Real- time speed estimation of induction machines using rotor slot harmonics

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***Abstract*—This work proposes an algorithm for sensorless detection of the rotor speed applied to induction machines. The method relies on variable magnetic reluctance, caused by the rotor slots. The analysis shows that the reluctance changes produce slot-related harmonics in the stator current. The frequency of such harmonics is related to the rotor speed. Proposed is the algorithm that tracks the slot harmonics and derives the rotor speed. The paper includes the key details of the on- line DSP implementation that runs in parallel with the remaining drive- control functions. Experimental verification and comparison to the state of the art solutions is performed on a three phase induction motor.**

***Index Terms*—Induction machines; Speed estimation; Rotor slot harmonics; Digital signal processing;**

I. INTRODUCTION

Induction motors are most commonly used electrical motors. It is because of their robustness, price and low maintenance needed. Today, with the growth of renewable energy sources induction machines (IM) are getting another use as wind turbine generators. In a large variety of applications speed regulation is needed. For example, in order for wind turbines to exploit maximum wind energy, blades must change their rotational speed as the wind speed changes [1]. In traditional applications speed sensors are commonly used. Their greatest fault is impact on system reliability because if they fail speed regulation becomes impossible. That problem is even more significant for wind turbines because generators are mounted on towers which can be above 100m tall. Every intervention on those generators would require significant amount of time and money. Therefore, speed estimation would improve system reliability which would result in cheaper exploitation.

One of methods for speed estimation is analysis of rotor slot harmonics (RSH). Frequencies of RSH carry information on rotational speed so by being able to extract them from current signal it is possible to calculate speed of the induction machine. Detailed theoretical explanation and derivation of formulas for RSH are shown in [2]. In this paper principle of generation will be shortly explained.

II. ROTOR SLOT HARMONICS

For one stator phase of the induction machine, with neglect of stator coil resistance, it is possible to write Kirchhoff's second law equation in S- domain:

$$U = s\Psi \tag{1}$$

- $s=\sigma+j\omega$
- Ψ- magnetic flux

From (1) we conclude that if the voltage doesn't change neither does flux. While machine is spinning, rotor slots will periodically intersect path of the flux. Squirrel cage bars are made out of aluminum, which has smaller magnetic permeability than iron, so in order to maintain constant flux, required energy changes which results in pulsation of stator current. This is shown in (2) and (3).

$$R_\mu \sim \frac{1}{\mu} \tag{2}$$

- R_μ- magnetic reluctance
- μ- magnetic permeability

$$\Psi = \frac{Ni}{R_\mu} \tag{3}$$

- N- number of stator windings
- i- stator current

Stator current will pulsate at frequency which is directly proportional to number of rotor slots and rotational speed. These frequencies also depend on machine construction and number of poles. Frequencies of RSH are shown in (4).

$$f_{sh} = \left[N_r \frac{1-s}{p} \pm \delta\right] f_1 \tag{4}$$

- f_{sh}- frequency of RSH
- f_1- fundamental frequency
- N_r- number of rotor slots
- s- induction machine slip
- p- pole pair number
- $\delta = \pm 1$

It is explained in [3] that not all components of RSH can exist for every machine. Depending on pole and slot number one frequency component or components in pairs can be generated. It is necessary to calculate which RSH will exist in given machine. To formalize this, in [3] is given equation:

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$$N_r = 2p(3\alpha + \rho) \tag{5}$$

Nr is number of rotor slots, α is natural number (1, 2...) and ρ can take values of {-1, 0, 1}. If ρ takes value of -1, only RSH related to $\delta = 1$ in (4) will be generated. For $\rho = 1$, $\delta = -1$ and for $\rho = 0$, both harmonics will exist ($\delta = \pm 1$).

III. THE SPEED ESTIMATION ALGORITHM

In this paper, RSH are extracted from stator line current of induction motor. Spectral analysis is done using Fast Fourier Transform (FFT) algorithm. For stator current sensing, current transformer is used. Resistor is connected to the secondary windings in order to get voltage signal. Electronic circuit, shown in Fig. 1, is used to adapt the signal to AD convertor range (0-3) V. Before AD conversion, analog filter must be used for "anti-aliasing". For better signal/noise ratio, *oversampling* technique is used as a way of digital filtration. Signal is processed and speed is estimated on DSP based platform, which uses TMS320F28335 device.

