BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LIX No. 1/2007	33 - 40	Seria Tehnică

Implemented V-Hz Control of an Excited Synchronous Motor with Constant Field

Csaba Szabó, Ioan I. Incze, Maria Imecs, Enikő Szőke-Benk

Technical University of Cluj-Napoca, P.O. 1 Box 99, 400750 Cluj-Napoca, România
E-mail: csaba.szabo@edr.utcluj.ro

Abstract:

In order to achieve the highest torque per ampere ratio for the AC machines, the flux-linkage amplitude has to be maintained at his rated value. This can be achieved by adjusting in a proper way the amplitude of the stator-voltage and its frequency. Based on this fact the first control method, which assures the so-called "loss-less" operation for the motor was developed, that is the well known constant Voltage-per-Hertz operation. The only control variable is the frequency, while the stator voltage is computed. The main back-draw of this method consists in the presence of the stator-voltage drop, i.e. loss of torque, which may cause also stability problems at low speed, if they are neglected. Different methods were studied in order to compensate the voltages. Computer-based simulation and experimental operations were performed for validation.

Key words: *Scalar control, Indirect flux control, Salient-pole synchronous motor, Stator-voltage-drop compensation, Boost voltage.*

Introduction

In AC drives historically the first control method, which assures loss-less operation for the motor was the so-called constant Voltage-per-Hertz procedure. The constant stator-flux operation is obtained indirectly and empirically, (no flux identification is required) by an open-loop feed-forward scalar control procedure, without mechanical sensors. The only reference variable is the supply frequency, while the stator-voltage is computed based on the simplified stator equation resulting from the steady-state equivalent circuit.

In spite of the development considering the vector control procedures for the AC machines, the scalar control method still finds his place in various industrial applications. Most of the electrical drives present on the market include beside the vector control structures, also scalar control based strategies. Usually, the scalar control is preferable in reduced speed-range applications ($\omega_{min}/\omega_{max} \approx 1:10$), where is no need for high dynamic behavior, like pumps, ventilators, etc.

In industrial applications the Volt-per-Hertz control is frequently used, due to his simplicity. The stator construction of the induction motors and the synchronous machines are the same, consequently this control method theoretically may be applied without any changes for both machine types. Because the synchronous motor operates at synchronous speed, there are no slip-related problems to be solved in comparison with other motor types. The mechanical characteristics speed versus torque are constant, only the load angle will be variable depending on the load torque modification, which has no importance on this scalar control procedure.

Fig. 1 presents the block diagram of the salient-pole synchronous motor drive system using the constant Volt/Hertz scalar control procedure. Considering the f_s^{Ref} reference frequency, the U_s^{Ref} amplitude and Ω_s synchronous angular speed of the stator-voltage vector are computed by means of the "**Voltage Reference Computation**" block, which provides the input signals serving as parameters for the block "**3~ Sine Wave Generator**", which generates the modulation signals of the three-phase sine-wave stator-voltage. The DC-link inverter "amplifies" them and drives the synchronous motor. The basic arrangement usually is without feed-back, because the original control method is a feed-forward one, consequently it does not require any feedback for the computation of the control variables.

