# Steady State Speed Error Reduction in Sensorless PWM Induction Motor Drives

Nebojsa Mitrovic, Milutin Petronijevic, Borislav Jeftenic and Vojkan Kostic

*Abstract* - **This paper presents a method for speed control of an AC drive with variable frequency PWM inverter without a speed sensor. The proposed control algorithm is based on the speed compensation as a function of the load torque estimated with a single current sensor in the DC link of the inverter.**

*Keywords:* **Induction motor, Variable Frequency, Speed control, Sensorless.**

## I. Introduction

Speed sensorless control is a challenging field, because speed sensor elimination not only reduces the cost of the drive, but also eliminates a very sensitive point in the system, and considerably increases its robustness. Digital implementation enables the use of different speed control algorithms without the direct speed measurement. During the last decade, several schemes have been proposed to identify the induction machine speed [1, 2]. Due to all the difficulties and limitations of the methods for speed control without direct measurement, the investigation of a new algorithm for the sensorless speed control was done. Basic characteristics of the drive with the applied algorithm are the simplicity of the practical realization, fair steady state and transient characteristics, and the price not higher than the open loop frequency controlled drive. The laboratory prototype was built and the experimental results are presented in the paper.

## II. Description of the Control Concept

In the variable frequency AC drive the ratio of the stator voltage ($u_s$) and the frequency ($f_s$) is predetermined, therefore the active component ($i_{sa}$) of the induction motor stator current is a function of the stator frequency and the speed ($n$):

$$i_{sa} = \mathrm{F}_{\mathrm{sa}}(f_s; n) . \qquad (1)$$

[1]Nebojsa Mitrovic is with the Faculty of Electronic Engineering, Beogradska 14, 18000 Nis, Yugoslavia, E-mail: nesa@elfak.ni.ac.yu
[2]Milutin Petronijevic is with the Faculty of Electronic Engineering, Beogradska 14, 18000 Nis, Yugoslavia, E-mail: milutin@elfak.ni.ac.yu
[3]Borislav Jeftenic is with the Faculty of Electrical Engineering, Bulevar Revolucije 73, 11000 Belgrade, Yugoslavia, E-mail: jeftenic@etf.bg.ac.yu
[4]Vojkan Kostic is with the Faculty of Electronic Engineering, Beogradska 14, 18000 Nis, Yugoslavia, E-mail: nikola2105@elfak.ni.ac.yu

On the other hand, the following equation expresses the power balance of the voltage source inverter:

$$\eta_c(f_s) \cdot u_{dc} \cdot i_{dc} = 3 \cdot u_s(f_s) \cdot i_{sa} \qquad (2)$$

with: $u_{dc}$- DC link voltage, $i_{dc}$- average value of the DC link current, and $\eta_c(f_s)$- efficiency of the inverter.
The first harmonic RMS value of the output voltage is

$$u_s(f_s) = \frac{1}{2\sqrt{2}} K_m(f_s) \cdot u_{dc} \qquad (3)$$

where $K_m(f_s)$ is the modulation index. From (2) and (3) follows:

$$i_{sa} = \frac{2\sqrt{2}}{3} \cdot \frac{\eta_c(f_s)}{K_m(f_s)} \cdot i_{dc} . \qquad (4)$$

Solving (1) and (4) for $f_s$ gives:

$$f_s = \mathrm{F}_{\mathrm{s}}(n, i_{dc}) \cong \mathrm{F}_{\mathrm{s}}(n_{ref}, i_{dc}) \qquad (5)$$

where $n_{ref}$ is the desired, reference speed.

The last equation points to the possibility of the induction motor speed control based on the DC link current measurement only. Complicated relationship given by (5) requires a table look-up realization of the real-time control algorithm. The table for the stator frequency compels to the digital implementation of the controller. The practical inverter DC link current incorporates higher order harmonics, hence a low pass filter should be used in the DC link current feedback to extract the average value. The simplified schematic of the drive and the control system is shown in Fig. 1.