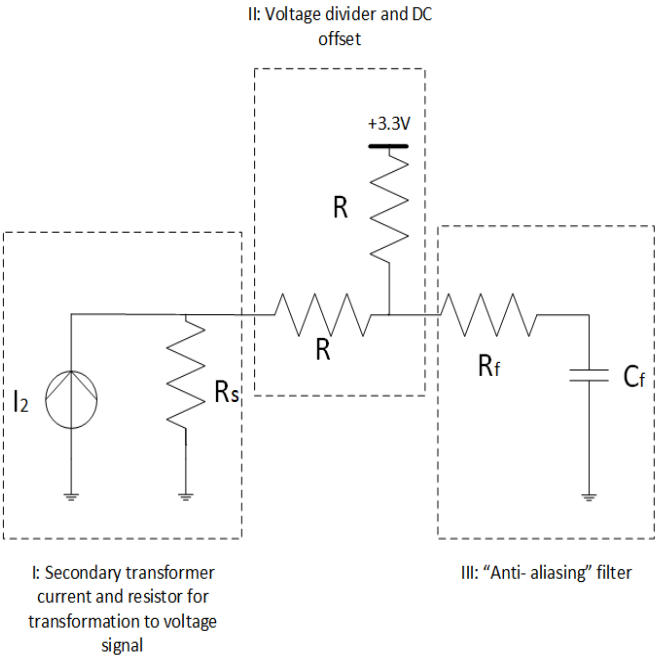

Fig. 1. Electronic circuit for signal adaptation

In order to implement real- time speed estimation, DSP algorithm must contain AD conversion, digital signal processing, FFT, extraction of RSH from array of spectral components and speed calculation. Signal must be sampled with high enough frequency to be able to extract RSH and data window length must be long enough to get satisfying resolution in spectrum. For maximum desired frequency f_{max} and resolution of f_{min}, sampling criteria are shown in (6) and (7).

$$f_s \geq 2 f_{max} \tag{6}$$

- f_s- sampling frequency

$$T_w \geq \frac{1}{f_{min}} \tag{7}$$

- T_w- time length of data window

DSP controllers such as TMS320F28335 have integrated fast 12-bit ADC peripheral, which can be synchronized with the PWM pulse generator. That way, we can sample current signal in exact moments of time. For optimized processing, *Direct Memory Access (DMA)* module is used to transfer data to RAM memory of DSP.

After initializing all the hardware modules, program enters the main loop. Firstly, timer is set to T_w in order to get enough samples in data buffer. Signal is oversampled and then stored in buffer which is used in FFT calculation. After T_w has expired FFT is applied in order to get spectral components of discrete stator current signal. For FFT algorithm we used library *FPU.h* which can be found in *ControlSuite* software that *Texas Instruments* offers. Functions used are *RFFT_f32u.asm* and *RFFT_f32_mag.asm.* Result of these functions is array which contains magnitudes of harmonics which are present in stator current. In next step we must define frequency span where RSH will be searched for. It must be defined specially for each machine in order to be certain that no other components than RSH will be dominant in chosen bandwidth. As shown in (4), slot harmonics can be generated in pairs or single so we must calculate from (5) which RSH are we searching for. One way for extracting desired slot harmonic is described here. Given that fundamental frequency of stator voltage is known and that maximum rotational speed of IM is just below synchronous speed we are certain that RSH will be generated on frequencies lower than frequency f_{sh}^{s}. That is the frequency calculated from (4) for s=0 (no slip) and it defines upper boundary for RSH search. Lower boundary is calculated by inserting IM's maximum slip in (4). After that, we simply search for maximum in defined boundaries of magnitude array and calculate that component's frequency as in (8).

$$f_{sh} = f_{per\ sample} * i_{max} \tag{8}$$

- $f_{per\ sample} = \frac{1}{T_w}$ – frequency resolution
- i_{max}- array index of maximum harmonic

In the end, (4) is used to calculate slip and then rotation speed. After that, timer is reset and data acquisition starts again.

IV. EXPERIMENTAL RESULTS

Estimation was experimentally tested on induction motor which was mechanically coupled to DC generator. By changing resistance in generator's armature circuit we change the mechanical power provided by IM which results in change of rotor slip. Experimental setup is shown in Fig 2.

