Analysis of the Electrical Shift Angle Influence over a Variable Speed Two-Phase Induction Motor Drive

Mircea Popescu Tapani Jokinen Petri Lampola Antero Arkkio
HELSINKI UNIVERSITY OF TECHNOLOGY,
LABORATORY ELECTROMECHANICS
P.O.BOX 3000, FIN-02015-HUT, Espoo, Finland
Tel: (+358). 9451. 2383; Fax: (+358). 9451. 2991
E-mail: mirceap@ieee.org; Tapani.Jokinen@hut.fi; Petri.Lampola@hut.fi
http://www.hut.fi/Units/electromechanics

Elek Demeter
RESEARCH INSTITUTE FOR ELECTRICAL MACHINES
Bd. Tudor Vladimirescu 45, RO-79623 Bucharest, Romania
Tel: (+401). 410.0704; Fax: (+401). 410.6684
E-mail: office@elma.eunet.ro
http://www.4-1-1.com/offers/ICPE-ME.html

Valentin Navrapescu
POLYTECHNIC UNIVERSITY OF BUCHAREST;
DEPT. ELECTRICAL ENGINEERING
Spl. Independentei 313, RO-77206 Bucharest, Romania
E-mail: valin@temp.eltech.pub.ro
http://www.amotion.pub.ro

Keywords

<<AC machines>>, <<Adjustable speed drive>>,<< Motion control>>, <<Modelling>>, <<Simulation>>, <<Harmonics>>

Abstract

This paper presents the modelling and experimental studies, underlying the analysis of the electrical shifted angle influence over a variable speed two-phase induction motor drive.
The two-phase induction machine (TPIM) is widely used in many light-duty applications were three-phase supply is not readily available. During the development of such a machine, there are several options, including the spatial placement of the auxiliary winding. The torque-slip characteristics can be manipulated by shifting the auxiliary winding from the quadrature position. For the analysed model, the machine stator windings are realised for three different values of the electrical shifted angle. A median point pulse width modulation (PWM) inverter with full logic control is used as a variable frequency supply. A new strategy for the controller ratio of the PWM inverter is proposed. The analysis is made for steady-state and transient state operation.

I. Introduction

For the fractional horsepower applications the single-phase and two-phase induction motors are the most popular. With the advent of variable frquency inverters using power electronics devices, it was realised an important improvement of the torque control of two-phase or single-phase induction motors. In the last decade, several options were reported, regarding the control strategy:

- Integral-cycle control method, using the antiparallel thyristors or TRIACs as static convertors [6]. The variable stator effective voltage is obtained by varying the ratio on-off time of the power devices. The mechanical time constant has be longer than the on-off intervals, in order to avoid the speed fluctuations. However, the important content of harmonics influences the torque-speed characteristics.
- PWM inverter with voltage, frequency and phase-difference angle control, using a half-bridge inverter, controlled with microprocessor [7]. It is a workable solution for adjustable speed drives of two-phase induction motors. The motor torque is controlled by phase-difference angle control not by the modulation of the phase voltage. The commutation angles of the output voltages are fixed. If exists a variation of phase-difference angle, than is possible the speed reversal. The main problem of this control technique is the number of sections which divide the torque-speed characteristics, with a corresponding points of abrupt change of the torque.
- Two-phase inverter with four power devices, i.e. FET, MOSFET, IGBT or MCT devices [8]. It represents a suitable solution for speed control in a very wide speed range, with constant torque, by keeping the ratio *V/f* constant. Also, constant power operation is achieved by varying the output frequency and maintaining constant the output effective voltage. Although good performances can be obtained with symmetrical two-phase induction motors, the single-phase or unsymmetrical two-phase induction motors are not designed to work with this control device.

In this paper a new strategy for speed control of the unsymmetrical two-phase induction motors is proposed. A two-phase PWM inverter with constant *V/f* ratio is used. The phase difference angle-control between the two winding voltages can be varied from $-\pi/2$ to $+\pi/2$ electrical degrees, corresponding to the electrical shift angle stator windings. The amplitudes of two voltages are linked by their ratio which is equal to the turn-windings ratio [5]. The characteristics of the two-phase unsymmetrical induction motor are analysed for steady-state and dynamic operation.

