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Slip Frequency Calculation Method in Speed Sensorless Induction Motor Drives

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Abstract – **Analysis of the PWM induction motor drive, where the regulation is made without the speed sensor, with the method of frequency compensation is presented in the paper. On the basis of the proposed method, compensation for the slip frequency and voltage drop compensation, being very important especially at the low speed range, is done. Slip frequency is determined on the basis of non-linear torque-speed dependence.**

Keyword – **Variable frequency, Speed control, Sensorless**

I. Introduction

Induction motor drive based on full digital control is being applied in a great number of industrial application, begining from low cost drive to high performance. Great part of scientific efforts, in the last few yers had a goal of eliminating the speed sensor, saving good static and dynamic performances like a solution with speed sensors. AC drives without speed sensor, according at methods applied for speed regulation can be clasified in two groups: 1) low cost drive of general purpose, 2) high performance drive.

In the first group of drive some of the following methodology foor speed calculation are used: slip frequency calculation method, constant volts-per-herts control, slot space harmonics, frequency compensation method [1].

In the second group following methods are applied: speed estimation, model reference adaptive method, speed observers, Kalman filter techniques, neural nerwork based estimator [1]. Most of these method for speed estimation is carried out from methods applied in vector control techniques which had a purpose of determination of "inaccessable" quantities (flux and torque).

All of these methods are based on procedure which comprehends measurement of electrical stator quantities, directly or in DC link of the inverter with phase current reconstruction performed switching function and knowing motor parameters. However, in practice, simple, cheap and reliable drive are often needed, where it is possible to control speed, with more modeset requests regarding dynamical features.

In this paper one of the slip compensation method is analysed. The proposed control algorithm is based on frequentcy calculation by using air gap power estimation and nonlinear relationship between slip frequency and air gap power. Besides frequency compensation, the stator resistance voltage drop compensation is realized.

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The proposed control scheme requires motor name-plate data, the stator resistance value and instataneous stator current in two phases. The basic characteristics of the drive with the applied algorithm are the simplicity of the practical realizetion, fair steady state and transient characteristics, and the price not higher than the open loop frequency controlled drive.

II. Frequency and Voltage Drop Compensation

The criterion for the stator frequency selection for a given load and the reference speed is illustrated in Fig. 1.

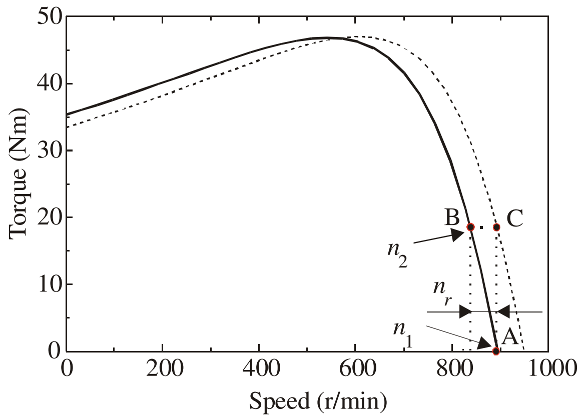

Fig. 1. The speed compensation principle

If the speed at no load was n_1 (point A), with the load increase operating point moves to the point B, with the speed "drop" of n_r. To compensate for the speed "drop", the cont–roller increases the speed to $n_2 + n_r = n_1$ by means of increasing the frequency, thus moving the operating point to C. In this way, the actual speed is again equal to the reference speed n_1 from the point A.

In order to implement this scheme it is necessary to know the relationship between load torque and slip. One of the possibilities is to assume a linear relationship between them [2]. Although this technique gives good results for high speeds its usefulness at low frequency and large torques is limited due to large steady state errors introduced by the linear approximation. To avoid above mentioned problem it is necessary to take account non-linear torque-speed characterristic of the motor [3,4].

The Electrical Machine Theory establishes the relationship for the electromagnetic torque (M_m) and break down torque (M_{pr}):

$$M_m = \frac{2M_{pr}}{s / s_{pr} + s_{pr} / s} \tag{1}$$

where s_{pr} is the slip at which the break down torque occurs. Eq. (1) is valid for any torque it is also valid for rated conditions. Defining $M_{pr}=\nu \cdot M_n$ and using Eq. (1) yields:

$$s_{pr} / s_n = k = \nu + \sqrt{\nu^2 - 1} \tag{2}$$

which is the break down slip in per unit of the rated slip (s_n).

