose this frequency 10 kHz). [2]

The PWM command signals obtained from DSP board control are send to a power inverter realized with an ASIPM module PS12017 from Mitsubishi Electric. [7]

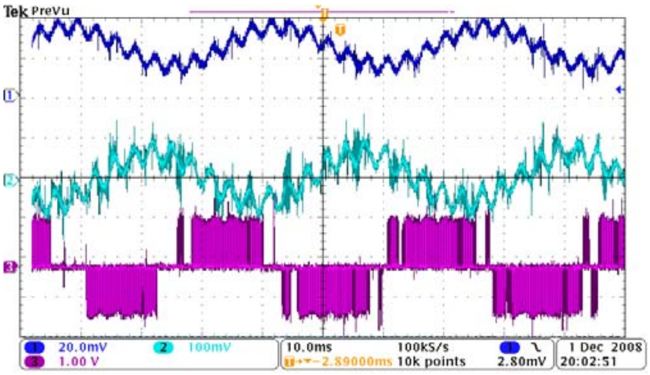
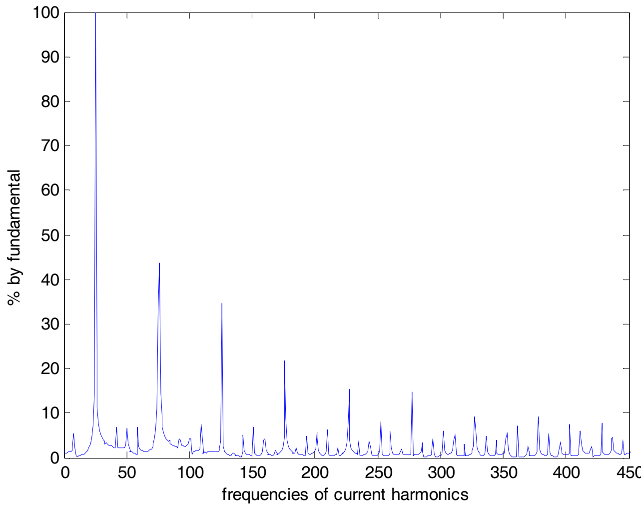
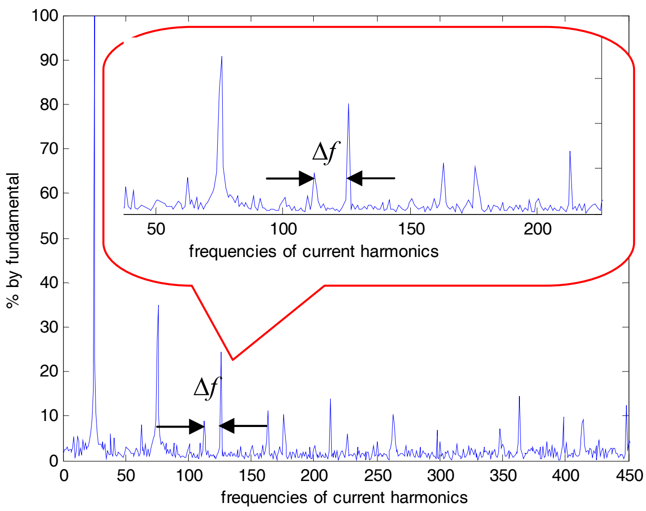


Figure 4. The motor signals with carrier signal.

In Figure 4 is presented the motor current and voltage obtained with fixed frequency carrier signal.



a)

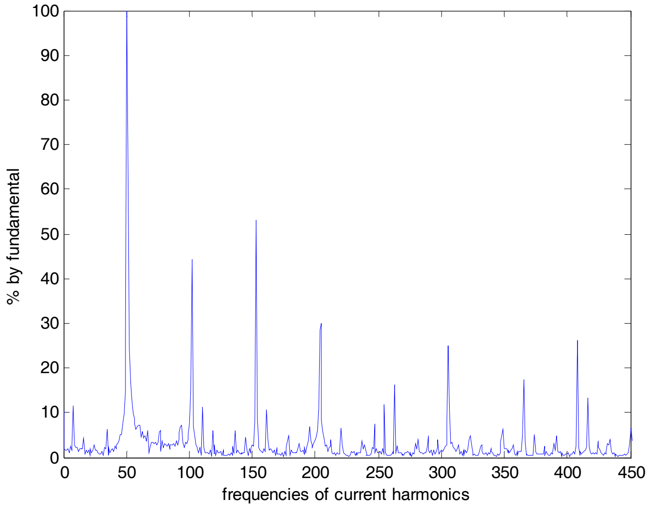


b)

