DESIGN OF NEW TWO-STAGE ELECTRONIC SYSTEM WITH TWO-PHASE ORTHOGONAL OUTPUT USING MATRIX CONVERTERS

Kašša Ján[1], Podmanický Michal[2], Praženica Michal[3]

University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic

Abstract

The paper deals with two-stage power electronic system with two-phase variable orthogonal output for industrial and transport drives applications. Such a two-phase supply with 90 degrees between phases can be easily created using power electronic converters supplied from battery. The proposed system with AC interlink in comparison with currently used conventional systems uses either three-phase cyclo-converter or two single phase matrix converters. Modeling and simulation of two matrix converters with both R-L and motor load is shown in the paper. Results of simulation are compared to experimental verification ones.

1 Two-Phase Power System

In the very early days of commercial electric power, some installations used two-phase four-wire systems for motors. Next two-phase systems have been replaced with three-phase systems. However, some applications of two-phase systems have been produced, especially with 90 degrees between phases. In these days new fields of application come up – in industrial or transport area [1]-[3]. A two-phase supply can be derived from three-phase system using a Scott-connection [5]. Two-phase circuits typically use two separate pairs of current-carrying conductors, Fig. 1. Alternatively, three wires may be used, but the common conductor carries the vector sum of the phase currents, which requires a larger conductor.

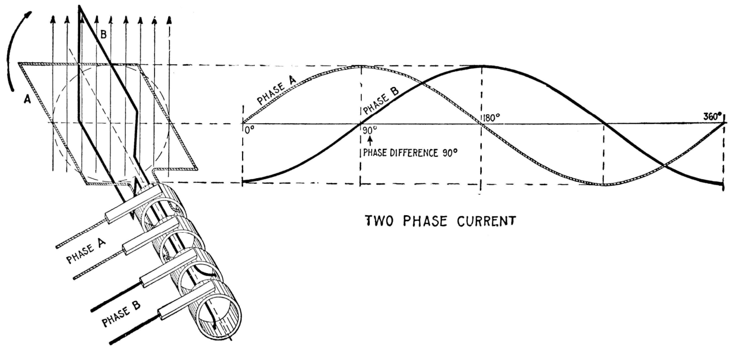

Figure 1: A simplified diagram of a two-phase power system

Three-phase can share conductors so that the three phases can be carried on three conductors of the same size. In electrical power distribution, a requirement of only three conductors rather than four represented a considerable distribution-wire cost savings due to the expense of conductors and installation. On the other hand, it can be also easily created using power electronic converters e.g. from battery supply, with two-phase transfer of energy for zero distance. The certainly advantage of these is that the winding configuration is the same as for a single-phase capacitor-start motor, and, by using a four-wire system, conceptually the phases were independent and easy to analyze with mathematical tools.

[1] *University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic, kassa@fel.uniza.sk*
[2] *University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic, podmanicky @fel.uniza.sk*
[3] *University of Zilina, Faculty of Electrical Engineering, 010 26 Zilina, Slovak Republic, prazenica@fel.uniza.sk*

Two-phase converter system can be performed as single-stage (DC/2AC) – without galvanic isolation, or two-stage (DC/HF_AC/2AC) – with HF transformer due to galvanic isolation input from output [6].

2 Single-Stage DC/AC Converter with DC Voltage Interlink for Two-Phase System

Instead of 3-phase inverter in case of 3-phase AC motor load is possible to use single-phase inverters that principle scheme is shown in Fig. 2.

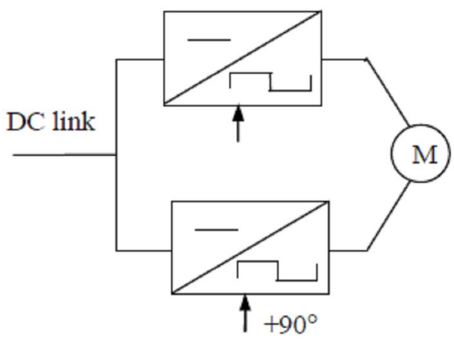

Figure 2: Principle diagram for two-phase supply system

Such a system (Fig. 3a,b) usually consist of DC-source (e.g. accu-battery), DC interlink with filter capacitor, two-phase voltage VSI inverter, and 2-phase AC motor.

