Acta Universitatis Sapientiae
Electrical and Mechanical Engineering, 2 (2010) 16-26

Synchronous Motor Drive at Maximum Power Factor with Double Field-Orientation

Csaba SZABÓ, Maria IMECS, Ioan Iov INCZE

Department of Electrical Drives and Robots, Faculty of Electrical Engineering,
Technical University of Cluj-Napoca,
e-mail: csaba.szabo@edr.utcluj.ro, imecs@edr.utcluj.ro, ioan.incze@edr.utcluj.ro

Manuscript received Oct 1, 2010; revised Oct 15, 2010.

Abstract: The paper presents a vector control structure for a wound-excited salient-pole synchronous motor, fed by a voltage-source converter, working at unity power factor. The variable exciting current is ensured by a DC chopper. Due to this additional intervention possibility the motor may have three degrees of freedom from the control point of view, and three control loops will be formed instead of two: one for the control of the mechanical quantities, and two for the magnetic ones. The three prescribed references are the rotor angular speed, the stator flux (both directly controlled by using PI regulators) and the power factor that is only imposed at its maximum value. In the control structure two types of orientation procedure are used: stator-field-orientation for power factor control, and rotor-orientation for computation of the voltage-control variables and self commutation. There is also presented a speed-computation procedure used in practical implementation regarding the signal processing of the incremental encoder position. The method is based on the derivation with respect to time of both sine and cosine functions of the rotor position. The angular speed is obtained then by computing the module of the two resulted sinusoidal signals. This method avoids the division by zero related issue that occurs at every zero crossing if the angular speed is computed by dividing the time based derivative of one signal with the other one. For validation of the presented control strategy simulations were carried out in Matlab/Simulink® environment.

Keywords: Vector control, unity power-factor, voltage-controlled drive, rotor speed identification, voltage-source inverter, stator-field orientation.

1. Introduction

For high performance dynamic applications the most suitable solution is the vector controlled AC drive fed by a static frequency converter (SFC). The wound-excited synchronous motor (Ex-SyM) is the only machine capable to operate at unity or leading power factor (PF). The structure of the vector control system is determined by the combination between the type of the SFC used including the pulse width modulation (PWM) procedure, the orientation field and its identification method [2], [8], [9].

The rigorous control of the PF can be made only with the resultant stator-field orientation. If the PF is maximum, there is no reactive energy transfer between the armature and the three-phase power source.

Some motor-control-oriented digital signal processing (DSP) equipments present on the market don’t dispose over implementation possibility of the current-feedback PWM, suitable for current-controlled VSIs, consequently in the control structure it is necessary the computation of the voltage control variables from the current ones, imposed or directly generated by the controllers.

The proposed control structure is based on both types of orientation. The stator-field orientation is used for control of the unity power factor and stator-flux, and also for generation of the armature-current control variables. The orientation according to the rotor position (i.e. exciting-field orientation) is applied for self-commutation and for generation of the armature-voltage control variables for the inverter control. The transition between the two orientations is performed by using a coordinate transformation block (CooT), which rotates the stator-field oriented reference frame with the value of the load angle ($\delta = \lambda_s - \theta$).

2. The mathematical model of the Ex-SyM

The mathematical model (MM) of the Ex-SyM is suitable for simulation and also in implementation because, the computation of the control and feedback variables in the control structure is performed also based on the MM. Usually the equations are written in rotor-oriented rotating reference frame ($d\theta - q\theta$), where θ is the rotor position. The state equations based on the quasi-flux model may be written, as follows:

$$\begin{cases} \dfrac{d\Psi_{sd\theta}}{dt} = u_{sd\theta} - R_s \cdot i_{sd\theta} + \omega \cdot \Psi_{sq\theta}; \\ \dfrac{d\Psi_{sq\theta}}{dt} = u_{sq\theta} - R_s \cdot i_{sq\theta} - \omega \cdot \Psi_{sd\theta}; \\ \dfrac{d\Psi_e}{dt} = u_e - R_e \cdot i_e; \\ \dfrac{d\Psi_{A_d}}{dt} = u_{A_d} - R_{A_d} \cdot i_{A_d}; \\ \dfrac{d\Psi_{A_q}}{dt} = u_{A_q} - R_{A_q} \cdot i_{A_q}; \\ \dfrac{d\omega}{dt} = \dfrac{z_p}{J_{tot}} \cdot \left[\dfrac{3}{2} z_p (\Psi_{sd\theta} \cdot i_{sq\theta} - \Psi_{sq\theta} \cdot i_{sd\theta}) - m_L \right], \end{cases} \tag{1}$$

