Two-stage converter, direct - matrix converter, PWM modulation, sinusoidal filter, modelling and simulation

PRAŽENICA Michal[1]
KAŠČÁK Slavomír[2]
RADVAN Roman[3]

SIMULATION AND VERIFICATION OF TWO-STAGE CONVERTER WITH SINUSOIDAL FILTER

The paper deals with two-stage converter with using direct matrix converter for feeding Two-Phase Induction Motor (TPIM) with or without output sinusoidal LC filter. Simulation and experimental verification of proposed system is presented. The simulation models of TPIM and 2nd order LC filter are created in computing program Matlab.

SYMULACJA I WERYFIKACJA DWUSTOPNIOWEGO PRZEKSZTAŁTNIKA Z FILTREM SINUSOIDALNEM

W artykule przedstawiony jest przekształtnik matrycowy zasilający dwufazowy silnik indukcyjny. Przekształtnik może pracować z/bez filtra sinusoidalnego LC lub bez jego użycia. *Wyniki symulacyjne oraz weryfikacja laboratoryjna przekształtnika zasilającego silnik indukcyjny przedstawione są w artykule. Modele symulacyjne dwufazowego silnika indukcyjnego oraz filtra drugiego rzędu LC są stworzone w środowisku Matlab.*

1. INTRODUCTION – TWO-STAGE

Such a system usually consist of single-phase voltage inverter, AC interlink, HF transformer, 2-phase converter and 2-phase AC motor. Due to AC interlink direct converter (cyclo-converter or matrix converter) is the best choice. One of the possible schemes without transformer and using 2-phase direct matrix converter is depicted in Fig. 1, [1], [2]. System with matrix converter and high frequency AC interlink can generate two-phase orthogonal output with both variable voltage and frequency [3] - [5]. Switching frequency of the converter is rather high (~tens of kHz). Since the voltages of the matrix converter system should be orthogonal ones, the second phase converter is the same as the first one and its voltage is shifted by 90 degree. Proposed scheme of two-stage two-phase converter system is shown in Fig. 3a. Basically, it consists of single-phase fast IGBT inverter, and of two single-phase matrix converters, both in full-bridge connection.

[1] University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic, *michal.prazenica@fel.uniza.sk*
[2] *University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic, slavomir.kascak@fel.uniza.sk*
[3] *University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic, roman.radvan@fel.uniza.sk*

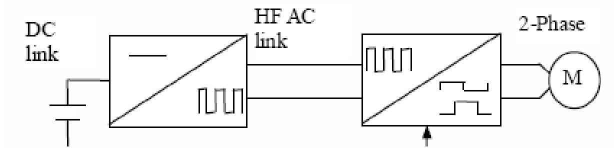


Fig.1. Principle block diagram of 2-stage DC/AC/AC converter (without HF transformer)

Since the switches of the inverter operate with hard commutation, switches of matrix converters are partially soft-commutated in the zero-voltage instants of the AC voltage interlink using unipolar PWM. Therefore, the expected efficiency of the system can be higher as usually by using of classical three-phase inverter.

Inverter of first stage can be connected as:

1. Full or Half - bridge converter,
2. Push-Pull or LLC converter.

Inverter of second stage can be connected as:

1. Full bridge converters connection,
2. Two half bridge ones with central point of the source using HF transformer Fig. 2a or
3. Half-bridge ones with central points of the motor load Fig. 2b.

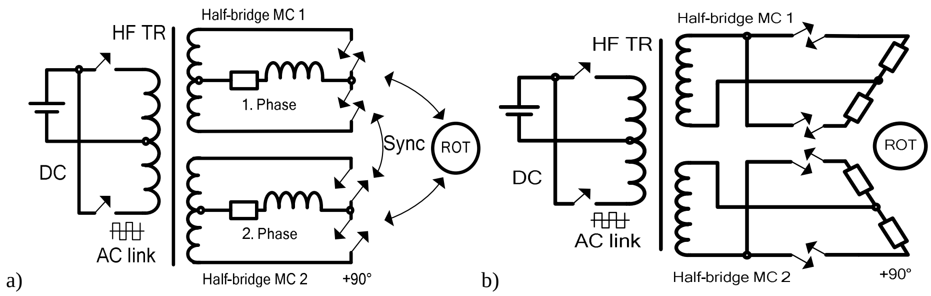


Fig.2. Circuit diagram of half-bridge converters system with a) central points of AC source; b) central points of motor loads

The advantage is then less number of semiconductor devices of the converters (four instead six). Disadvantage of the half-bridge is, of course, double voltage stress of the semiconductor switching elements. About to 2-phase AC electric motors there are many works, [3], [6] - [8] and others.