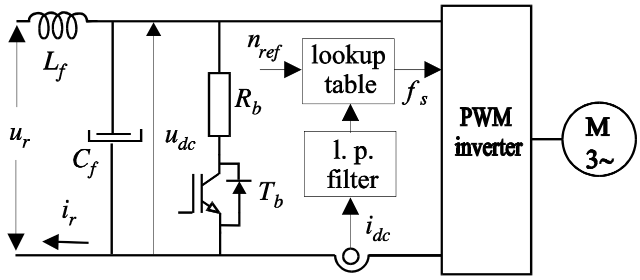


Fig. 1. Simplified scheme of the drive.

The proposed algorithm assumes that the reference speed is equal to the actual speed $n_{ref} = n$. With the digital realization of the controller, the inverter output frequency has a finite resolution, with the quantisation step ($\Delta f_s$), therefore, in general, it will be $n_{ref} \cong n$. Careful selection of the look-up table values can ensure: $n_{ref} - n \le 60 \cdot \Delta f_s / P$, where $P$ is the number of pole pairs. From the above, one can conclude that the steady-state accuracy will strongly depend on the look-up table forming.

## III. THE FORMING OF THE LOOK-UP TABLE

The criterion for the stator frequency selection for a given load and the reference speed is illustrated in Fig. 2. 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 $n_r$. Based on a new value of the DC link current and the reference speed, the controller determines the value of the required frequency to establish the operating point C. In this way, the actual speed is again equal to the reference speed $n_1$. For a given range of the reference speed $n_{ref}$ and the possible range of the load $i_{dc}$, two-dimensional look-up table with predetermined stator frequencies is incorporated in the control algorithm.

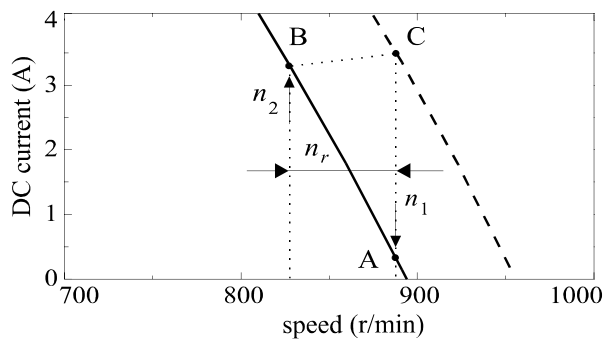


Fig. 2. The speed compensation principle

The table forming can be accomplished in different ways. The method presented in this paper is based on calculation of (5) and the steady state model of the machine. The variation of certain parameters with the frequency [3] was taken into account. Fig. 3. shows the calculated function $f_s(i_{dc}, n_{ref})$ for a wide range of $i_{dc}$. For a chosen reference speed and the given DC link current value, the function gives multiple values for the stator frequency. However, limiting the range of $i_{dc}$ and the reference speed to the values expected in the practical application (shaded part on Fig. 3.), gives a single-valued function. This function was used for the look-up table of the stator frequency values. Organization of lookup tables is shown in Fig. 4.

## IV. STABILITY AND DYNAMICS

Special attention was paid to the stability and dynamics of the drive, for the following two reasons. First, discretized values of the stator frequency could cause oscillations in the system, as a consequence to disturbances. Second, unstable operation is possible, since no direct speed feedback exists. 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 [4,5]. 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 as shown in principle block diagram presented in Fig. 5.

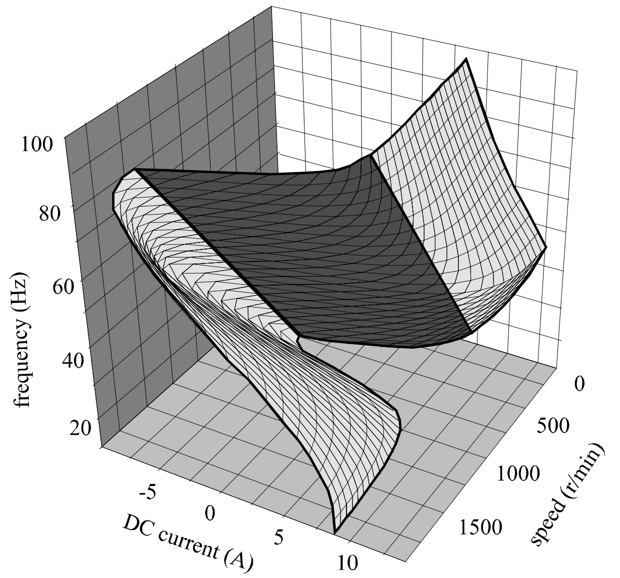


Fig. 3. The stator frequency vs. the DC current and the rotor speed (wide range $i_{dc}$ ).