The integration of the state equations is made directly from the derivatives of the angular rotor speed and fluxes, then the currents are computed from the fluxes expressed according to the longitudinal $d\theta$ rotor axis:

$$\begin{cases} i_{sd\theta} = \dfrac{1}{L''_{sd}} \Psi_{sd\theta} - \dfrac{1}{L''_{m(sd\theta - A_d)}} \Psi_{A_d} - \dfrac{1}{L''_{m(sd\theta - e)}} \Psi_e \\ i_{A_d} = -\dfrac{1}{L''_{m(sd\theta - A_d)}} \Psi_{sd\theta} + \dfrac{1}{L''_{A_d}} \Psi_{A_d} - \dfrac{1}{L''_{m(e - A_d)}} \Psi_e \\ i_e = -\dfrac{1}{L''_{m(sd\theta - e)}} \Psi_{sd\theta} - \dfrac{1}{L''_{m(e - A_d)}} \Psi_{A_d} + \dfrac{1}{L''_e} \Psi_e \end{cases} \tag{2}$$

and according to the quadrature $q\theta$ rotor axis:

$$\begin{cases} i_{sq\theta} = \dfrac{1}{L''_{sq}} \left(\Psi_{sq\theta} - \dfrac{L_{mq}}{L_{A_q}} \Psi_{A_q} \right) \\ i_{A_q} = -\dfrac{1}{L''_{Aq}} \left(\Psi_{Aq} - \dfrac{L_{mq}}{L_{sq}} \Psi_{sq\theta} \right) \end{cases} \tag{3}$$

As state-variables were chosen the fluxes (i.e. the direct and quadrature axis components of the stator flux ($\Psi_{sd\theta}$ and $\Psi_{sq\theta}$) and of the damper winding flux (Ψ_{Ad} and Ψ_{Aq}), the exciting winding flux (Ψ_e) and the rotor electrical angular speed (ω).

3. Double field-oriented control of the Ex-SyM

In the proposed control structure, presented in *Fig. 1*, the salient pole Ex-SyM is fed by a voltage-source inverter (VSI). Three control loops are formed: two magnetical (for flux and PF control) and a mechanical one (for speed). The flux and the speed are controlled directly by PI controllers, and the PF is controlled indirectly. The PF is maximum, if the stator voltage and stator current are in phase. Consequently, the stator-current space phasor $\underline{i}_s$ results perpendicular onto the stator-flux vector $\underline{\Psi}_s$ [2], [8].

The perpendicularity can be achieved by canceling the stator-field-oriented longitudinal armature reaction ($i_{sd\lambda s} = 0$). The reference armature-current components are oriented according to the direction of the resultant stator-flux phasor. The longitudinal component $i_{sd\lambda s}^{Ref}$ is an imposed value, and it is cancelled, while the quadrature component $i_{sq\lambda s}^{Ref}$ results at the output of the speed controller. However the stator-current control is recommended to be made in exciting field- (i.e. rotor-position-) oriented ($d\theta$–$q\theta$) rotating reference frame, because the self-commutation of the motor, based on the rotor position, is made inherently by means of the reverse Park transformation block. The re-orientation (from the resultant stator field to the exciting one) is made by means of a reverse CooT block, which rotates the stator-field-oriented reference frame with the value corresponding to the load angle $\delta = \lambda_s - \theta$ [2], [8], [9].