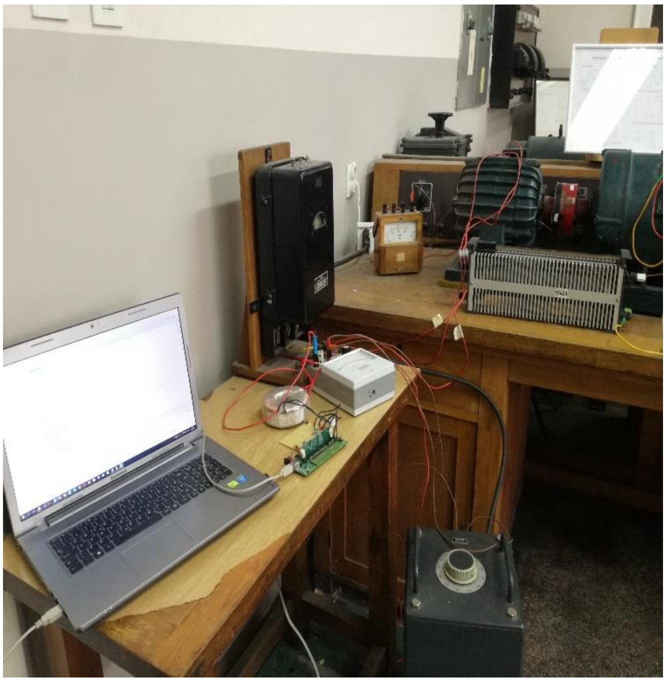

Fig. 2. Experimental setup

Relevant motor data and electronic circuit parameters calculated for given motor are given in the Appendix. From (4) and (5), for given motor data (see Appendix) we conclude that both components of RSH will be generated and that their frequencies won't be higher than 1 kHz. That information is used to calculate sampling frequency from (6). As good enough resolution we chose $f_{min}=1.85Hz$ which resulted in calculating T_w from (7). For maximum calculation speed, used FFT function requires data window size to be 2^n. All these criteria together resulted in next sampling parameters:

- $N = 4096$ – *number of data samples for FFT*
- $T_w = 540ms$ –*length of data window*
- $f_s = 7.585\ kHz$ –*sampling frequency*

Signal is oversampled 32 times, which results in sampling frequency over 200 kHz. This allows use of *RC* filter with higher cutoff frequency, f_{rc}. Chosen is the filter with $f_{rc}=22$ kHz.

First measurements were done to determine the RSH in spectrum. Speed was measured with infrared speed sensor and results of FFT were exported to PC and plotted in MATLAB. Fundamental frequency has much higher magnitude than any other in current spectrum which is why results were plotted in logarithm scale relative to fundamental component. Results for speed $n_n=1496min^{-1}$ (no load) are shown in Fig. 3 and 4.

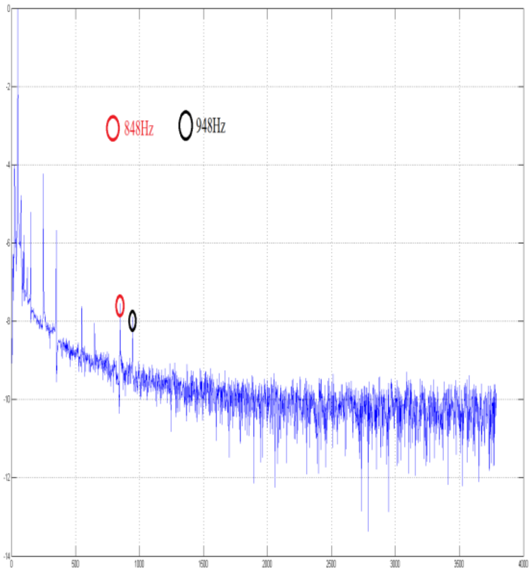

Fig. 3. Spectral components of stator current at $n_n=1496min^{-1}$

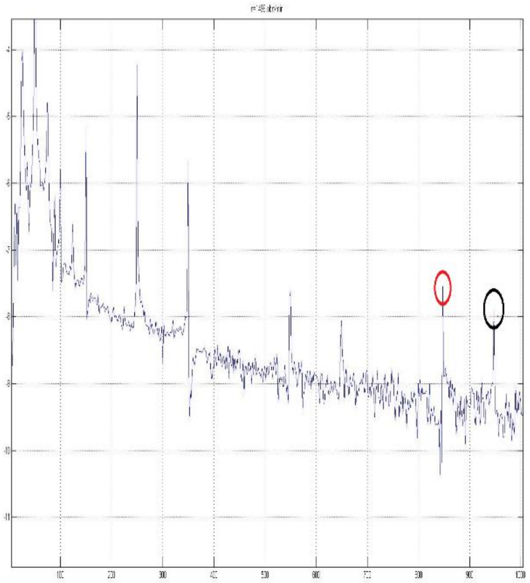

Fig. 4. Zoomed in spectral components of stator current at $n_n=1496min^{-1}$

Two slot harmonics (marked with red and black circles) are present at 848Hz and 948Hz which is in accordance with (4) and (5).