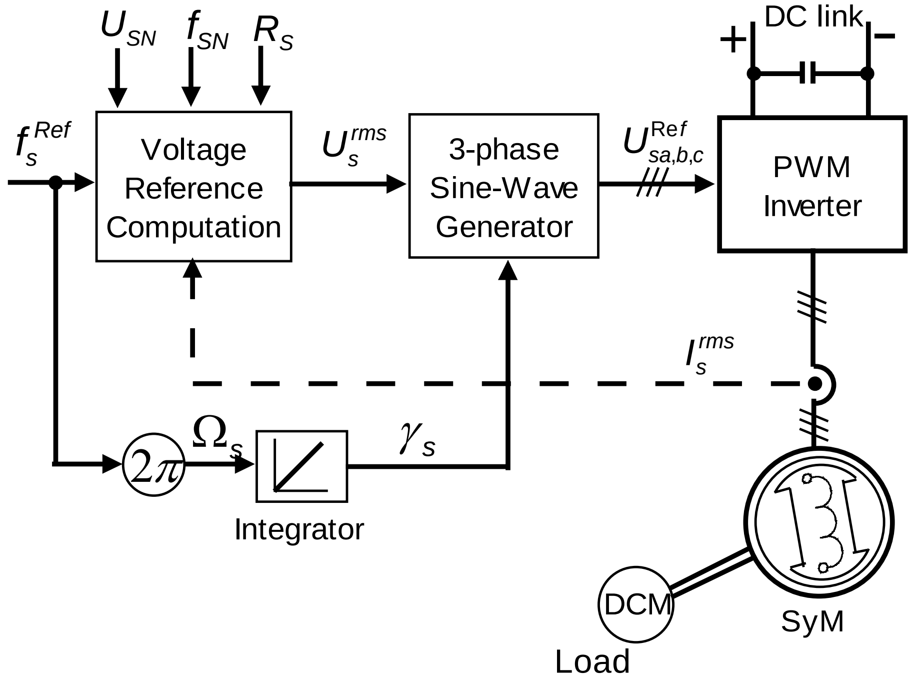


Fig. 1. Block diagram of a salient-pole synchronous motor drive, based on the Volt/Hertz scalar control procedure using stator-current feed-back.

In this case the r.m.s. value of the stator-voltage may be computed approximately according to the following expression:

$$U_s^{rms} = \frac{U_{sN}}{f_{sN}} f_s , \tag{1}$$

where U_{sN} is rated stator voltage, f_{sN} the rated and f_s the actual stator frequency. The ratio U_{sN} / f_{sN} gives the theoretical value of the basic V/Hz procedure constant.

Nevertheless, the main drawback of the constant Volt/Hertz procedure consists in the effects of the voltage drop due to the stator resistance, which cause difficulties especially at low speed operation. The voltage drop at low frequency may have the same order in magnitude with the computed voltage; due this fact the method becomes inadequate for low speed region. This problem can be eliminated by adopting different improving techniques, which compensate the voltage drop, like:

- programmed voltage versus frequency characteristics [1];
- formula based voltage-drop compensation [2];
- voltage-drop compensation using current-feedback [3, 4, 5].

All the above mentioned compensation procedures are based on providing more voltage on the motor phases, than in case of the basic control method. In the first case a constant “boost” voltage is added to the initially computed value. The second method computes the corresponding voltage reference based on the imposed frequency and motor parameters. Neither of the two methods takes into account the mechanical load effect. In the third case the motor load is also taken into account in the reference voltage computation by means of the measured actual stator current. This procedure will be presented in the followings.

Current-Feedback-Based Voltage-Drop Compensation

The former evolved constant voltage-per-frequency procedure applies load-dependent compensation of stator-voltage drop. In a simple approach, an actual stator-current dependent U_b “boost” component is added to the computed reference voltage. It provides torque even at low frequencies, but the voltage-frequency characteristics will be parallel shifted, and the voltage limit (set at the U_{sN} rated stator-voltage value) will be achieved at lower frequencies than f_{sN} (i.e. the rated one), leading to an inadequate compensation near the rated N operation point. This inaccuracy may be avoided by current-dependent modification of the characteristics slope, as is shown in Fig. 2. It is performed by computing the r.m.s. value of the voltage references, according to the following expression [3, 4]:

$$U_s^{rms} = U_b + \frac{U_{sN} - U_b}{f_{sN}} f_s^{Ref} \,. \tag{2}$$

The boost voltage is given by

$$U_b = R_s I_s^{rms} \,, \tag{3}$$

where R_s is the stator resistanc. The variable slope of the characteristics from Fig. 2 results as

$$\frac{\mathrm{d}U_s^{rms}}{\mathrm{d}f_s} = \frac{U_{sN}^{rms} - R_s I_s^{rms}}{f_{sN}} = f(I_s^{rms}) \tag{4}$$

and it is depending on the actual stator current.