II. Mathematical Model

This paper proposes a mathematical model in stationary reference frame for the two-phase induction machine with a shifted auxiliary winding. This model permits the prediction of the transient or steady-state performance of the machine for fixed-frequency supply or for variable voltage-frequency supply. Once developed, the model is verified by comparing the measured steady-state torque slip curves of the TPIM for three values of the electrical auxiliary phase stator shift, to that obtained by a computer simulation based on the model set forth herein. The mathematical model of a TPIM with a shifted auxiliary winding is also used to analyse the effects of operating under variable voltage-variable frequency supply (PWM inverter).
It is assumed that the stator windings are sinusoidally distributed, and that the machine is magnetically linear. The iron losses have been neglected.

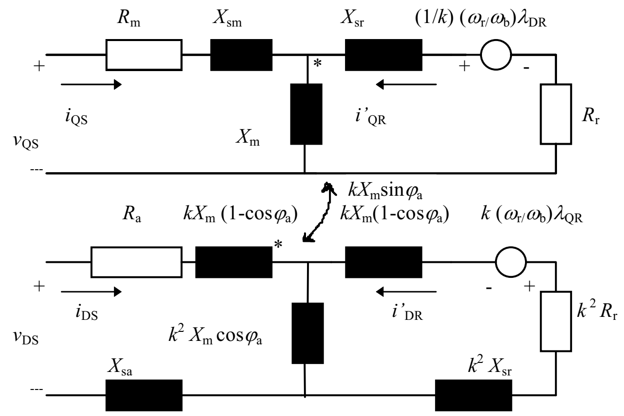


Fig. 1. Equivalent circuit of a two-phase induction machine
with non-orthogonal stator windings

A machine mathematical model with non-orthogonal stator windings in stationary reference frame is presented in Fig. 1. The positive direction for the electrical shift angle φ_a is opposite the direction of rotation. The mechanical shift angle is obtained by dividing the electrical one with *P*/2, where *P* denotes the number of magnetic poles.

$$v_{QS} = R_m i_{QS} + \frac{p}{\omega_b}\psi_{QS} \quad (1)$$

$$v_{DS} = R_a i_{DS} + \frac{p}{\omega_b}\psi_{DS} \quad (2)$$

$$0 = R_r i'_{QR} - \frac{1}{k}\frac{\omega_r}{\omega_b}\psi'_{DR} + \frac{p}{\omega_b}\psi'_{QR} \quad (3)$$

$$0 = k^2 R_r i'_{DR} + k\frac{\omega_r}{\omega_b}\psi'_{QR} + \frac{p}{\omega_b}\psi'_{DR} \quad (4)$$

$$\psi_{QS} = (X_{sm} + X_m) i_{QS} - kX_m \sin\varphi_a i_{DS} + X_m i'_{QR} \quad (5)$$

$$\psi_{DS} = -kX_m \sin\varphi_a i_{QS} + (X_{sa} + k^2 X_m) i_{DS} - kX_m \sin\varphi_a i'_{QR} + k^2 X_m \cos\varphi_a i'_{DR} \quad (6)$$

$$\psi'_{QR} = X_m i_{QS} - kX_m \sin\varphi_a i_{DS} + (X_{sr} + X_m) i'_{QR} \quad (7)$$

$$\psi'_{DR} = k^2 X_m \cos\varphi_a i_{DS} + k^2 (X_{sr} + X_m) i'_{DRT} \quad (8)$$

$$T_e = \frac{P}{2}\frac{X_m}{\omega_b} k (i_{QS} i'_{DR} - i_{DS} i'_{QR} \cos\varphi_a - k i_{DS} i'_{DR} \sin\varphi_a) \quad (9)$$

$$p\omega_r = (T_e - T_l)/J \quad (10)$$

where the used symbols have the classical significance and φ_a - electrical shift angle

The voltage and flux linkage equations are presented by the relations (1) - (9) and the dynamic equation (10) expresses the dependence of the speed rotation on the instantaneous electromagnetic torque and load torque.