2. TWO-PHASE INDUCTION MOTOR (TPIM)

Permanent progress in the field of power electronic devices has given a rise to two-phase induction machine (TPIM). These machines have two equal stator windings spatially shifted by 90 degrees. Supply is carried out by two phase converter with currents shifted 90 degrees in time. By means of this supply a waveform of flux density rotating in the air gap, similar to that of the three phase machines, is produced and vibrations and unfavourable noise are thus suppressed [9].

Let us consider the equivalent circuit of TPIM. Subscripts *D* and *Q* mean phases of TPIM (first and second). Subscripts *ns* and *ps* mean negative sequence and positive sequence of rotating fields in TPIM. Parameters R_s, $X_{\sigma s}$, $R_r´$, $X_r´$ and X_m are stator resistance, stator leakage reactance, rotor resistance referred to stator, leakage reactance referred to stator and magnetizing inductance, respectively. K is a ratio of turns of the phase *D* over the turns of the phase *Q*. The negative sequence of rotating field in air-gap is suppressed by symmetrical two-phase supply.

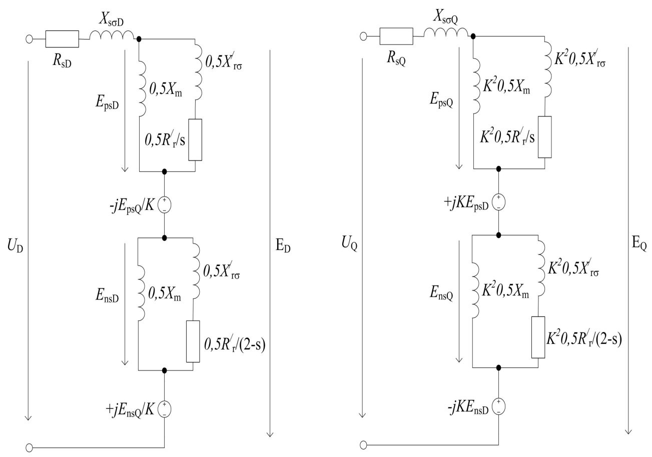


Fig.3. Equivalent circuit of TPIM

The equivalent circuit, Fig. 2, can be described by following formulas:

$$v_{Qs} = \frac{d\psi_{Qs}}{dt} + R_{Qs} i_{qs} \tag{1}$$

$$v_{Ds} = \frac{d\psi_{Ds}}{dt} + R_{Ds} i_{ds} \tag{2}$$

$$v_{Qr} = \frac{d\psi_{Qr}}{dt} + R_{Qr}´ i_{qr} - K\omega_r \psi_{Dr} \tag{3}$$

$$v_{Dr} = \frac{d\psi_{Dr}}{dt} + R_{Dr}´ i_{dr} + K\omega_r \psi_{Qr} \tag{4}$$

Flux linkages can be written as:

$$\psi_{Qs} = L_{sD} i_{Qs} + L_{mD}\left(i_{Qs} + i_{Qr}\right) \tag{5}$$

$$\psi_{Ds} = L_{sQ} i_{Ds} + L_{mQ}\left(i_{Ds} + i_{Dr}\right) \tag{6}$$

$$\psi_{Qr} = L_r´ i_{Qr} + L_{mD}\left(i_{Qs} + i_{Qr}\right) \tag{7}$$

$$\psi_{Dr} = L_r´ i_{Dr} + L_{mQ}\left(i_{Ds} + i_{Dr}\right) \tag{8}$$

In the case of squirrel-cage rotor the rotor voltages are equal to zero, thus:

$$v_{Qr} = v_{Dr} = 0 \tag{9}$$

If ϑ_r is angular displacement between stator and rotor axes, then

$$\omega_r = \frac{d\vartheta_r}{dt} \tag{10}$$

is angular speed of the rotor.