| | $i_{dc1}$ | $i_{dc2}$ | | | $i_{dck}$ |
|---|---|---|---|---|---|
| $n_{r\ ref1}$ | | | | | |
| $n_{r\ ref2}$ | | | | | |
| | | | stator frequency values ($f_s$) | | |
| | | | | | |
| $n_{r\ refn}$ | | | | | |

Fig. 4: Organization of the lookup tables.

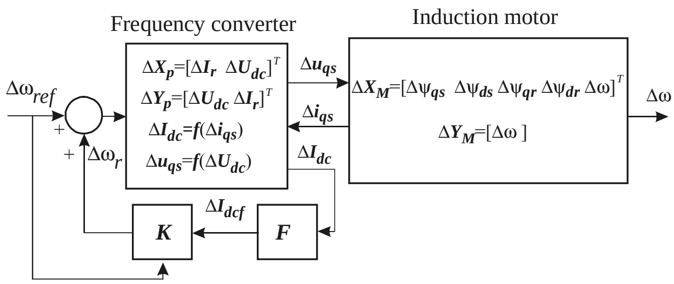


Fig. 5 Principle block diagram of the linearized model

Some results for different low-pass filter cut-off frequencies and for reference speed $n_{ref}$=400 r/min are shown on Fig.6 and Fig.7. The regions of instability are, in Fig.6, at low load and for filter cut-off frequency $f_{cutoff}$=150 Hz.

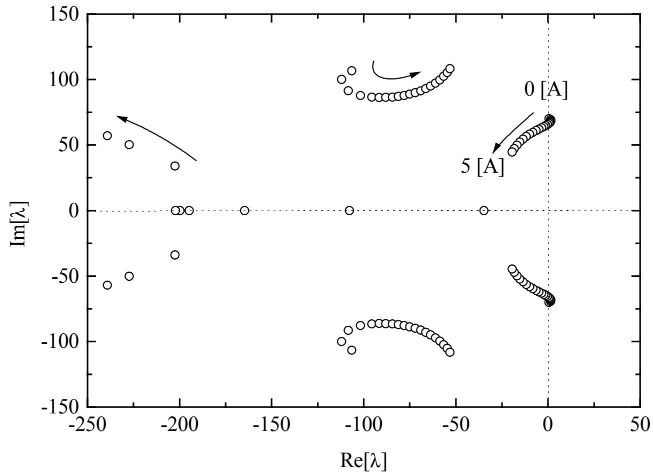


Fig. 6 Drift of eigenvalues for $n_{ref}$=400 r/min, $f_{cutoff}$=150 Hz

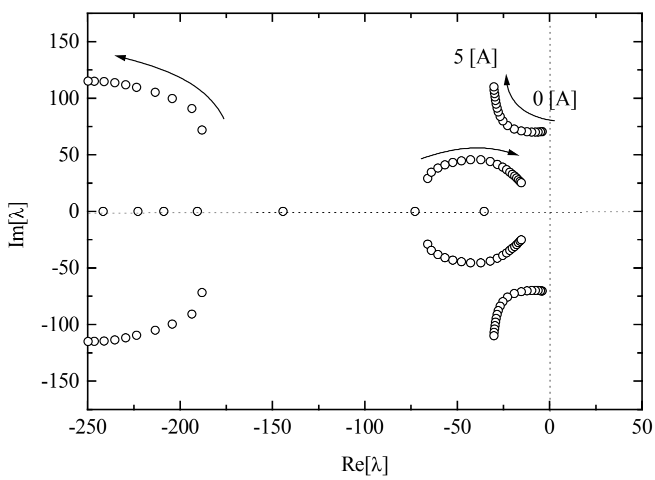


Fig. 7 Drift of eigenvalues for $n_{ref}$=400 r/min, $f_{cutoff}$=50 Hz

The analyses performed pointed out that the existence of the low-pass filter in the DC link current 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 [6]. This ensures a stable operation and good dynamic performance.