II. STEADY STATE OPERATION ANALYSIS

The main and the auxiliary stator windings are non-identical, so that the controller ratio for the two windings is selected according to a constant *V/f* ratio under rated frequency and a new strategy relation defined by:

$$\underline{V}_{DS} = e^{j\left(\frac{\pi}{2} - \varphi_a\right)} \cdot k \cdot \underline{V}_{QS} \quad (11)$$

where underline denotes complex variable, *j* is the complex operator, *k* is the auxiliary/main windings ratio. The subscripts *QS,DS* stand for main and auxiliary respectively. This maintains the ampere-turns of the two windings roughly the same at all frequencies. The two-phase induction machine has the parameters listed in Table I. In fact, the machine is a capacitor run induction motor with the capacitor removed.

Simulation was realised by using a MATLAB M-file. The steady-state operation can be described by substituting in equations (1)-(10) the differential operator $j\omega$.

Fig. 2 shows the schematic structure of the PWM inverter-fed two-phase induction motor. It comprises a two-phase induction motor, a half-bridge inverter, a microprocessor, a corresponding driving circuit, and a fixed DC voltage source. Both amplitude and frequency of the voltage are adjusted in order to obtain the constant ratio *V/f* criteria. The phase-difference angle control is applied only to the auxiliary winding, so one can control the amplitude of both windings voltage, and also the phase-difference angle between the two voltages. In Fig. 3 the waveforms of the output voltages of the two-phase inverter, for the case of phase-difference angle equal to π/2 electrical degrees, are presented.

Fig. 4. illustrates the torque-slip characteristics of a TPIM for three different values of the electrical shift angle (-π/8 rad; 0 rad; +π/8 rad). Physically, for the analysed motor, the selected shift angle corresponds to two stator slots, as the number of stator slots is 28. The PWM inverter supplies a range of output fundamental frequencies between 10 … 200 Hz. The analysed values are for 132 V/ 30 Hz, 176 V/40 Hz and 220 V/ 50 Hz. The positive value of the electrical shift angle ($\varphi_a = +\pi/8$ rad) determines increased starting and rated torque, while the negative value determines poor performances regarding torque-speed characteristics. The explanation of this phenomenon is given by the double revolving field theory [12], in which the reverse field component became weaker for $\varphi_a > 0$, and stronger for $\varphi_a < 0$ due to mutual inductances between the stator phases. It can be observed that the model set forth herein matches the measured results.

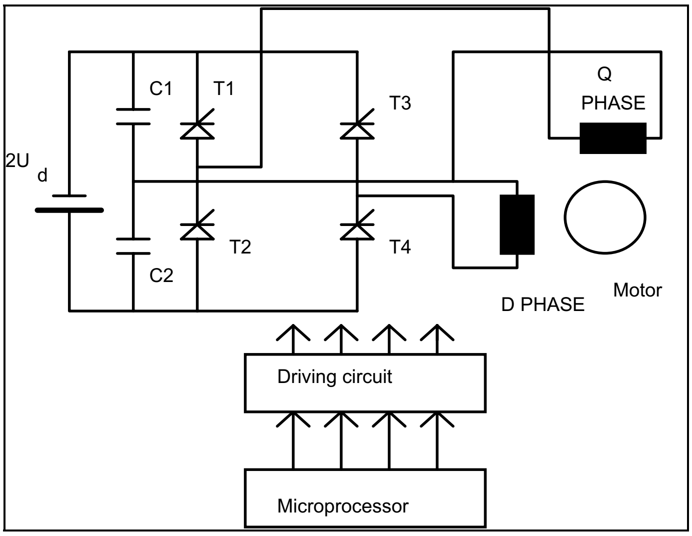


Fig. 2. Schematic structure of the voltage/frequency controlled inverter-fed two-phase induction motor