Substituing Eq. (2) into Eq. (1), the slip (s) required to produce electromagnetic torque M_m can be writen as:

$$s = k \cdot \nu \cdot M_n \cdot \frac{s_n}{M_m} \left[1 - \sqrt{1 - \left(\frac{M_m}{\nu} \cdot M_n \right)^2} \right] \tag{3}$$

For the practical reasons we need to eliminate the load torque from Eq. (3). The elimination can be done by using Eq. (4):

$$M_m = (p / 4\pi) P_{ob} / (f_m + f_r) \tag{4}$$

where p is the number of poles, P_{ob} is the air gap power, f_r is the slip frequency, and f_m is the frequency which corresponds ti the actual rotor speed.

Solving the Eqs. (3) and (4) for the slip frequency can be obtained:

$$f_r = \frac{1}{2 - a \cdot P_{ob}} \left(\sqrt{f_m^2 + \frac{k \cdot s_l}{2 \cdot \nu} P_{ob} - b \cdot P_{ob}^2} - f_m \right) \tag{5}$$

$$a = p / (4\pi k \nu M_n s_n f_n); \qquad b = \left(p / (4\pi \nu M_n) \right)^2$$

When the ratio between the break down and rated torque is enough large, constants a and b become small and can be neglected. The physical explanation of this is that we have linear aproximation of mechanical motor characteristics, i.e the break down torque assume infinite value. For the linear dependence, in this case, for the slip frequency can be aproximately writen as:

$$f_r \approx 1/2 \left(\sqrt{f_m^2 + s_l \cdot P_{ob}} - f_m \right) \tag{6}$$

where $s_l = p s_n f_n / \pi M_n$.

Air gap power (P_{ob}) can be obtained by using expresion:

$$P_{ob} = 3 V_s I_s \cos\varphi - 3 I_s^2 r_s - P_{Fe} \tag{7}$$

To determine power P_{ob} it is necessary to know rms value of induction motor stator currents and active component of stator current. Assuming the symetrical sysytem, the rms current value can be obtained by measuring instataneous phase current as:

$$I_s = \sqrt{2/3} \cdot \sqrt{i_{as}(i_{as} + i_{cs}) + i_{cs}^2} \tag{8}$$

The active stator current components can be obtained by qd transformation in synchronous reference frame as follows:

$$I_{s(\mathrm{Re})} = \sqrt{3} \{ i_{ac} \cos(\omega t - \pi / 6) - i_{cs} \sin(\omega t) \} \tag{9}$$

The last term in Eq. (7) under variable frequency operation is difficult to obtain but it can be approximated from the knowledge of rated values and constant flux operation. It can be easily shown that the core losses for nominal load:

$$P_{Fen} = P_{u\ln} (1 - \eta_n / (1 - s_n)) - 3 I_{sn}^2 r_s \tag{10}$$

Core losses can be devided into two components [5]:

$$P_{Fen} = K_h B_n^2 f_n + K_e B_n f_n^2 \tag{11}$$

where K_h i K_e are coeficient which depend of core type, B_n is rated flux density.

For constatnt flux operation these losses only vary with frequency. Assuming that at rated conditions both components are equal, after some manipulation, the total core loss at any frequency can be writen in terms of its rated value as:

$$P_{Fe} = \frac{1}{2} \left(\frac{1+s}{1+s_n} \left(\frac{f_s}{f_n} \right) + \frac{1+s^2}{1+s_n^2} \left(\frac{f_s}{f_n} \right)^2 \right) P_{Fen} \tag{12}$$

Substituting Eq. (12) into Eq. (7) gives air gap power as a function of reference frequency and measured variables. The slip measurement required in Eq. (12) is obtained from Eq. (5) or Eq. (6).