## V. Experimental results

The experimental setup for the control algorithm testing includes a 1.5kW induction motor and a PWM voltage source inverter with the frequency resolution of 0.5Hz. Remaining data for the drive are given in the Appendix.

Fig. 8. shows the motor speed and the stator frequency versus the DC link current, for the reference speed of 400÷1800 r/min, from braking to the maximum allowed load ($i_{dc}$=(−0.6÷4)A).

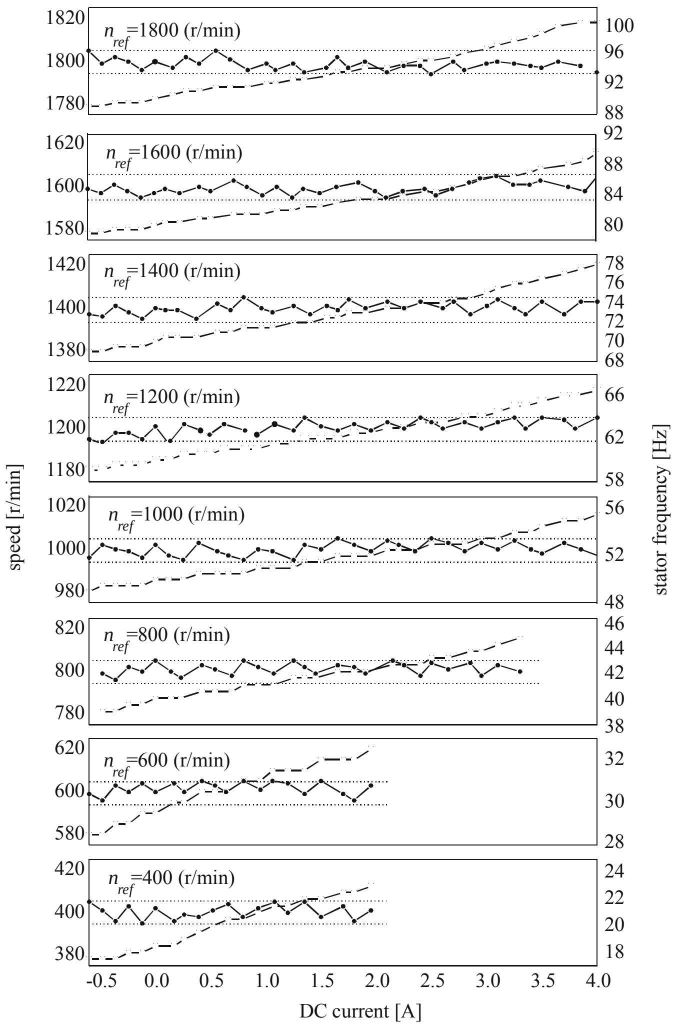


Fig. 8. Steady state characteristics of the drive (●- speed and -- stator frequency).

The dynamic characteristics of the drive are presented in Fig. 9. The response of the system to the changes of the reference speed (points A and B), and the load (points C and D) is demonstrated.

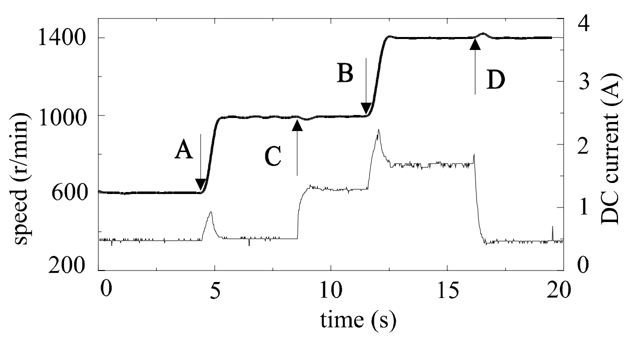


Fig. 9. Changes of the reference speed (A and B) and the load (C and D)

Fig. 10 and Fig. 11 shows the response of the system to the consecutive increase and decrease of the reference speed, with no load.