Such system is based on simply topology, however it has a fallowing disadvantages:

- low DC voltage (accu-battery supplied),
- without galvanic isolation input from output,
- more power switches as can be seen on Fig. 3b.

Detailed comparison of systems in Figs. 3a and 3b is done in [7]. Due to some drawbacks and orientation direct AC supply voltages we have to considerate two-stage schemes with galvanic separation using HF transformer and half-bridge connection of the direct matrix converters.

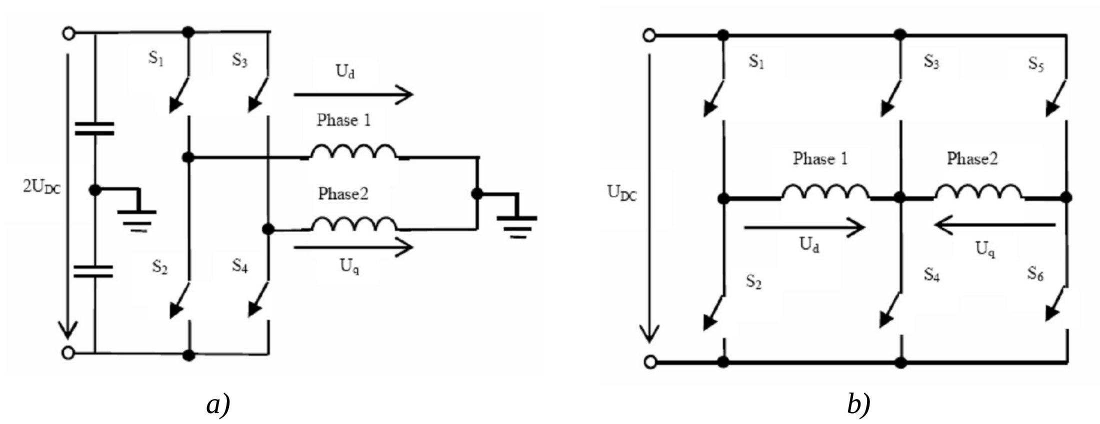

Figure 3: Principle circuit diagrams of two-phase inverters

3 Two-Stage DC/AC/AC Converter with AC Voltage Interlink for Two-Phase System

Two-Stage system usually consist of single-phase voltage inverter, AC interlink, HF transformer (because of neediness galvanic isolation bad also voltage adjustment) , 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. 4, [8], [10].

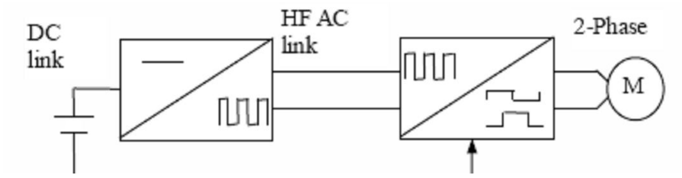

Figure 4: Principle block diagram of 2-stage DC/AC/AC converter (without HF transformer [7]) and with 2-phase second stage

Instead of 3-phase converter is possible to use two single-phase cycle- or matrix converters under the condition that motor load with induction-, or synchronous motors is also two-phase one, and AC HF interlink is with central point.

Each matrix- or cyclo-converter can be connected as:

1. full bridge converters connection, fig. 5,
2. two half bridge one with central point of the source (using of HF transformer), fig. 6,
3. half-bridge one with central points of the motor load, fig. 7.

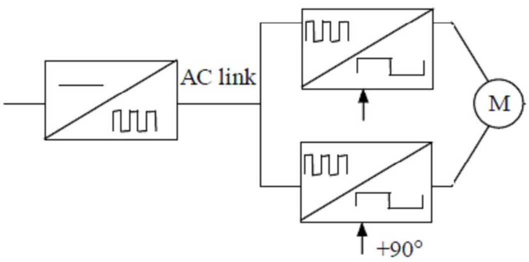

Figure 5: Principle diagram of full bridge converters connection

The proposed system with AC interlink in comparison with currently used conventional systems uses two single phase half-bridge matrix converters. The advantage is then less number of semiconductor devices of the converters (four instead of six).