The voltage-control variables are generated by the two current controllers in the active and the reactive control loops. In the voltage-computation block UsC the electromagnetic cross-effect is taken into account, realizing the re-coupling of the two decoupled control loops, the active and the reactive ones, by means of the rotating EMF components [2], [8], as follows:

$$\begin{cases} u_{sd\theta}^{Ref} = v_{sd\theta}^{Ref} - \omega \Psi_{sq\theta}; \\ u_{sq\theta}^{Ref} = v_{sq\theta}^{Ref} + \omega \Psi_{sd\theta} \end{cases} \tag{4}$$

The inverter control is made by feed-forward voltage-PWM procedure with simple on-off controllers [5], based on the following PWM logic:

$$m^{\log} = \begin{cases} -1, \text{ if } u_{cr} < u^{Ref}; \\ 1, \quad \text{if } u_{cr} > u^{Ref}. \end{cases} \tag{5}$$

The exciting current is controlled also with voltage PWM by means of a DC chopper.

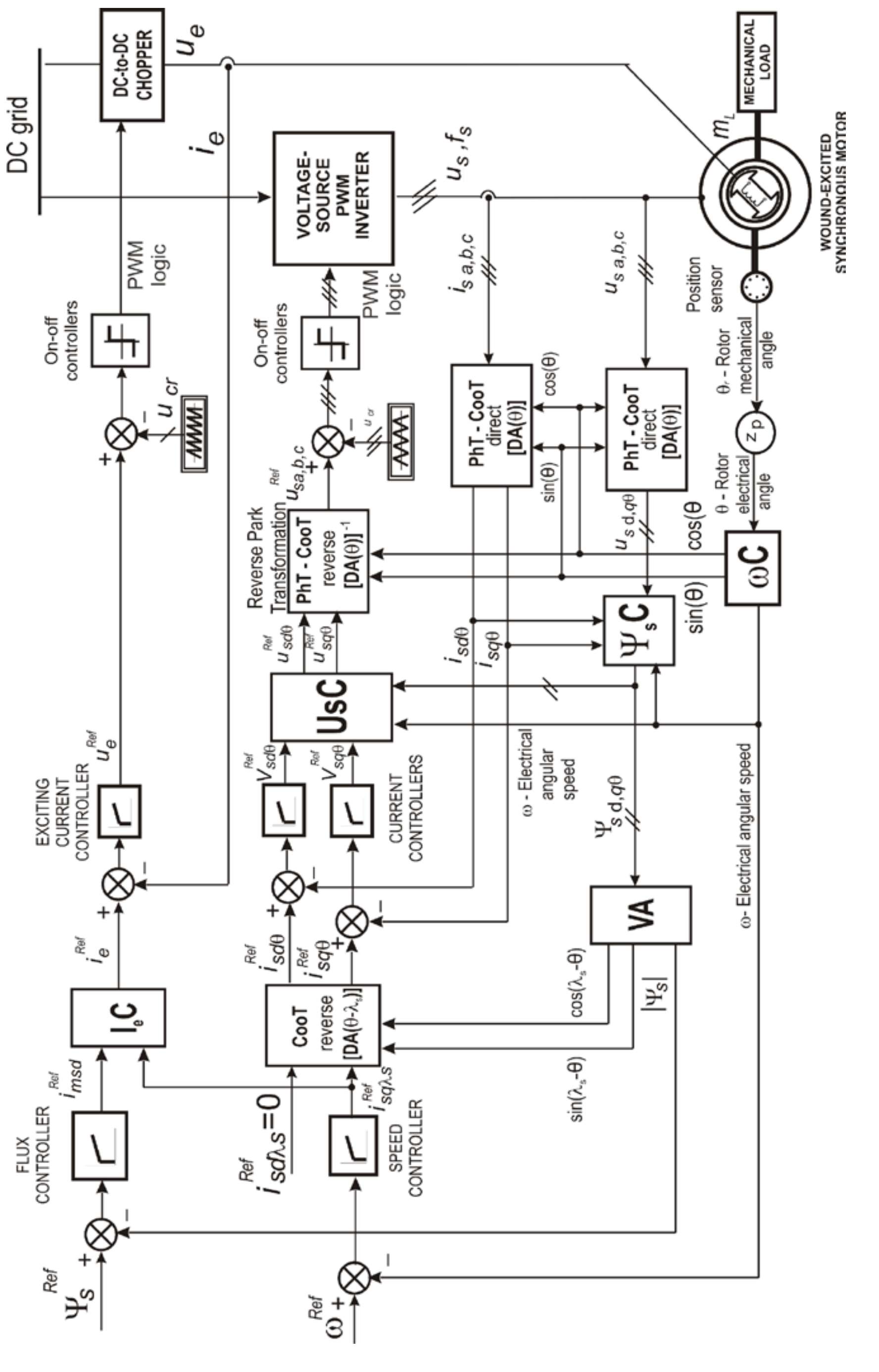

Figure 1: Vector control system of the adjustable excited synchronous motor fed by a static frequency converter with feed-forward voltage-PWM and double field orientation, operating with controlled stator flux and imposed unity power factor.

In the third control loop the resultant stator-flux is directly controlled with a PI controller, which outputs the i_{ms} magnetizing current, necessary for the computation of the excitation current in the IeC block [2], [8].

4. Angular speed computation

For the self-control of the Ex-SyM it is important an accurate information about the rotor position. This was realized using an incremental encoder, mounted on the motor shaft. The mounting is realized in a manner, that the encoder index signal is synchronized with respect to the rotor position. The encoder generates a number of pulses proportional to the angular position of the shaft. It gives information also about the sense of the rotating motion: positive values for direct and negative ones for reverse running. The counter resets it to zero at every full rotation. The amplitude of this signal will be equal to the number of the increments/revolution of the encoder. This position signal θ_{enc} provided by the encoder is processed in order to obtain a position signal θ between $[0, 2\pi]$ for direct, and $[0, -2\pi]$ for reverse rotation respectively, based on the following expression:

$$\theta = \frac{\theta_{enc}}{N_r} 2\pi , \tag{6}$$

where N_r is the number of increments per revolution of the digital encoder.

The electrical angular speed of the rotor is also required in the UsC block for the computation of the voltage control variable. The angular speed can be determined using the sine and cosine functions of the rotor position. The amplitude of these functions is equal to 1. The method presented in [1] is based on the derivation of either the sine or the cosine function of the position, and uses the following relation:

$$\omega = \frac{d\theta}{dt} = (\cos\theta)^{-1} \frac{d(\sin\theta)}{dt} \tag{7}$$

The drawback of this method is, that division by zero occurs at every zero crossing of the sinusoidal function, because the $\frac{d(\sin\theta)}{dt}$ is shifted by 90°, and is in phase with the $\cos\theta$. The resulting angular speed is inaccurate and presents infinite peaks at these moments, that cannot be processed correctly, as is shown in *Fig. 2*. In order to avoid this situation different methods were implemented. A known method is to filter the obtained signal, but this method leads to inappropriate results especially in transient operation when the speed is not constant. Another approach is based on avoiding the division by zero by introducing a discontinuity in the sine function around zero, assigning instead of this a very small, but nonzero value.

In this paper a different approach is used, which consists in the derivation of both, the sine ($S = \sin\theta$) and cosine ($C = \cos\theta$) functions of the angular position θ, where $S = f(\theta)$, $C = f(\theta)$, and $\theta = f(t)$ [4], [15]:

$$\frac{dS}{dt} = \cos\theta \frac{d(\theta)}{dt} \tag{8}$$

$$\frac{dC}{dt} = -\sin\theta \frac{d(\theta)}{dt} \tag{9}$$

The angular speed is determined by the following relation [15]:

$$|\omega| = \sqrt{\left(\frac{dS}{dt}\right)^2 + \left(\frac{dC}{dt}\right)^2} = \sqrt{\cos^2\theta\left(\frac{d(\theta)}{dt}\right)^2 + \sin^2\theta\left(\frac{d(\theta)}{dt}\right)^2} = \left|\frac{d\theta}{dt}\right| \tag{10}$$

Using this procedure the zero crossing is avoided, and leads to an accurate result, as shown in *Fig. 3*.