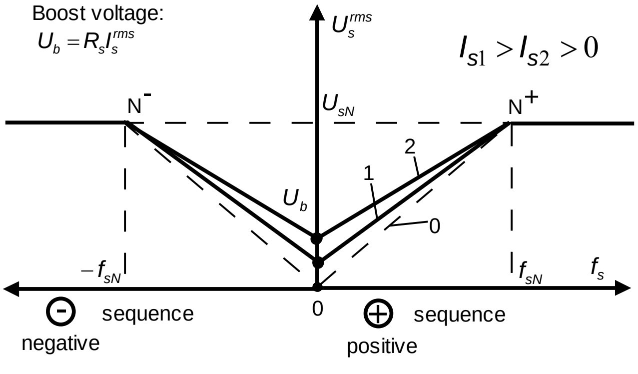


Fig. 2. Voltage-frequency characteristics with variable slope of the current-feedback compensated Volt/Hertz procedure.

The structure of the voltage computation block, based on eq. (2), is shown in the Fig. 3.

By 100% compensation of the current-dependent voltage drop often stability problems are observed [1, 6]. Therefore in order to stabilize the drive it would be necessary to make low-pass filtering of the current-dependent voltage component [6].

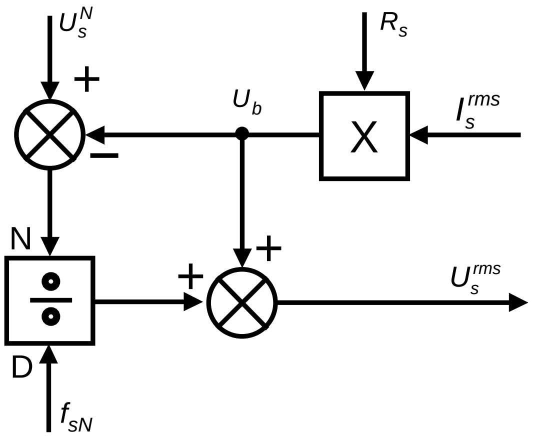
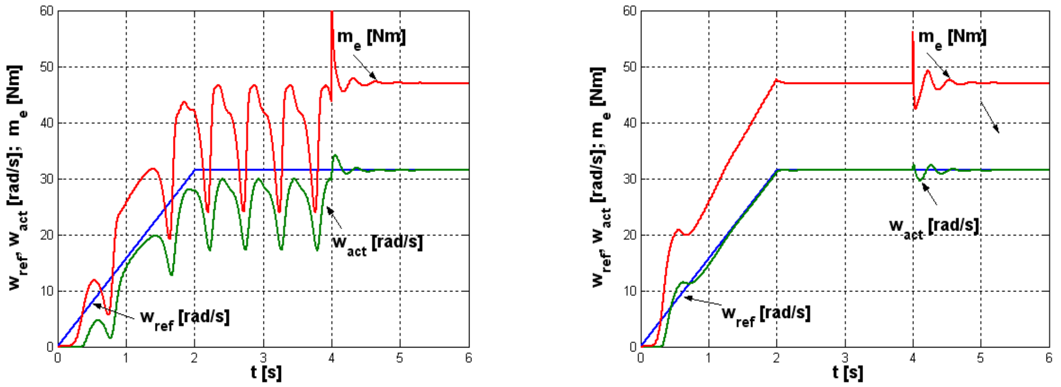


Fig. 3. Structure of the voltage computation block with current-feedback compensation.

Comparison of Procedures with and without Compensation

For validation of the proposed voltage-drop compensation technique, using the MATLAB/Simulink dynamic simulation environment, computer simulation was performed.

In simulation the salient-pole synchronous motor with damper windings is started in asynchronous operation mode (without feeding of the excitation winding). A speed-dependent linear load-torque profile is applied, i.e. its value increases from the motor no-load torque (at zero speed) to the rated electromagnetic torque (at the reference speed) corresponding to the steady-state operation. Because the presented technique is developed to enhance operation at low speed region, the imposed reference frequency was chosen at 5 Hz.



a) The basic V/Hz procedure without voltage-drop compensation.

b) Current-feedback based voltage-drop compensation procedure.

Fig. 4. Simulation results of the salient-pole synchronous motor controlled by different Volt/Hertz procedures: the electrical angular speed (ω_{ref} – reference value, ω_{act} – actual value) and electromagnetic torque (m_e) versus time.