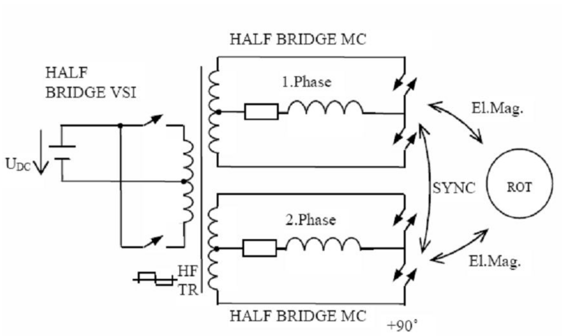

Figure 6: Circuit diagram of two half-bridge converter system with central points of AC source (using of HF transformer)

Instead of central points at the AC sources is possible to use half-bridge connection with central points of the motor load.

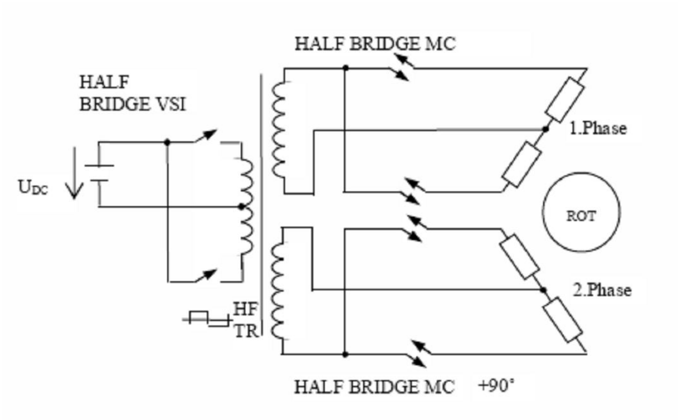

Figure 7: Circuit diagram of two half-bridge converters system with central points of motor loads

To choose right connection for applications the comparison between schemes, from the point of view of power electronics and of the electric motors, have to be done.

In case of:

1. Fig. 5 - Switches of full-matrix converters are soft-commutated in the zero-voltage instants of the AC HF interlink voltage [20]. Therefore, the expected efficiency of the system can be higher as usually by using of classical DC/AC three-phase VSI inverter. On the other side, the phase current will be higher at the same output power and output voltages, using two-phase AC motor.
2. Fig. 6 - there are both hard and ZVS commutations of half-bridge connection of matrix converters. So, they should be operated using bipolar PWM modulation. Detailed switching strategy is the subject of another paper of this Proceedings [4],[21]. Anyway, contrary to full-bridge connection, half-bridge matrix converter need less number of power semiconductor switches (only two per phase). The HF transformer has all windings (primary and secondary) with central tapes. Its power utilization is not optimal one, but dimensions and weight are still sufficiently small due to used high frequency (in order of 10 – 100 kHz).
3. Fig. 7 - commutation circumstances and numbers of switches are the same as in scheme No. 2. Certain disadvantage comparing to above scheme is rather complicated two-phase AC motor. It should be designed with central points of the phase windings, so their utilization is worse as in previous case.

Regarding to 2-phase AC electric motors there are many works, see list of references [7] ,[11] – [16], and therefore the motor will not be described in great detail in this paper.

4 Modelling and Simulation of Two-Stage Converter Using Single-Phase Matrix Converters

Theoretical analysis of single-phase matrix converter has been done, e.g. [17], [18], [19]. Substituted circuit diagram of 2-stage system with using two full-bridge single-phase matrix converter (without HF transformer) is depicted in Fig. 8 and circuit diagram of 2-stage system with using two half-bridge single-phase matrix converter with central points of AC source (using of HF transformer) is depicted in Fig. 6.

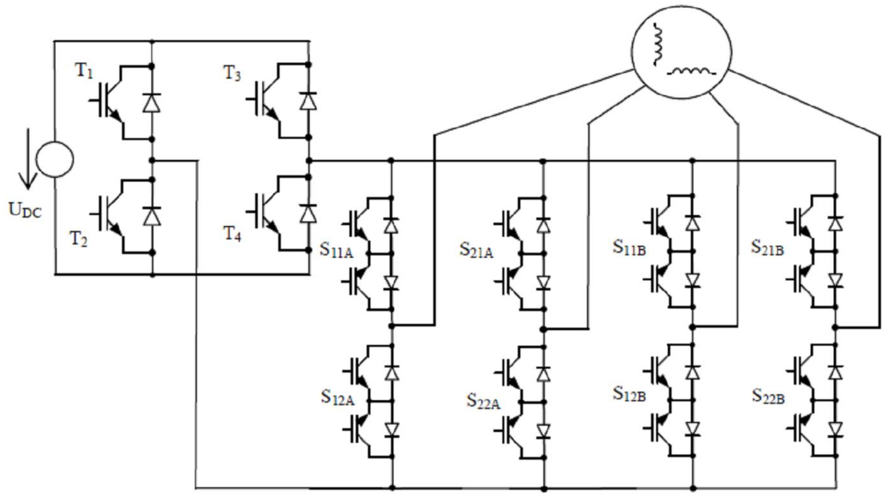

Figure 8: Circuit diagram of 2-stage system: single-phase inverter as a 1st stage
and two full-bridge single-phase matrix converters as a 2nd stage