An expression for the instantaneous electromagnetic torque can be obtained by applying the principle of virtual displacement. This relation (positive for motor action) is expressed as:

$$T_e = p\left(\frac{N_a}{N_m}\psi_{qr} i_{dr} - \frac{N_m}{N_a}\psi_{dr} i_{qr}\right) \tag{11}$$

where p is a number of pole-pairs.
The real TPIM was used with name-plate:

Tab.1. Nameplate of investigated TPIM

P_N (W)	V_N (V)	n_N (rpm)	I_N (A)	T_N (Nm)
150	230	2730	1.0	0.55

Parameter used in simulation are:

Tab.2. Parameters of TPIM

	R_s [Ω]	R'_r [Ω]	$X_{\sigma s}$ [Ω]	Method	X_m (Ω)	L_m (H)
	19.92	50.1	21.37	Classical	374.9	1.1933
	X'_r [Ω]	L_s [H]	L'_r [H]	Suhr´s	233.5	0.7417
D	21.37	0.0679	0.0679	2-phase	452	1.4388
	R_s [Ω]	R'_r [Ω]	$X_{\sigma s}$ [Ω]	FEM	398.5	1.2599
	21.32	51.1	22.3			
	X'_r [Ω]	L_s [H]	L'_r [H]			
Q	22.3	0.0709	0.0709			

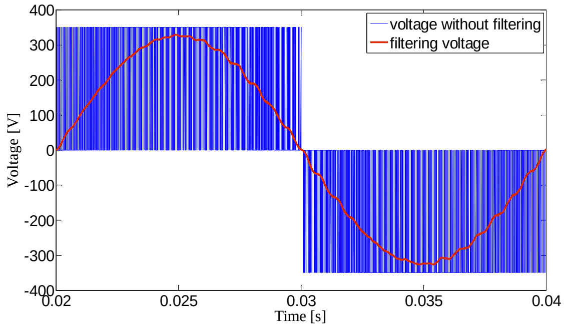
3. MODELLING OF 2nd ORDER LC FILTER UNDER UNIPOLAR PWM CONTROL

The harmonic spectrum of output voltage of inverter, which is depicted in Fig. 4a is shown in Fig. 4b. The harmonics in the inverter output voltage waveform appear as a sidebands, centered around the odd multiples of switching frequency. It follows, that output voltage does not have higher harmonic components around the fundamental frequency. Now is not necessary use the output resonant filter tuned to fundamental frequency, but it can be used output resonant filter tuned to switching frequency, which is depicted in Fig. 5.

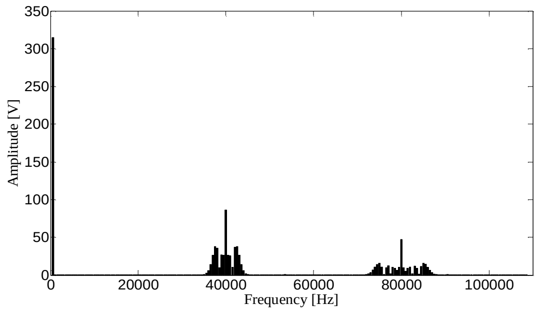
Equations for calculation of LC parameters:

$$L_f = \frac{\Delta U_L}{2.\pi.f_D.I} \qquad C_f = \frac{1}{L_f.(2.\pi.f_D)^2}$$

ΔU_L – it choose in the range of 1 – 5 % U_{OUT}
f_D – damping frequency
I – load current



a)



b)

Fig.4. The output voltage of the 1-phase inverter under bipolar PWM control (a) and its harmonic content without filtering (b)

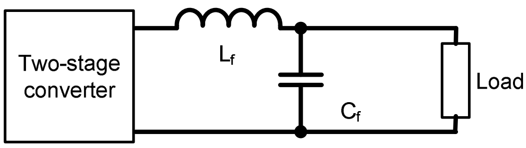


Fig.5. Connection of 2nd order LC filter between load and two-stage converter

Considering converter scheme in Fig. 5 then the state-space equations can be written [10]:

$$\frac{di_L}{dt} = \frac{1}{L} u_{PWM} - \frac{r_L}{L} i_L - \frac{1}{L} u_C \tag{12}$$

$$\frac{du_C}{dt} = \frac{1}{C} i_L - \frac{1}{C.r_C} u_C - \frac{1}{C} i_{D(Q)S} \tag{13}$$

$$\frac{di_{D(Q)S}}{dt} = \frac{1}{L_{D(Q)S}} u_C - \frac{R_{D(Q)S}}{L_{D(Q)S}} i_{D(Q)S} - \frac{L_{D(Q)M}}{L_{D(Q)S}} \frac{di_{D(Q)R}}{dt} \tag{14}$$