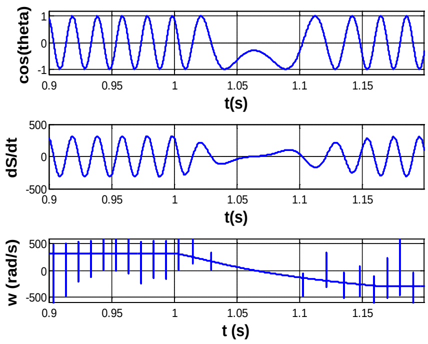

Figure 2: The rotor angular speed computed with the classical method, leading to an inaccurate result

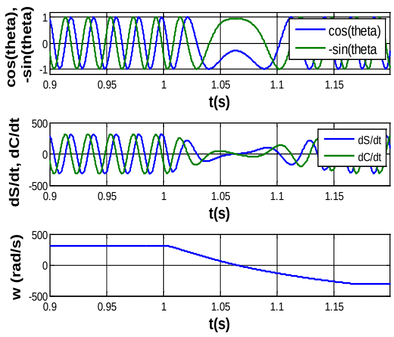

Figure 3: The rotor angular speed computed using the proposed method avoiding the division by zero issue.

The sign of the position signal θ gives the direction of the rotation. The computation of the angular speed is based on the following expression:

$$\omega = |\omega| sign(\theta) = \sqrt{\left(\frac{d(\sin\theta)}{dt}\right)^2 + \left(\frac{d(\cos\theta)}{dt}\right)^2} sign(\theta), \tag{11}$$

and its computation may be processed with the structure presented in *Fig. 4* [4].

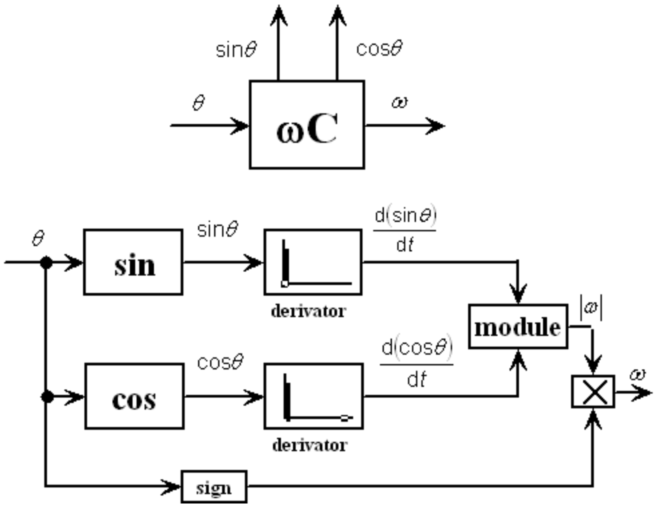

Figure 4: Block symbol and structure for computation of the rotor angular speed based on the encoder position signals.

5. Simulation results

Based on the structure from *Fig. 1* simulations were performed in Matlab-Simulink® environment. The rated data of the simulated salient pole Ex-SyM are: U_{sN} = 380 V, I_{sN} = 1.52 A, P_N = 800 W, f_N=50 Hz, n_N = 1500 [rpm], cosφ= 0.8 (capacitive).

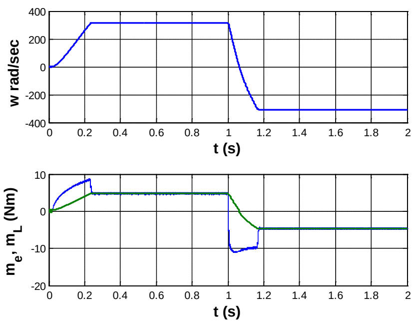

Figure 5: Electrical angular speed (*w*), electromagnetic (m_e) and load torque (m_L)

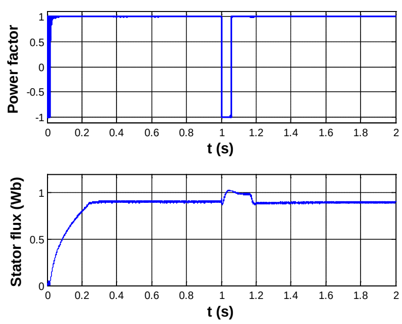

Figure 6: The power factor and the stator-flux amplitude versus time.