The simulation schemes of modelled 2-stage system with using two full-bridge single-phase matrix converter (without HF transformer) is depicted in Fig. 9 and simulation schemes of modelled 2-stage system with using two half-bridge single-phase matrix converter with central points of AC source (using of HF transformer) is depicted in Fig. 10.

Both models for R-L load and PMSM motor has been modeled in MatLab 2007b programming environment.

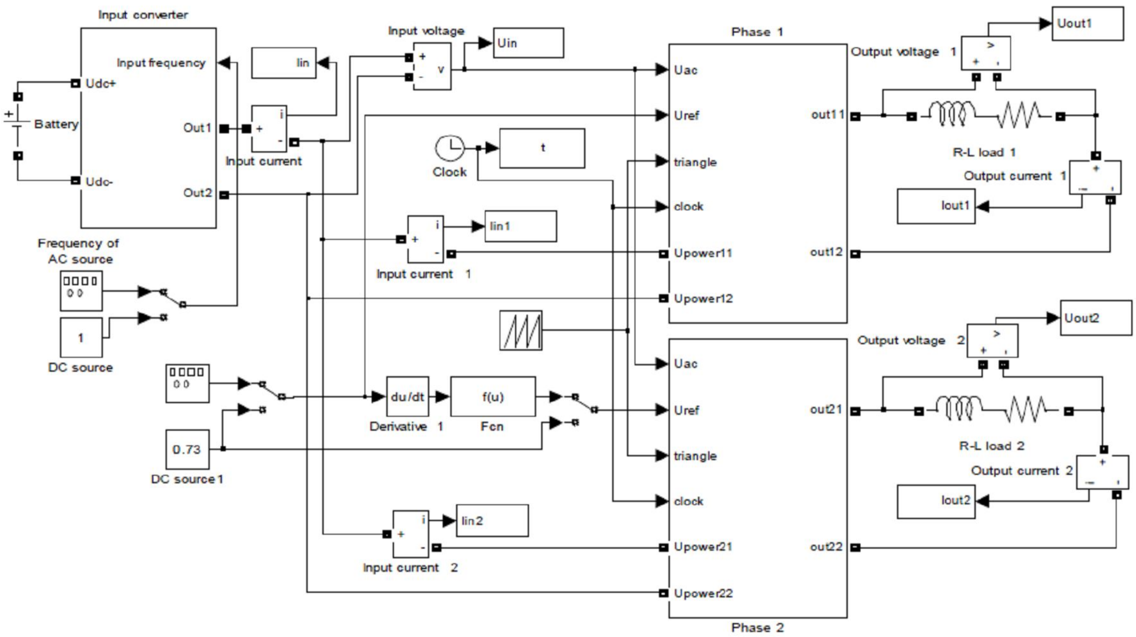

Figure 9: Block diagram for modelling of 2-stage converter system using two full-bridge
single-phase matrix converter (without HF transformer) with R-L load