After time discretization of system equations using implicit Euler's methods

$$\begin{bmatrix} i_L(i+1) \\ u_C(i+1) \\ i_{LOAD}(i+1) \end{bmatrix} = [\mathbf{J} - h\mathbf{A}]^{-1} * \begin{bmatrix} i_L(i) \\ u_C(i) \\ i_{D(Q)S}(i) \end{bmatrix} + [\mathbf{J} - h\mathbf{A}]^{-1} * \begin{bmatrix} \frac{1}{L} \\ 0 \\ -\frac{L_{D(Q)M}}{L_{D(Q)S}} \end{bmatrix} * \begin{bmatrix} u_{PWM} \\ 0 \\ \frac{di_{D(Q)M}}{dt} \end{bmatrix} * h \tag{15}$$

where

$$\mathbf{A} = \begin{pmatrix} \frac{-r_L}{L} & \frac{-1}{L} & 0 \\ \frac{1}{C} & \frac{-1}{C \cdot r_C} & \frac{-1}{C} \\ 0 & \frac{1}{L_{D(Q)S}} & \frac{-R_{D(Q)S}}{L_{D(Q)S}} \end{pmatrix} \tag{16}$$

and

i_L - inductor current of LC filter
u_C - capacitor voltage of LC filter
$i_{D(Q)S}$ - load current

4. SIMULATION OF TWO-STAGE CONVERTER

Simulation model for TPIM motor load has been modelled in MatLab programming environment. Simulation results of two-stage converter without and with 2nd order LC filter are depicted in next figures.

Simulation and verification of proposed system was realized only with single-phase two-stage converter and start-up capacitor.

Parameters for simulation:

U_{inDC} = 50 V, $U_{outACmax}$ = 40 V, f_{outSW} = 20 kHz, f_{outAC} = 35 Hz, parameters of TPIM used in simulation are shown in part 2.

- **without sinusoidal filter**

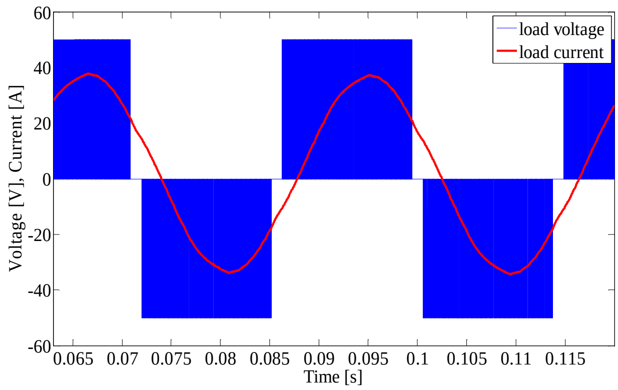


Fig.6. Matrix converter output voltage and current without LC filter with motor load (current waveform was fitted to the picture)

- **with sinusoidal filter**

Parameters for simulation:

- $U_{inDC} = 40$ V, $U_{outACmax} = 30$ V, $f_{outSW} = 20$ kHz, $f_{outAC} = 20$ Hz,
- *parameters of TPIM used in simulation are shown in part 2.*

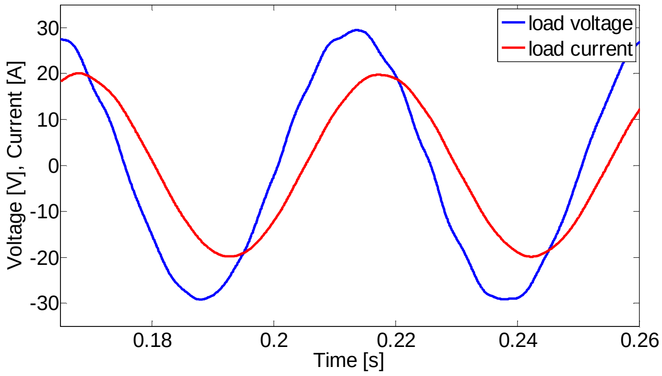


Fig.7. Matrix converter output voltage and current with LC filter with motor load (current waveform was fitted to the picture)

Simulation results were compared with experimental measurements and the results give good coincidence (see next part).

5. EXPERIMENTAL VERIFICATION

Experimental verification has been done using single-phase bridge inverter and single-phase bridge matrix converter for test rig system. There is shown test rig in fig. 8. The first power stage – inverter is integrated type of Fairchild FSB50450T, the second one is assembled of classical IGBT devices type of IRG4PH40KD. It is also possible to use bidirectional switches. The whole test rig system is controlled by Freescale DSP 56F8013DEMO.