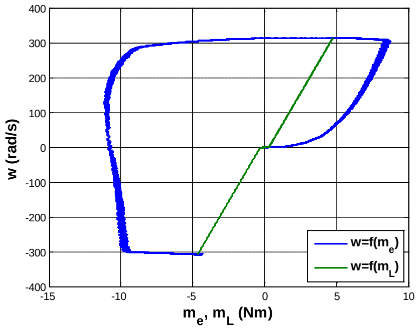

Figure 7: Mechanical characteristics*:* speed versus torque of the motor *w*=f(m_e) and of the mechanical load *w*=f(m_L).

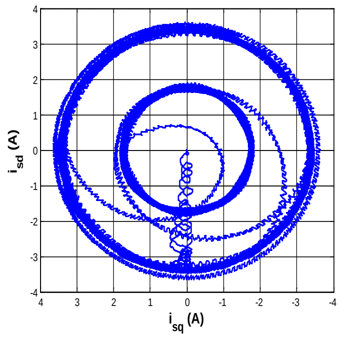

Figure 8: The trajectory of the armature-current space-phasor in natural stator-fixed coordinate frame.

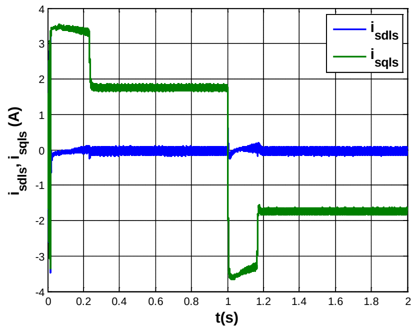

Figure 9. The armature-current two-phase components ($i_{sd\lambda s}$ and $i_{sq\lambda s}$) in stator-flux-oriented coordinate frame.

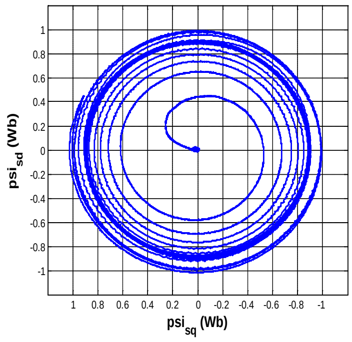

Figure 10. The trajectory of the stator-flux space-phasor in natural stator-fixed coordinate frame.

After the starting process the motor runs at the rated speed value corresponding to a frequency of 50 Hz. At t = 1 s under the full rated load a speed reversal is applied. The mechanical load has reactive character and it is linearly speed-dependent.

The simulation results show that the proposed control structure from *Fig. 4* is a viable one with improved performances with respect to the conventional vector control systems [2].

The results show a good performance of the drive also in transient operation at starting, and also at speed reversal (*Fig. 5*). The power factor is maximum also during the speed reversal, when the drive is in regenerative running for a short period of time, as is shown in *Fig. 6*. Unity power factor is realized by canceling the stator-field-oriented longitudinal armature reaction, as in *Fig. 9*.

6. Conclusion

The presented control structure uses two types of orientations: resultant stator-field and exciting-field, i.e. rotor-position orientation.

For a rigorous control of the power factor, stator-field orientation was applied, and in order to achieve unity power factor operation in the reactive control loop the stator-flux oriented longitudinal armature reaction was cancelled.

In order to obtain improved control performances, the computation of the control variables were made in rotor-oriented reference frame, so the self-control of the motor and the synchronization of the inverter trigger signal are made based on a directly measured value of the rotor position.

In the control structure of the voltage-controlled Ex-SyM drives the dual field-orientation combines the advantages of the two types of field-orientation procedure, on the one hand of the stator-field orientation suitable for power factor control and on the other hand of the exciting-field orientation for computing feedback- and control-variables based on the rotor-position-oriented classical MM, in order to ensure sophisticated calculus due to the geometry characteristics, i.e. two-axis symmetry of the salient-pole rotor.

The applied computation procedure of the synchronous angular speed corresponding to the rotating the stator-flux avoids the division by zero and gives an accurate result.