Fig. 4 shows the evolutions of the electrical angular speed and the electromagnetic torque versus time. A slow starting was simulated, with a slope of 2.5 Hz/s. At 4s from the starting the excitation is connected to the DC-supply, consequently the motor operates in synchronous mode. Simulations were performed for both, the basic Volt/Hertz operation and the procedure with current-feedback compensation. Analyzing the simulated results, it can be observed, that the motor speed presents oscillations during the starting process, and the so-called hunting characteristic phenomenon appears, because of the torque perturbations. After synchronization the torque and speed are stabilizing. In comparison with current-feedback compensation of the stator-voltage drop a smooth starting is ensured and the additional current-dependent voltage component also eliminates the hunting phenomenon. In this case the motor transient operation is significantly improved.

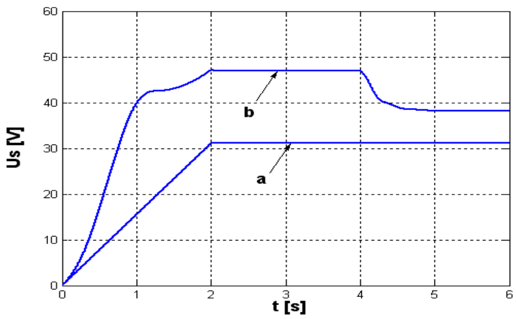


Fig. 5. Stator-voltage amplitude versus time for

a) the basic Volt/Hertz procedure

b) the current-feedback compensation procedure

In fig. 5 there are presented the evolution of the computed stator-voltage amplitude for the two cases mentioned before. It can be observed that the difference between the two voltages is significant and it has the same order of magnitude with the initially computed reference value. The sudden voltage-drop, which may be observed on the current-feedback compensated characteristic, occurs when the excitation is connected.

Simulation and Experimental Results of the Implemented V/f Control

For first there was implemented a fixed slope compensation characteristic without current feedback and with a constant boost voltage at zero frequency. The motor data are: U_{sN} = 380 V, I_{sN} = 1,54 A, P_N = 800W, f_N=50 Hz, n_N = 1500 [rpm], cosφ= 0.8 (capacitive).

Simulation and experiments were performed for a constant load torque (1 Nm) with a trapezoid profile of the reference frequency, which has a 10s variation periodicity between 10 - 20 Hz, and a ramp of 20 Hz/s. The excitation is coupled to its supply (18 V^{DC}) after 1 s. The load torque is given by a not supplied DC machine.

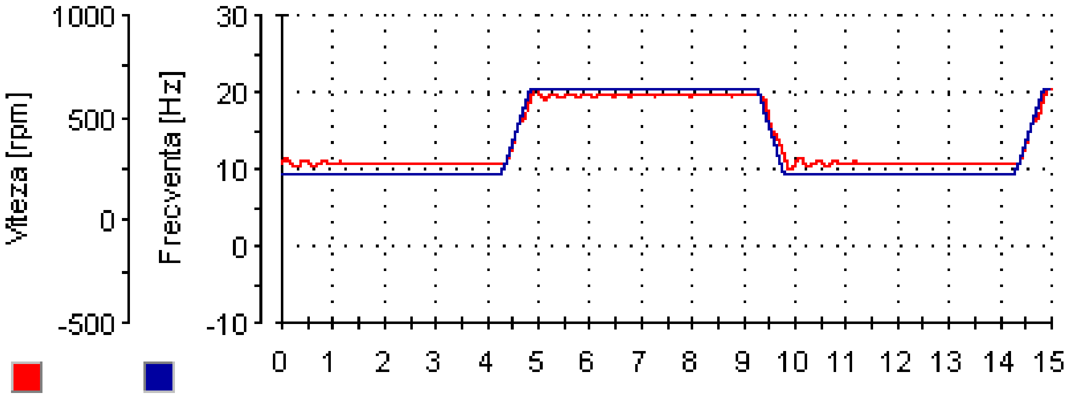
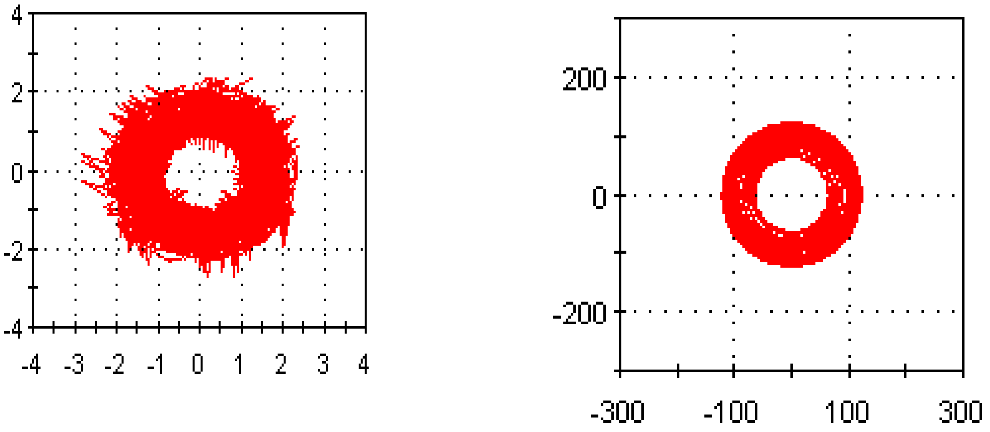