Voltage drop compensation can be obtained by keeping magnitude of the leakage stator flux at the constant and rated value. Based on the phasor diagram shown in Fig.2 can be writen:

$$V_s = I_s r_s \cos\varphi + \sqrt{(V_{s0} f_s / f_n)^2 - (I_s r_s \sin\varphi)^2} \tag{13}$$

where with V_{s0} is marked amplitude of E_m at rated frequency f_n. The value for E_m needed for constant flux keeping (V/f=const.) at any another frequency f_s can be obtained as:

$$E_m = V_{s0} f_s / f_n.$$

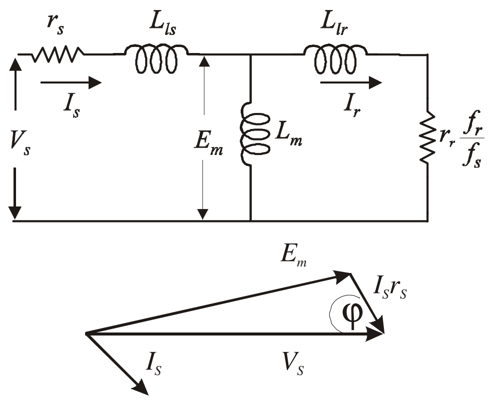

Fig. 2. Induction motor eqivalent circuit and phasor diagram

For implementation of equation (13) the value of rms stator current I_s is needed like its active components which can be obtained based on the equation (8) and (9). Final expression for stator voltage at any frequency and based of the instantaneous measurements of motor current is:

$$V_s = \frac{\sqrt{2}}{3} \cdot I_{s(\mathrm{Re})} r_s + \sqrt{\left(\frac{V_{s0} f}{f_n}\right)^2 + \frac{2}{9}\left(I_{s(\mathrm{Re})} r_s\right)^2 - \left(I_s r_s\right)^2} \quad (14)$$

III. Simulation and experimental results

In Fig.3 the block diagram of the drive is shown so the basic idea of applied speed regulation modus can be seen. Due to existing positive feedback at frequency compensation and voltage it is necessary to stabilize the system by using low-pass filter in the feedback loop.

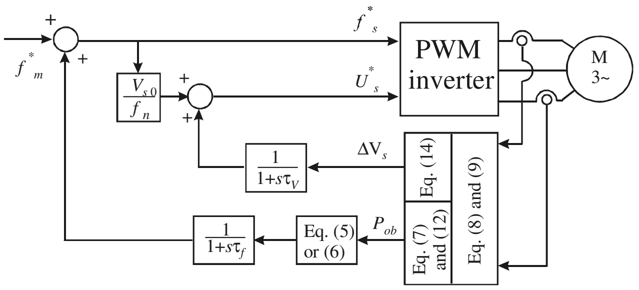

Fig. 3. Block diagram of the drive

The system is complex and nonlinear, therefore the dynamics were investigated on the corresponding model based on the fundamental component of the variables (large model) and the adequate linearized model [6,7]. The model that considers only the fundamental components of the varible was formed in Matlab/Simulink, after that the linearized model was developed by using incorporated linearization function.

Some results for different low-pass filter cut-off frequencies and for reference speed n_{ref} =400 r/min are shown on Fig. 4 and Fig. 5. The regions of instability are, in Fig.4, at low load and for filter cut-off frequency f_{cutoff}=150 Hz.

The analyses performed pointed out that the existence of the low-pass filter in the voltage and slip frequency feedback path has the crucial influence on the stability of the system. The filter cut-off frequency was chosen to be as low as the characteristic frequencies in the mechanical subsystem transients. This ensures a stable operation and good dynamic performance. The proposed speed control method is after that analysed by computer simulation on a detailed drive model, and than on the experimental results obtained on laboratory model.

Simulation results are obtained by using Matlab program package. In Fig. 6 simulation results obtained for reference speeds of 200, 600 and 1000 r/min are shown. First, drive system operated at the no-load while load torque in stedy state was 50% of rated torque. The speed regulation effect with and without speed regulation is illustrated in Fig.6. In it is clearly marked the moment of switching off regulation resulting in speed reduction. Dependence of the load torque versus time is also shown in figure.