The applied computation procedure of the rotor angular speed, which avoids the division by zero, gives accurate results also in computation of the synchronous angular speed of the rotating resultant orientation flux in any field-oriented vector control structure, including induction motor drives, too.

The presented control structure was validated by simulation in Matlab/Simulink®, and the obtained result shows the reliability of this method.

The practical implementation was realized on an experimental rig based on the *dSpace DS1104* controller board. The results were published in [8].

References

[1] Kelemen, Á., and Imecs, M., "Vector Control of AC Drives, Volume 1: Vector Control of Induction Machine Drives", OMIKK-Publisher, Budapest, Hungary, 1991.

[2] Kelemen, Á., Imecs, M., "Vector Control of AC Drives, Volume 2: Vector Control of Synchronous Machine Drives" Ecriture Budapest, Hungary, 1993.

[3] W. Leonhard, "Control of Electrical Drives", Springer Verlag. Berlin, Heidelberg, New York, Tokyo, 1985.

[4] Szabó, Cs., "Implementation of Scalar and Vector Control Structures for Synchronous Motors (in Romanian)", PhD Thesis, Technical University of Cluj-Napoca, Romania, 2006.

[5] Kazmierkowski, M. P., Tunia, H., "Automatic Control of Converter-Fed Drives", Elsevier, Amsterdam, 1993.
[6] Vauhkonen, V., "A cycloconverter-fed synchronous motor drive having isolated output phases", in *Proc. International Conference on Electrical Machines, ICEM '84, Lausanne, Switzerland*, 1984.
[7] Imecs, M., Szabó, Cs., Incze, I. I., "Stator-field-oriented control of the variable-excited synchronous motor: numerical simulation", in *Proc. 7th International Symposium of Hungarian Researchers on Computational Intelligence HUCI 200*6, *Budapest, Hungary*, 2006, pp. 95-106.
[8] Szabo, C., Imecs, M., Incze, I. I., "Vector control of the synchronous motor operating at unity power factor", in *Proc. 11th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM 2008*, *Brasov, Romania*, 2008, vol. II-A pp. 15-20.
[9] Szabo, C., Imecs, M., Incze, I. I., "Synchronous motor drive with controlled stator-field-oriented longitudinal armature reaction", in *Proc The 33rd International Conference of the IEEE Industrial Electronics Society, IECON 2007*, *Taipei, Taiwan*, 2007, CD-ROM
[10] Davoine, J., Perret, R., Le-Huy H., "Operation of a self-controlled synchronous motor without a shaft position sensor", *Trans. Ind Applications*, IA-19, no. 2, pp. 217-222, March/April 1983.
[11] Shinnaka, S., Sagawa, T., "New optimal current control methods for energy-efficient and wide speed-range operation of hybrid-field synchronous motor," *IEEE Trans. Ind Electronics*, vol. 54, no. 5, pp. 2443-2450, Oct. 2007.
[12] Imecs, M., Incze, I. I., Szabó, Cs., "Double field orientated vector control structure for cage induction motor drive", *Scientific Bulletin of the „Politehnica" University of Timisoara, Romania*, *Transaction of Power Engineering*, Tom 53(67), Special Issue, pp. 135-140, 2008.
[13] Imecs, M., Incze, I. I., Szabó, Cs., "Dual field orientation for vector controlled cage induction motors", in *Proc. of the 11th IEEE Internat. Conference on Intelligent Engineering Systems, INES 2009, Barbados*, 2009, pp 143-148.
[14] Imecs, M., Szabó, Cs., Incze, I. I., "Stator-field-oriented vector control for VSI-fed wound-excited synchronous motor", in *Proc. International Aegean Conference on Electrical Machines and Power Electronics*, *ACEMP-ELECTROMOTION Joint Conference*, *Bodrum, Turkey*, 2007, pp. 303-308.
[15] Wallfaren, W, "Method and apparatus for determining angular velocity from two signals which are function of the angle of rotation", US Patent No.4814701, Mar. 21 1989.
[16] Bose K. B., "Modern Power Electronics and AC Drives", Prentice-Hall PTR. Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA, 2002.