Fig. 6. The reference frequency and motor speed of the implemented V/f control system.



a) Stator current of the motor with the implemented control system (experimental result).

b) The stator-voltage reference before PWM of the implemented system (experimental result).

Fig. 7. Space-phasor diagrams.

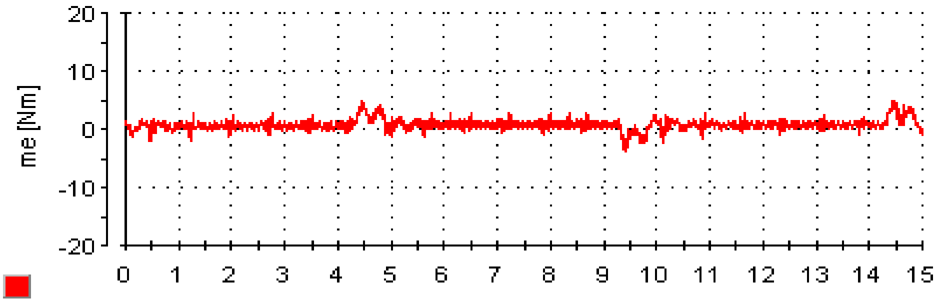


Fig. 8. The identified electromagnetic torque of the implemented drive (experimental result).

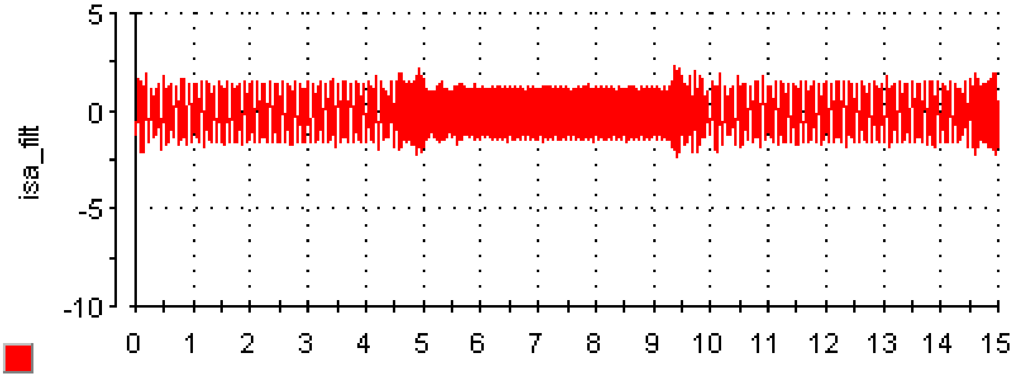
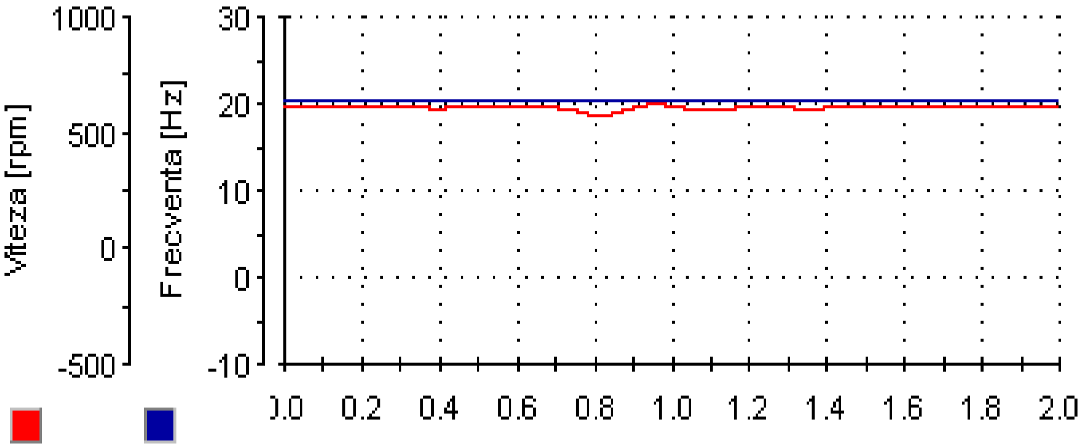
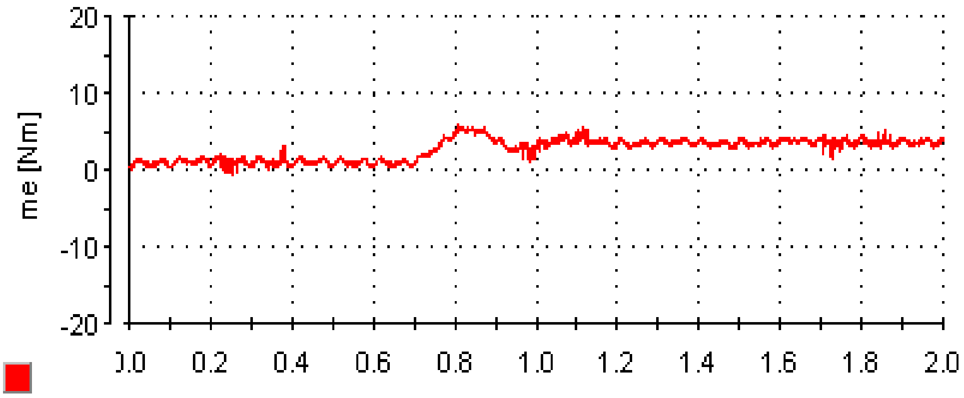


Fig. 9. The stator current (i_{sa}) in phase $\boldsymbol{a}_s$ versus time in the motor (experimental result).

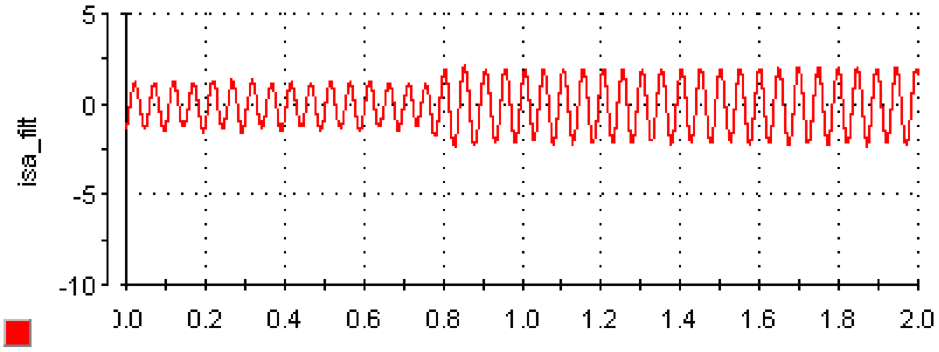
There was simulated and experimentally studied the behaviour of the system by step-like mechanical loading. The synchronous motor was started at 20 Hz reference frequency with a ramp of 20 Hz/s and excitation voltage set at 18 V. After starting in moment 0.7 s a load step is applied. The load torque is generated by a DC motor working as generator. The excitation of the DC motor is set to ensure the rated load torque of the synchronous machine (4.5 Nm). The results are presented in Fig. 10.



a) The reference frequency and motor speed versus time (experimental result).



b) The identified electromagnetic torque versus time (experimental result).



c). The stator current (i_{sa}) in phase $\boldsymbol{a_s}$ versus time in the motor (experimental result).