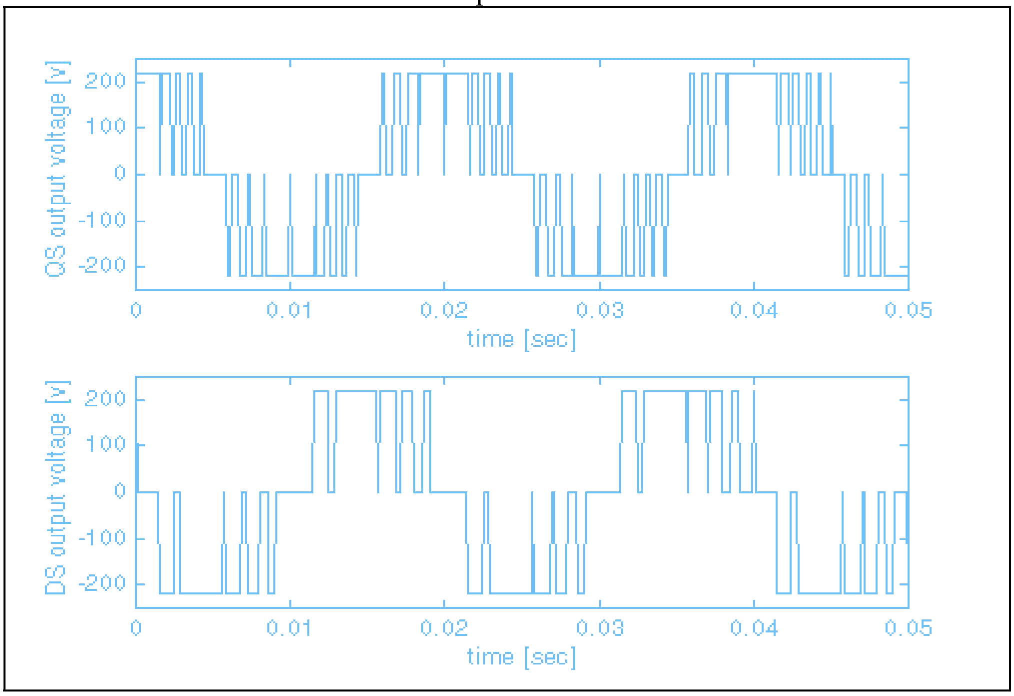
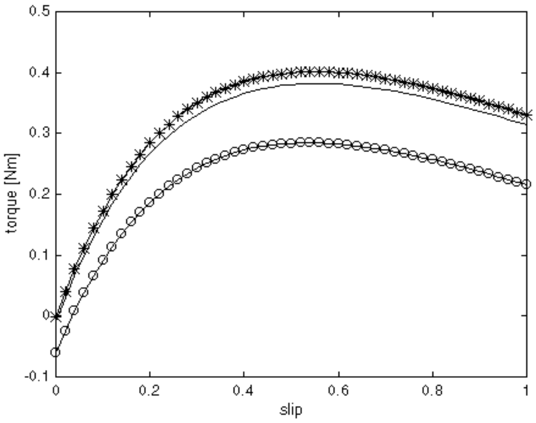
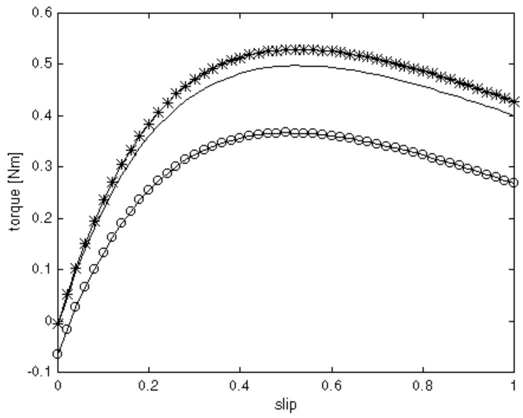