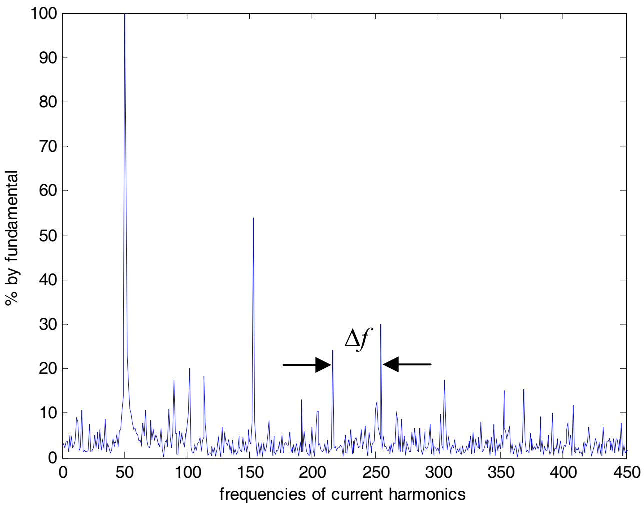
Figure 5. Harmonics motor current at 25 Hz .

The harmonic analysis for the motor current is realized. For that it's used the DSP tracebuffer structure where the current values can be saved in a data array. These data are imported in Matlab software for harmonic analysis.

The FFT algorithm is applied for these data. FFT transform can only process a sampled waveform where N (number of samples) is a power of 2. Acceptable values of N include 128, 256, 512 and 1024. We choose 1024 samples. In accordance with Shannon's theorem the sample frequency must be more than twice the highest frequency of the spectrum signal. [8]. If we analyze 40 harmonics it is necessary to have 40 KHz sample frequency.



a)



b)

Figure 6. Harmonics motor current at 50 Hz .

First it is thought that the motor has 1/2 nominal speed (in this case the fundamental is at 25 Hz), second it is thought that the motor has nominal speed (in this case the fundamental is at 50 Hz). Harmonics spectrum of motor current is analyzed in these cases. In Figure 5 is presented the induction motor current harmonics spectrum for 25 Hz (it can see that the fundamental is at 25 Hz), without carrier-signal voltage in the fundamental reference voltage (figure 5.a) and with carrier-signal in the fundamental reference voltage (figure 5.b). The Δf frequency is measured between harmonics at frequency at $5f$ (where, f = 25 Hz is fundamental frequency) and corresponding slot harmonics. Figure 6 present the same signals, but for 50 Hz for fundamental frequency.

We can observe the difference of Δf width in these two situations presented in Figure 5.b and 6.b.

It can remark that the Δf is depending by fundamental reference voltage and of course by speed motor.

Figure 7 shows the arrangement for the experimental data.

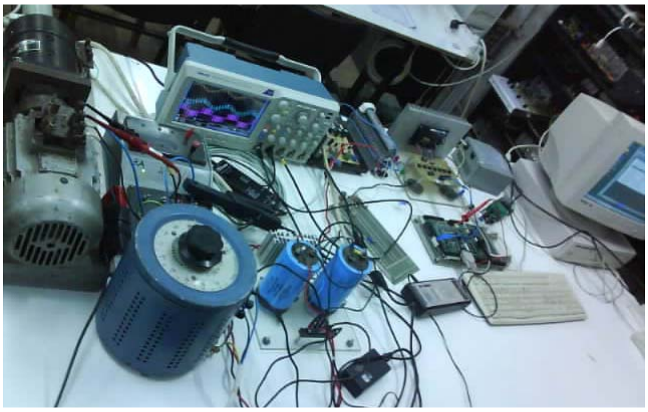


Figure 7. The experimental arrangement.

IV. CONCLUSION

The sensorless control has many advantages. Some of these are the low cost and good reliability. The rotor speed information is obtained from measured stator voltages and currents at the motor.

In this paper we estimate the speed through the detection of irregularities in the rotor (e.g. slot harmonics), that generate amplitude oscillation in the motor currents (generated by the carrier). So, the motor speed is proportional with the amplitude modulations frequency.

The estimator is based on the introduction of a constant-frequency carrier signal in the stator currents. Because in the last years the microprocessors have improved in speed a hundredfold, now is very easy to realize this stator currents.

We can estimate the induction motors speed by measuring of the Δf width.

Because the synchronous machines have high reluctance variation produced by the poles it's clear that, this method can be used also for these machines.

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