Fig. 10. Experimental results by applying a load step to the V/Hz controlled drive system.

Conclusions

The experimental results of the implemented drive and the simulation results are very similar, that means the mathematical model of the drive system is adequate for further study of other control structures, before implementation. The results confirm that a compensation of the stator-voltage drop has to be compensated in order to ensure the motor torque and steady-state operation in low speed region. In order to avoid the hunting phenomenon, the motor load should be taken into account, using the current-feedback information for the reference stator-voltage compensation. Further improvements to this method may be achieved by a vectorial compensation of the voltage drop component achieving the indirect control of the air-gap field instead of the stator flux, which improves the drive performance, too.

References

1. Abbondanti A. - Method of flux control in induction motors driven by variable frequency, variable voltage supplies, *Reprinted from IEEE IAS Annual Meeting.* pp 177-184, 1977.
2. Kelemen A. - *Electrical Drives* (in Romanian *Actionari Electrice*), Editura Didactica si Pedagogica, Bucuresti, 1979.
3. Imecs M., Szabo Cs. - Control Structures of Induction Motor Drives – State-of-the-Art, *Proc. of 4th Workshop on European Scientific and Industrial Collaboration WESIC 2003 - Advanced Technologies in Manufacturing*, Miskolc-Lillafüred, ISBN: 963 661 570 5, pp. 495-511, 2003.
4. Imecs M., Incze I. I., Szabo Cs., Adam T. - Scalar and vector-control structures of AC motors, *Conference of Energetics and Electrical Engineering, ENELKO 2003*, Cluj-Napoca, Romania, pp. 82-98, 2003.
5. Incze I. I., Imecs M., Szabo Cs. - Simple Voltage-Hertz Control With Current Feedback of the Induction Machine*,* In *Proc. of 2004 IEEE-TTTC AQTR 2004 – THETA 14,* Cluj-Napoca, ISBN 973-713-046-4, Tome I, pp. 389-394, 2004.
6. Munoz-Garcia A., Lipo T.A., Novotny D. W. - A new induction motor V/f control method capable of high-performance regulation at low speeds, *IEEE Transactions on Industry Applications*, Vol.34, No.4, July/August, pp. 813-821, 1998.
7. Das J. C. - Effects of momentary voltage dips on the operation of induction and synchronous motors, *IEEE Transactions on Industry Applications,* Vol. 26, No. 4. July/August, 1990. pp. 711-718, 1990.
8. Kelemen A. Imecs M. - *Vector Control of AC Drives. Volume 2: Vector Control of Synchronous Machine Drives.* Budapest, Ecriture, ISBN 963 593 140 9, 1993.

Control V-Hz implementat pentru un motor sincron excitat cu câmp constant

Rezumat

Pentru a obţine la o maşina de curent alternativ cuplu maxim raportat la curent statoric absorbit, se va menţine amplitudinea fluxului rezultant statoric la valoarea lui nominală. Aceasta se obţine ajustând printr-o metodă corespunzătoare amplitudinea tensiunii şi a frecvenţei de alimentare din stator. Pe acest principiu se bazează procedura fundamentală de control fără pierderi – aşa numitul control V/Hz= ct., la care singura mărime prescrisă este frecvenţa, iar tensiunea statorică rezultă cu un coeficient de proporţionalitate. Dezavantajul metodei constituie faptul că la viteze mici căderile de tensiune statorică devine comparabilă cu tensiunea de alimentare. Din această cauză scade valoarea fluxului care conduce la micşorarea capacităţii de cuplu a maşinii Este studiată metoda de compensare a căderilor de tensiune pe rezistenta statorică, realizată cu reacţie de curent. Sunt prezentate rezultate de simulare şi de implementare.