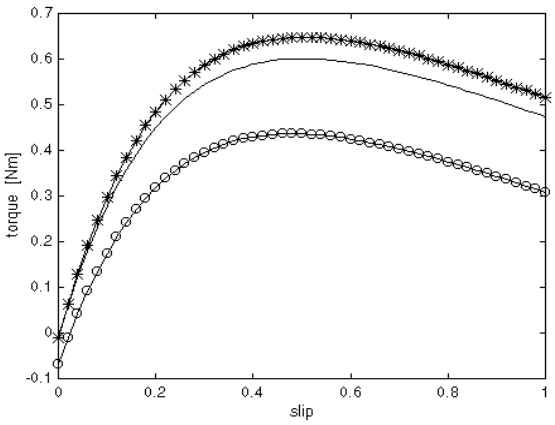
Fig. 3. Waveforms of the output voltages of the controlled PWM inverter



a) $V = 132$ V; $f = 30$ Hz



b) $V = 176$ V; $f = 40$ Hz



c) $V = 220$ V; f=50 Hz

Fig. 4. Torque-slip characteristic of a PWM inverter fed TPIM with shifted stator windings for constant V/f ratio (-- φ_a=0 rad; -* φ_a= π/8 rad; -o φ_a=-π/8 rad)

TABLE I

TPIM Parameters					
k	0.47	R_r	76 Ω	X_{sa}	7 Ω
φ_a	+/- 0.393 rad	X_{sm}	22 Ω	X_m	706 Ω
J	0.0004 kgm^2	X_{sr}	29 Ω	P	2
R_m	37 Ω	R_a	56 Ω	$\|V_{QS}\|$	220 V

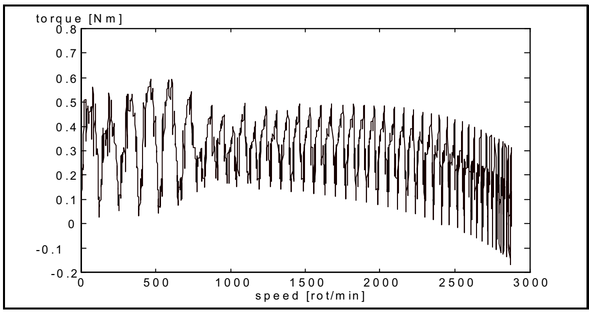
III. TRANSIENT STATE OPERATION ANALYSIS

For a TPIM, the dynamic analysis represents an important task, since one can obtain information regarding current and torque behaviour for any load modification.

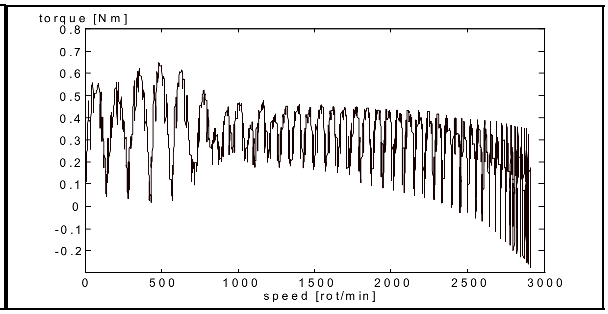
The dynamic modelling of the inverter fed two-phase motor has been carried out considering an identical distribution for main and auxiliary windings.

A SIMULINK program was implemented using equations (1)-(10). Simulations presented in Figs. 5, 6 are valid for no-load starting period and fundamental output frequency f_0 was 50 Hz. The PWM carrier frequency f_c was 1050 Hz.

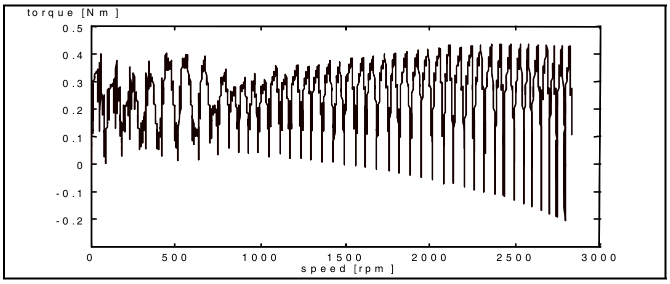
Fig. 5a,b,c illustrates the torque behaviour of a two-phase induction motor for different values of the electrical shift angle (φ_a= -π/8; 0; +π/8 rad). Note that the positive value of the electrical shift angle determines mainly an important decrease of the pulsating torque. Fig. 6a,b,c shows the torque harmonics content for a two-phase induction motor for different values of the electrical shift angle (φ_a= -π/8; 0; +π/8 rad). The torque harmonics distortion (THD), for each of the simulated cases, reveals how the torque behavior depends on the value and sense of the electrical shift angle.