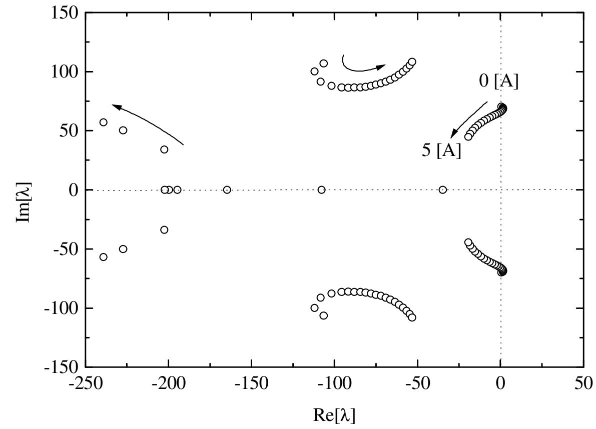

Fig. 4. Drift of eigenvalues for n_{ref}=400 r/min, f_{cutoff}=150 Hz

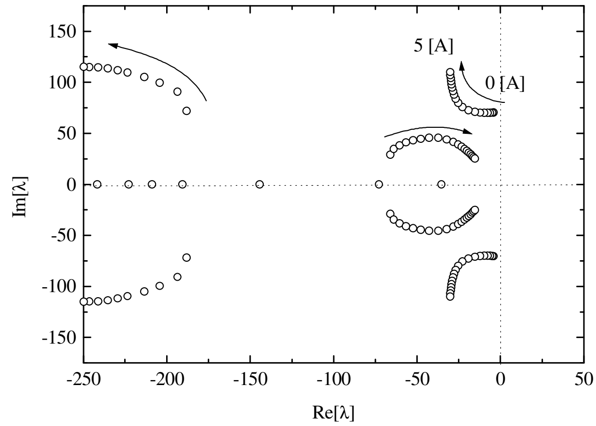

Fig. 5. Drift of eigenvalues for n_{ref}= 400 r/min, f_{cutoff}= 50 Hz

Experimental verification of the proposed algorithm were made on the induction motor drive; its parameters are given in appendix A.

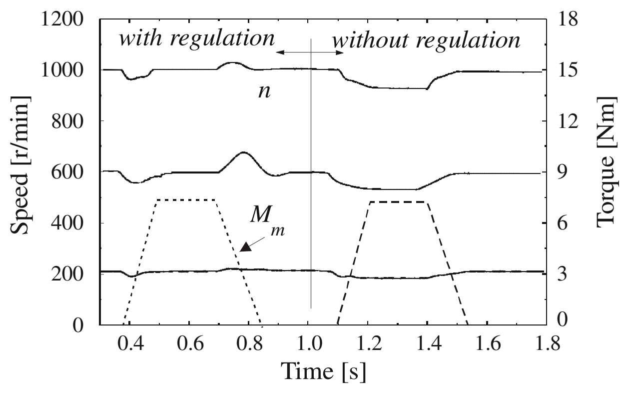

Fig. 6. Speed response. Simulation results.
(n_{ref}=200; 600; 1000 r/min)

Motor load was performed by the separately excited DC motor in dynamic braking regime. In Fig. 7 and Fig. 8 steady state speed-torque characteristics for different reference speed values in range of 100-1800 r/min are shown. The drive ability for keeping reference speed even at a very low speed is obvious.

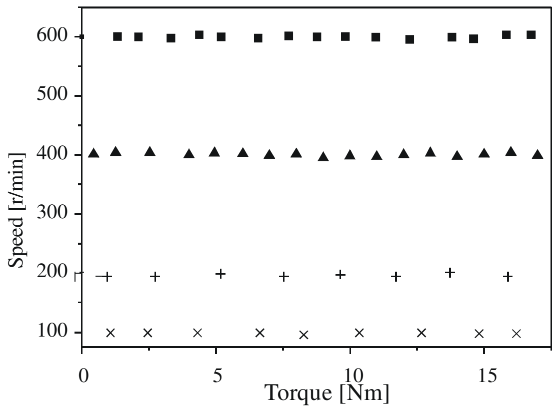

Fig. 7. Steady state speed response. Experimental results (n_{ref}=100 ÷ 600 r/min)