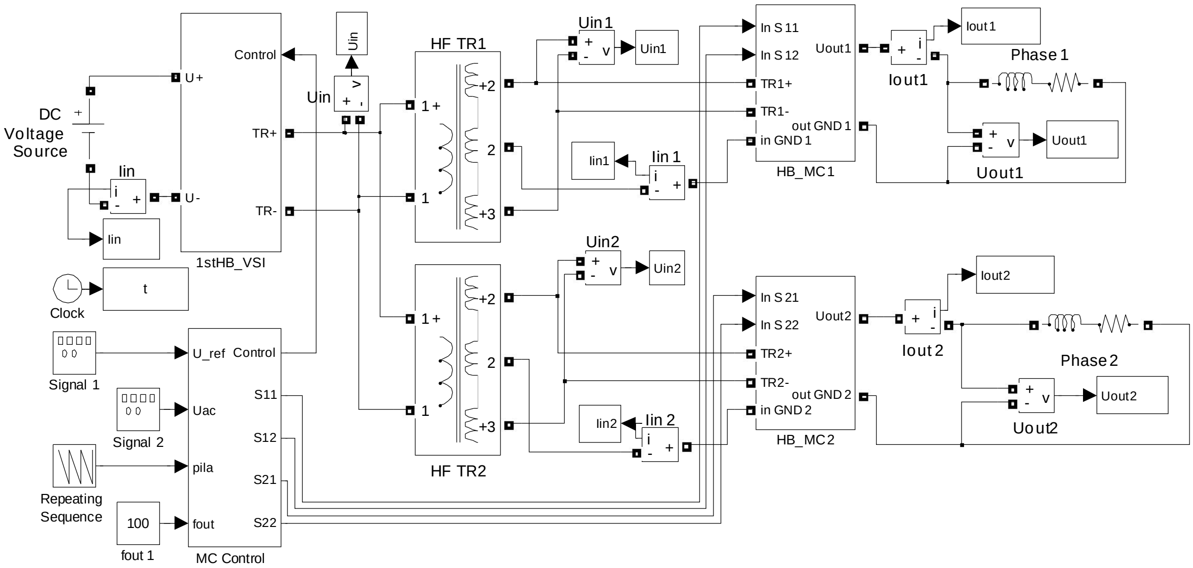

Figure 10: Block diagram for modelling of 2-stage converter system using two half-bridge single-phase matrix converter with central points of AC source (using of HF transformer) with R-L load

Motoric load – synchronous motor with PM – has been also simulated. Block diagram for modelling of 2-stage converter system using two-phase full bridge matrix converter with PMSM motor is depicted in Fig. 11. Second phase is shifted against the first one by 90 deg. el. to be created complex orthogonal system.

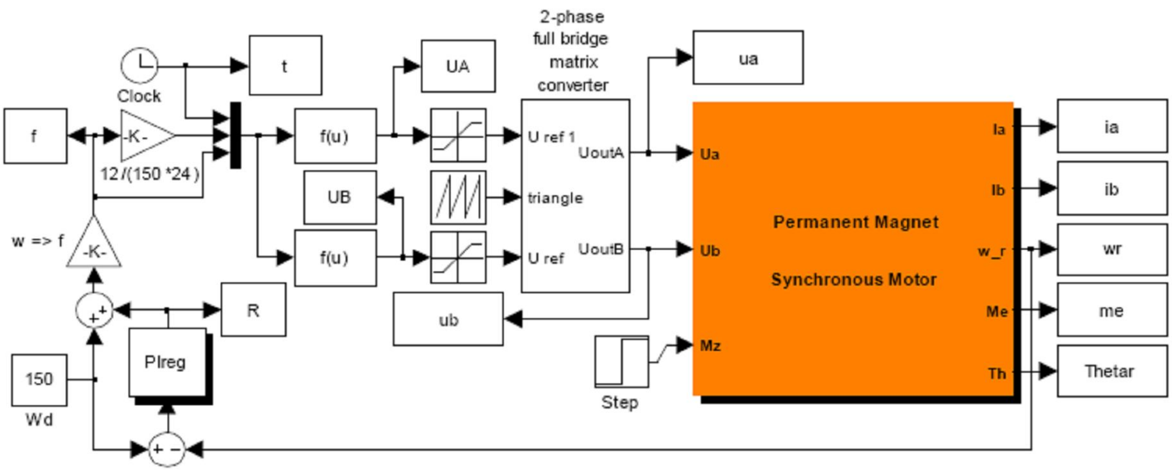

Figure 11: Block diagram for modelling of 2-stage converter system with PMSM motor load

Simulation model of half-bridge matrix converter with PMSM motor load is not showed. Dued to same simulation results.

Parameters of the simulation R-L load:

U = 24 V, fs = 20 kHz, f = 100 Hz, R = 6.8 W, L = 33.5 mH

Parameters of the simulation and simulated motor:

$U_{iSQUARE}$ = 24 V, f_i = 10 kHz, U_O = 12V, w_d = 150 rad.s^{-1}, R_S = 0.1275 Ω,
$L_{d,q}$ = 0.216 mH, p = 3, J = 125.10^{-6} kg.m^2, ψ_{PM} = 9.3.10^{-3} Wb , M_N = 0.45 Nm

5 Simulations Results:

Simulation results of 2-stage converter system with *R-L* load are given in Figs. 12-13.