a) φ_a=π/8 rad;

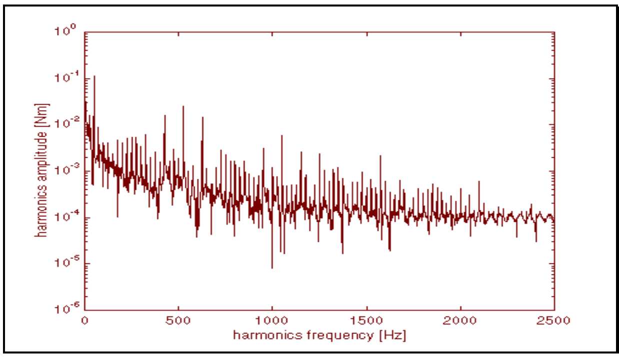


b) φ_a=0 rad;

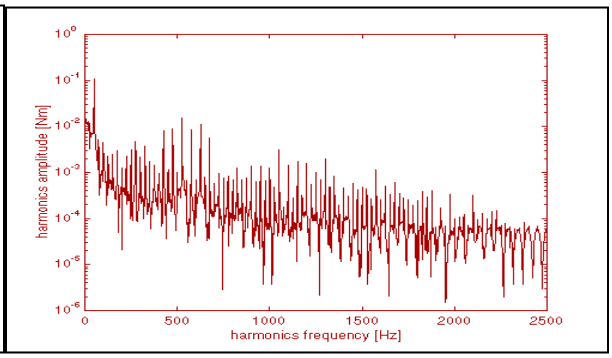


c) φ_a=-π/8 rad

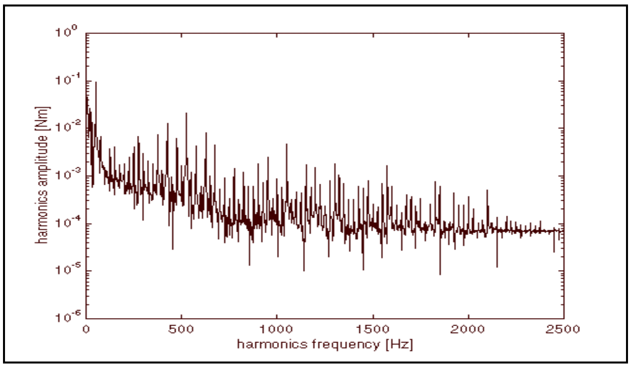
Fig. 5. Transient variation of the electromagnetic torque for a PWM inverter fed TPIM with shifted stator windings



a) φ_a= 0 rad;



b) φ_a=-π/8 rad;



c) φ_a=π/8 rad

Fig. 6. Harmonic contents of the electromagnetic torque for a PWM inverter fed TPIM with non-orthogonal stator winding

A wide range of harmonics is present, but with small amplitudes. The fundamental torque harmonic is the most important harmonic components, while the double frequency component, very important for a usual single-phase motor (capacitor run, capacitor start, or split-phase) is minimise to the other harmonics amplitude. The total harmonic torque is computed from

$$T_h = \sqrt{T_s^2 - T_{50}^2} \qquad (12)$$

where T_s is the average rated electromagnetic torque and T_{50} is its 50 Hz component. The total harmonic distortion (THD) of the instantaneous electromagnetic torque may be calculated as T_h / T_{50}. For the rated speed 2900 min^{-1} , the calculated THD obtained by computer simulation is:

- $\varphi_a = +\pi/8$ rad, THD = 8.77%
- $\varphi_a = 0$ rad, THD = 11.84%
- $\varphi_a = -\pi/8$ rad, THD = 17.21%

Harmonic distortion can be reduced by choosing the optimum value of the electrical shift angle. The simulation model predicts a low level for the pulsating torque, but further investigation is necessary in order to consider the iron losses, saturation level and mechanical variables which have been neglected in this model.