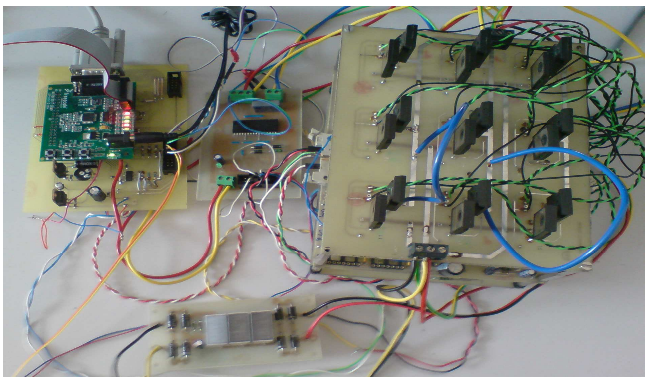


Fig.8. Physical model of two-stage converter

The output quantities of the two-stage converter and TPIM load, i.e. its voltage and current, are presented in next figures.

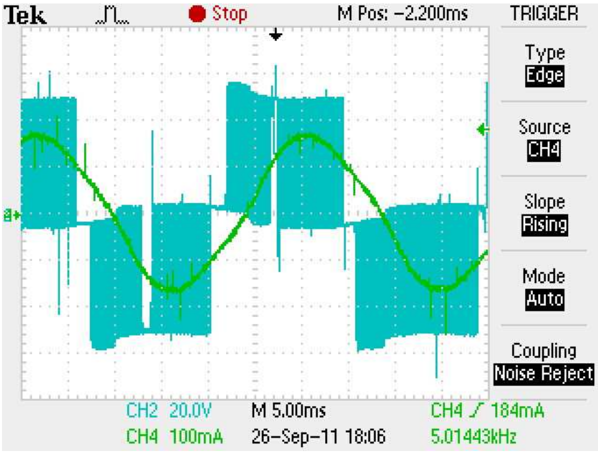


Fig.9. Matrix converter output voltage (blue) and current (green) without LC filter with motor load

We use LC filter with parameters:

$L_f = 1.1$ mH,

$C_f = 1$ μF,

$f_D = 4.8$ kHz.

for working range 20 Hz – 50 Hz.

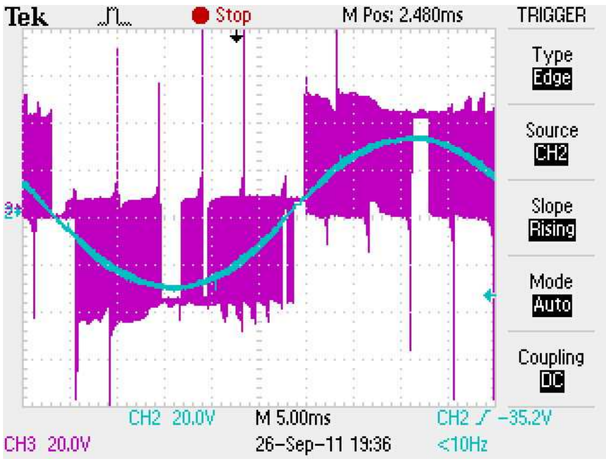


Fig.10. Input (magenta) and output (blue) voltage of LC filter

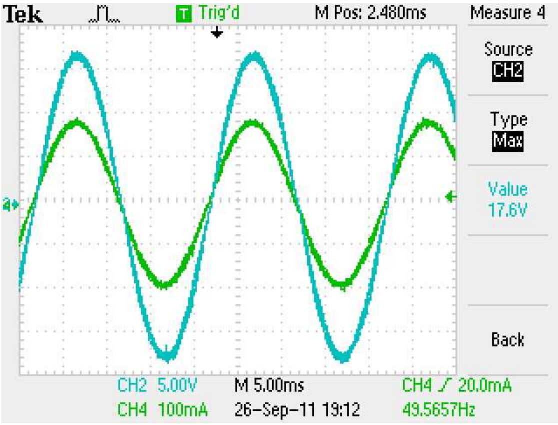


Fig.11. Output voltage (blue) and current (green) of two-stage converter with LC filter and resistive load

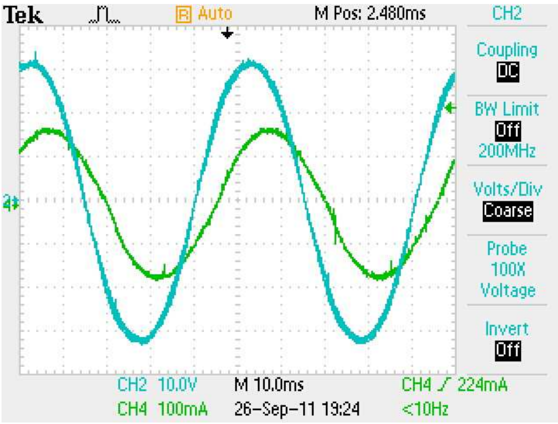


Fig.12. Output voltage (blue) and current (green) of two-stage converter with LC filter and motor load

6. CONCLUSIONS

This paper has discussed modelling, simulation and measurement of proposed system - two-stage converter, 2nd order LC filter and two-phase induction motor.