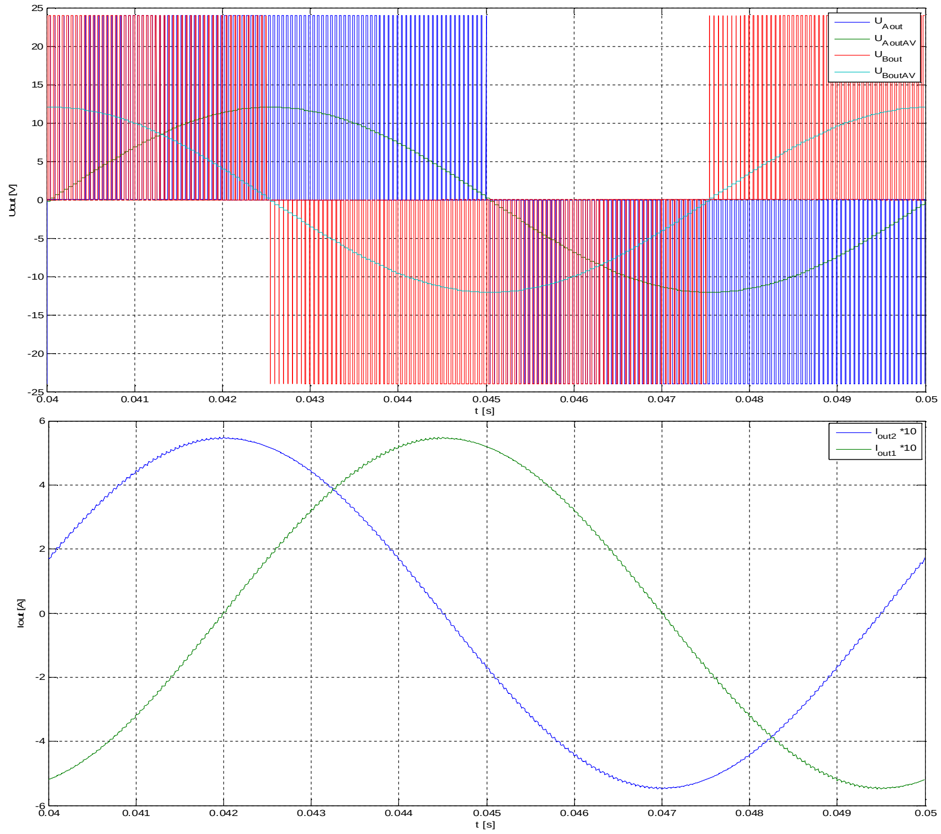

Figure 12: Simulated waveforms of output voltages and currents under R-L load with using of full-bridge matrix converter

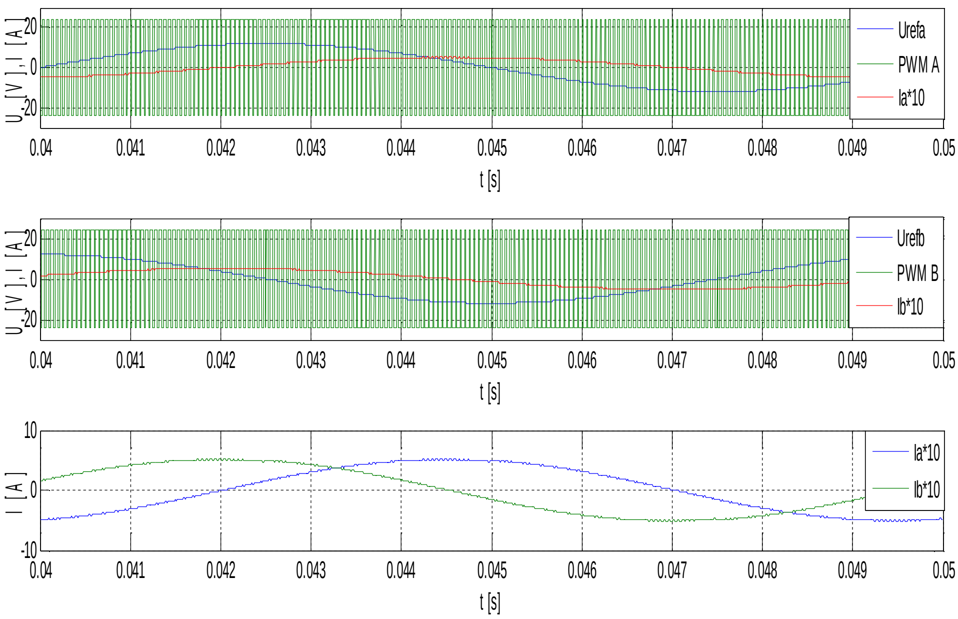

Figure 13: Simulated waveforms of output voltages and currents under R-L load with using of half-bridge matrix converter