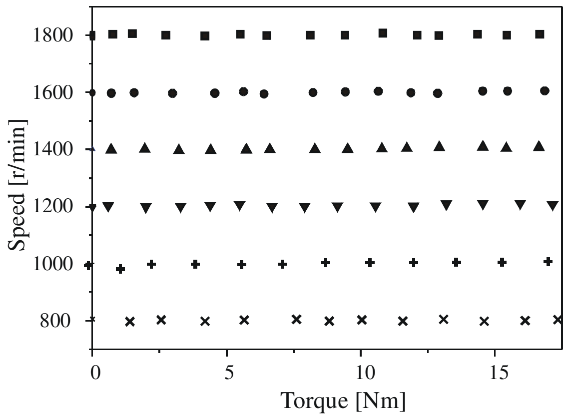

Fig. 8. Steady state speed response. Experimental results (n_{ref}=800 ÷ 1800 r/min)

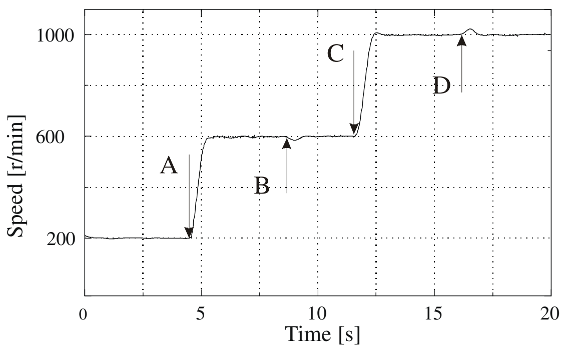

Fig. 9. Speed response. step change of reference speed and load. Experimentla results

The dynamic characteristics of the drive are presented in Fig.9 showing the response of the system to the change of reference speed and load change. First, the drive operated at no load at the speed of 200 r/min. At the moment related to point A the change of reference speed at 600 r/min had been done, so that the drive at the moment related to the point B was loaded. Afterwords at the point C the reference speed of 1000 r/min was changed, and at point D no-load resulted.

IV. Conclusion

Induction motor drive frequency compensation method based on *V/f* control has been presented. The proposed compensation method requires the knowledge motor nominal data, stator resistance and motor stator currents measurements. The control algorithm can be simply implemented in the existing drives which use the clasic *V/f* control. The theoretical and experimental analysis, the applicability of the frequency compensation method for drives with modest dynamic characteristics has been confirmed.

Appendix A

Induction machine data:

1,5 kW; 50Hz; 930 r/min; 220V; 4A; cosφ=0,8.

r_s=4Ω; r_r=3,4Ω; L_{ls}=0,01383H; L_{lr}=0,01383H; L_m=0,245 H

References

[1] K. Rajashekara, A. Kawamara, K. Matsuse, *Sensorless Control of AC Drives*, IEEE Press, 1996.

[2] A. Garcia, T. Lipo, D. Novotny “A New Induction Motor Open-Loop Speed Control Capable of Low Frequency Operation” *Annual Meeting*, New Orleans, Oct.1997. pp. 121-128.

[3] Nebojša Mitrović, “Regulacija brzine asinhronog pogona sa PWM invertorom kompenzacijom učestanosti bez senzora brzine”, *Doktorska Disertacija*, Elektronski fakultet, Niš 1998,

[4] B. Jeftenić, N. Mitrović, M. Bebić, “A Simple Speed Sensorless Control For Variable Frequency Induction Motor Drive”, *IEEE Trans. on Energy Conversion*, Vol.14, No.3, Sept.1999.

[5] D. Novotny, S. Nasar, B. Jeftenic, “Frequency Dependence of Time Harmonic Losses in Induction Machines”, *ICEM*, Boston, July 1990.

[6] Paul C. Karause, Thomas Lipo, “Analysis and Simplified Represenatations of a Rectifier-Inverter Induction Motor Drive” *IEEE Trans. App. Syst.*, vol. PAS-88, No.5, May 1969, pp. 588-596.

[7] M. M. Ahmed, J. A. Taufiq, C. J. Goodman, M. Lockwood, “Electrical Instability in a Volatage Source Inverter-Fed Induction Motor Drive at Constant Speed”, *IEE Proc.*, Vol. 133, Pt. B, No. 4, July 1986