IV. CONCLUSIONS

A two-phase induction motor supplied from a PWM inverter, can present improved performances when:

a) the loading and windings temperature are maintain constant;
b) the system of the non-orthogonal stator windings is used;
c) a new strategy relation for the controller ratio of the PWM inverter is implemented.

The influence of the sense and value of the electrical shift angle between the stator windings, over the two-phase induction machine's torque behaviour supplied from variable voltage-variable frequency devices (type PWM inverter), is described by the following remarks:

1) higher starting, break-down and rated torque, lower pulsating torque if positive value of the electrical shifted angle between the stator windings (opposite to the rotation sense) is realised;
2) higher pulsating torque, lower starting, rated and break-down torque if negative value of the electrical shifted angle (toward the rotation sense) is used;
3) the auxiliary voltage amplitude is modified by phase difference angle control;
4) the phase voltage amplitude ratio have to be identical with the windings turns ratio, and the phase difference angle value will depend on the electrical shift angle between the stator windings.

The dynamic behaviour of a TPIM with non-orthogonal stator windings, supplied from variable voltage-variable frequency devices, may be analysed as well. The same conclusions are valid for this situation.

REFERENCES

1. Krause, P.C., Wasynczuk, O., Sudhoff, S.D.: *Analysis of Electric Machinery*, IEEE Press, 1995

2. Puuchstein, A.F., Lloyd, T.C.: *Capacitor Motors with Winding not in Quadrature*, AIEE Trans, nov. 1935. p. 1235-1239

3. Lyon, W.V., Kingsley, C. jr.: *Analysis of Unsymmetrical Machines*, AIEE Trans, may 1936, p.471-476.

4. Walls, T.A., Sudhoff, S.D.: *Analysis of a single-phase induction machine with a shifted auxiliary winding*, IEEE, Trans. on En.Conv., dec. 1996, p.681-686

5. Collins, E.R., Puttgen, H.B., Sayle, W.E.: - *Single-Phase Induction Motor Adjustable Speed Drive Direct Phase Angle Control of the Auxiliary Winding Supply*, IEEE-IAS Annual Meeting, 1988, USA, vol. I, p.246- 252

6. Longya, X.: *Dynamic model of an Integral-Cycle Controlled Single-Phase Induction Machine*, IEEE Transactions on Energy Conversion, vol.7, No.4, December 1992, pp.761-767

7. Do-Hyun, J., Jong-Soo, W.: *Voltage, Frequency, and Phase-Difference Angle Control of PWM Inverters-Fed Two-Phase Induction motors*, IEEE Transactions on Power Electronics, Vol..9, No.4, July 1994, pp.377-383

8. Mhango, L.M.C., Perryman, R.: *Analysis and Simulation of a High-Speed Two-Phase AC Drive for Aerospace Applications* IEE Proc. -Electr. Power Appl., Vol144, No.2, March 1997, pp.149-157

9. Popescu, M., Jokinen, T., Demeter, E., Micu, D., Navrapescu, V.: - *Analysis and Design of a PWM Voltage Regulator for Single-Phase Induction Motor Drive* - In Proceedings of Conference PCIM'98, May 1998, Nurnberg, Germany, pp. 405-410

10. Popescu, M., Jokinen, T., Demeter, E., Micu, D., Navrapescu, V.: - *Two-Phase Variable Speed Induction Motor Drive* - In Proceedings of Conference SPEEDAM'98, June 1998, Sorrento, Italy, pp. P5-43-P5-47

11. Popescu, M., Arkkio, A., Demeter, E., Micu, D., Navrapescu, V.: - *Development of An Inverter Fed Two-Phase Variable Speed Induction Motor Drive* - In Proceedings of Conference PEMC'98, Sept. 1998, Prague, Czech Rep.

12. Veinott, C.G.: *Theory and Design of Small Induction Machines*, McGraw-Hill, New-York, 1959

13. Popescu, M., Jokinen, T., Demeter, E., Navrapescu, V.: - *Modeling and Analysis of a Two-Phase Induction Machine with Non-Orthogonal Stator Windings* – In Proceedings of Conference IEEE IEMDC'99, May 1999, Seattle, USA