After this, real- time measurements were performed from no-load (maximum) speed to minimum speed (determined by stator rated current) and back to no- load speed again. Estimated speed was compared to the measured one and absolute and relative errors were calculated. Results are shown in Table 1.

TABLE I
RESULTS OF REAL- TIME ESTIMATION

Measured speed [min^{-1}]	Estimated speed [min^{-1}]	Absolute error [min^{-1}]	Relative error [%]
1496	1495.8	0.2	0.013
1480	1483.33	3.33	0.225
1465	1471.67	6.67	0.45
1447	1458.33	11.33	0.783
1416	1435	19	1.34
1405	1425.88	20.879	1.486
1428	1444.397	16.397	1.148
1446	1459.829	13.829	0.956
1464	1472.174	8.174	0.558
1480	1484.519	4.519	0.305
1496	1496.865	0.865	0.0578

Results show that used method provides good results. Error grows with increasing load but stays in satisfying boundaries. Biggest absolute error is around 21 min^{-1}, which is less than 1.5%. Comparison of estimated and measured speed is given in Fig 5.

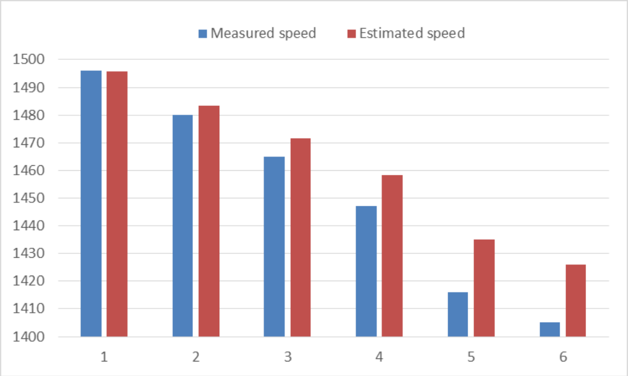

Fig. 5. Results of real- time estimation

V. CONCLUSIONS

This paper presents real- time implementation of FFT based method for rotor speed estimation using rotor slot harmonics. Advantages of given method are simple hardware and insensitiveness to machine parameters changes which occur during operation. Method provides good results under real-time load changes and has refresh rate of about 540ms. It is suitable for wind generators as their rotational speeds are low. The disadvantage is imprecise measurement for high speeds because of lack of the memory space in DSP. For high rotating speeds, RSH will be on higher frequencies which results in higher sampling frequency (6). To keep satisfying resolution (7) T_w must be long enough. Those two conditions combined result in high DSP memory demands.

For further work, FFT related memory problems can be solved by using digital adaptive band pass filter instead.

APPENDIX

Motor used in experimental setup:

Rated power $P_n = 2.4kW$
Rated voltage $U_n = 380V$
Rated current $I_n = 5.3A$
Rated speed $n_n = 1405\ min^{-1}$
Rated frequency $f_n = 50Hz$
Winding connections Y
Number of poles $2p = 4$
Number of rotor slots $N_r = 36$

Electronic circuit for signal adaptation

Resistor in secondary circuit $R_s = 6\Omega$
Voltage divider resistors $R = 47k\Omega$
Filter resistor $R_f = 330\Omega$
Filter capacitor $C_f = 22\ nF$

REFERENCES

[1] Ke Ma, Power Electronics for the Next Generation Wind Turbine System, Springer, 2015.

[2] VAS,P.: Parameter Estimation, Condition Monitoring, and Diagnosis of Electrical Machines, Clarendon Press, Oxford, 1993

[3] W. L. Silva, A. M. N. Lima, A. Oliveira "Speed Estimation of an Induction Motor Operating in the Nonstationary Mode by Using Rotor Slot Harmonics," *IEEE Transactions on Instrumentation and Measurement*, Vol: 64, Issue: 4, April 2015, pp 984 – 994