Simulation results of two-stage converter with LC filter shows, that designed parameters of LC filter confirms good quality of output quantities (voltage and current). Change of parameters of LC filter (change of damping frequency) it can influence shape of output quantity. Measurement shows that there is not phase shift between the input and output voltage of LC filter (Fig.10). Current waveform in connection with LC filter has a smaller distortion and create less EMI.

Using of 2nd order LC filter is suitable for feeding devices which requires harmonic input voltage.

7. ACKNOWLEDGEMENT

The authors thank for the financial support to R&D operational program Centre of excellence of power electronics systems and materials for their components No. OPVaV-2008/2.1/01-SORO, ITMS 26220120046 funded by European regional development fund (ERDF), VEGA1/0470/09. Also the authors want to thank for the technical support to STMicroelectronics and PPI Adhesive Products.

8. REFERENCES

[1] Gonthier, L., *et al*.: High-Efficiency Soft-Commutated DC/AC/AC Converter for Electric Vehicles. In: *Journal Electro Motion 5* (1998), no. 2, pp. 54 – 64, ISSN 1223-057X.

[2] PRAZENICA, M., DOBRUCKY, B., SEKERAK, P., KALAMEN, L.: DESIGN, Modelling and Simulation of Two-Phase Two-Stage Electronic System with Orthogonal Output for Supplying of Two-Phase ASM, In: *Advances in electrical and electronic engineering – AEEE*, - ISSN 1804-3119. - Vol. 9, No. 1 2011, pp. 56-64.

[3] BLAABJERG, F. et al.: Evaluation of Low-Cost Topologies for Two-Phase IM Drives in Industrial Application. *Record of 37th IEEE IAS Annual Meeting on Industry Application, vol. 4*, pp. 2358-2365, ISSN 0197-2618.

[4] WHEELER, P.W. RODRIGUEZ, J., CLARE, J.C., EMPRINGHAM, L., AND WEINSTEIN, A.: Matrix Converters: A technology review. *IEEE Trans. on Industrial Electronics, Vol. 49, no*. 2, pp. 276–288, Apr. 2002.

[5] SOBCZYK, T.J., SIENKO, T.: Application of Matrix Converter as a Voltage Phase Controller in Power Systems, In: *Proc. of SPEEDAM'06 Int'l Conf., Taormina (IT), May 2006*. – ISBN 1-4244-0194-1 – P. 13-17.

[6] BLAABJERG, F., LUNGEANU, F., SKAUG, K., TONNES, M.: Two-Phase Induction Motor Drives. *IEEE Industry Applications Magazine, July-Aug. 2004*, vol. 10, no. 4, pp. 24- 32, ISSN: 1077-2618.

[7] POPESCU, M., DEMETER, E., MICU, D., NAVRAPESCU, V. JOKINEN, T.: Analysis of a Voltage Regulator for a Two-Phase Induction Motor Drive. In*: Proc. of IEMD - Int'l Conf. on Electric Machines and Drives*, Seattle (US), 1999, pp. 658-660.

[8] BALA, S.: *Dynamics of Single/Two Phase Induction Motors*. Department of Electrical and Computer Engineering, University of Wisconsin-Madison

[9] DOBRUCKY, B., FRIVALDSKY, M., PRAZENICA M., SPANIK, P., HABOVCOVA, V., SEKERAK, P., KALAMEN, L.: Two-Phase Power Electronic Drive with Split - Single- Phase Induction Motor. In: *36th Annual Conference of the IEEE Industrial Electronics Society, November 2010 Glendale, AZ, USA*, pp. 163, ISBN 978-1-4244-5226-2, ISSN 1553-572X

[10] DOBRUCKY, B., BENOVA, M., KASCAK, S.: Transient analysis and modeling of 2nd- and 4th-order LCLC filter under non-symmetrical control, In: *Electronics and Electrical Engineering*, KTU Kaunas (LT), Vol. 5 (111), 2011, pp. 89-94.