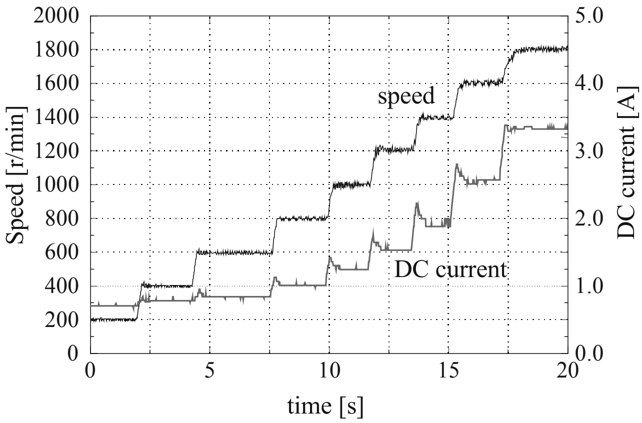

Fig.10. Consecutive increase of reference speed

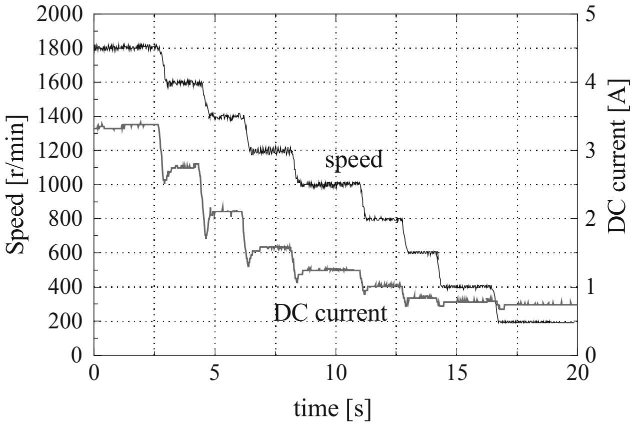

Fig.11. Consecutive decrease of reference speed

## VI. Conclusion

The analyses performed and the experimental results shown, confirm the application possibility of the presented speed control algorithm for induction motor drives. The steady state speed accuracy of the drive is better than the value defined by the frequency resolution of the inverter. The dynamic characteristics of the drive satisfy all the applications without high performance requirements, where field oriented control should be applied. The implementation of the algorithm does not require hardware modifications from the open-loop frequency control, thus offering better characteristics for the same cost.

## References

[1] Kevin D. Hurst, Thomas G. Habetler, "Sensorless Speed Measurement Using Current Harmonic Spectral Estimation in Induction Machine Drives," *IEEE Trans. Power Electronic*., vol. 11, no. 1, January 1996, pp. 66-73.

[2] K. Koga, R. Ueda, T. Sonoda, "Constitution of V/f Control for Reducing the Steady-State Speed Error to Zero in Induction Motor Drive System," *IEEE Trans. on Ind. Applications*, Vol.28, No.2, March/April 1992, pp. 463-470.

[3] D. Novotny, S. Nasar, B. Jeftenic, D. Maly, "Frequency Dependence of Time Harmonic Losses in Induction Machines," *Proc. Int. Conf. on Electrical Machines ICEM*, Boston, July 1990.

[4] 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.

[5] 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.

[6] 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.

## Appendix

| Induction motor | | | | | |
|---|---|---|---|---|---|
| $P_n$=1,5 kW; $U_n$=380V, $I_n$=4A; $n_n$=930 o/min, cosφ=0,8 | | | | | |
| $r_s$[Ω] | $r_r$[Ω] | $r_m$[Ω] | $L_{ls}$[H] | $L_{lr}$[H] | $L_m$[H] |
| 4 | 3,4 | 800 | 0.01383 | 0.01383 | 0.245 |
| Frequency converter | | | | | |
| $f_{min}$[Hz] | $f_{max}$[Hz] | $f_t$[kHz] | $L_f$[mH] | $C_f$[mF] | $R_f$[Ω] |
| 5 | 100 | 3,9 | 1,1 | 1 | 1 |