Simulation results of full-bridge matrix converter with motor load are given in fig. 14.

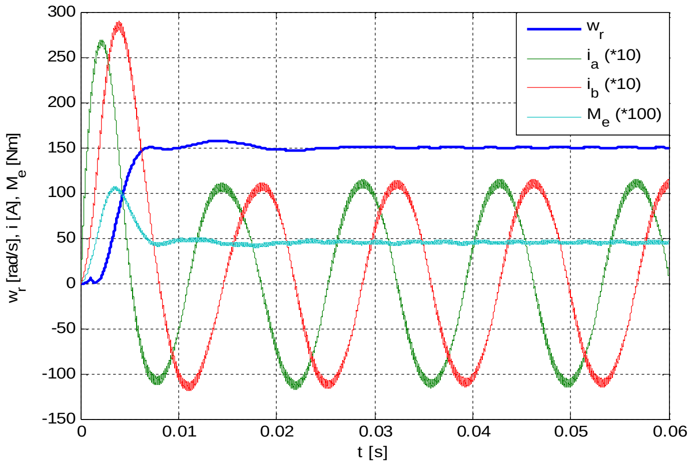

Figure 14: Simulated time-waveforms currents, torque and speed of PMSM motor during start-up

The vector trajectories of the a-b current components during starting-up under direct connection of the motor-load is shown in Fig. 10.

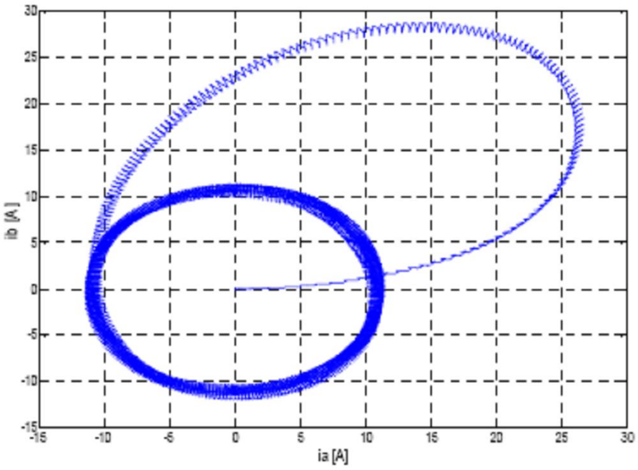

Figure 14: Simulated waveforms of the a-b currents components of PMSM motor during start-up (direct connection)

6 Experimental Verification of Single-Phase Full Bridge Matrix Converter with *R-L* load

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. 15. 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 [22] - [24].

The whole test rig system is controlled by Freescale DSP 56F8013DEMO [26]. The output quantities of the matrix converter, i.e. its voltage and current, are presented in Fig. 16.

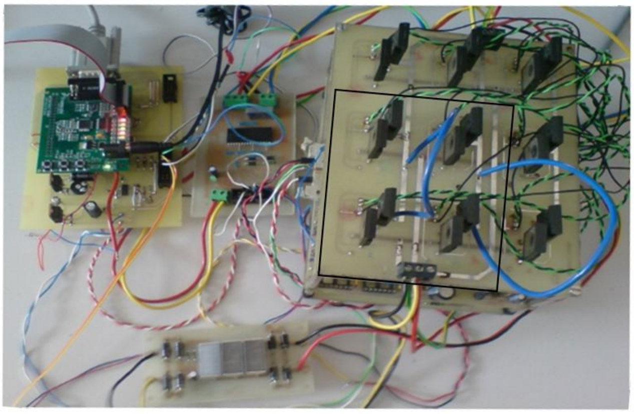

Figure 15: Physical model of single-phase inverter and matrix converter based on [17],[22],[25]

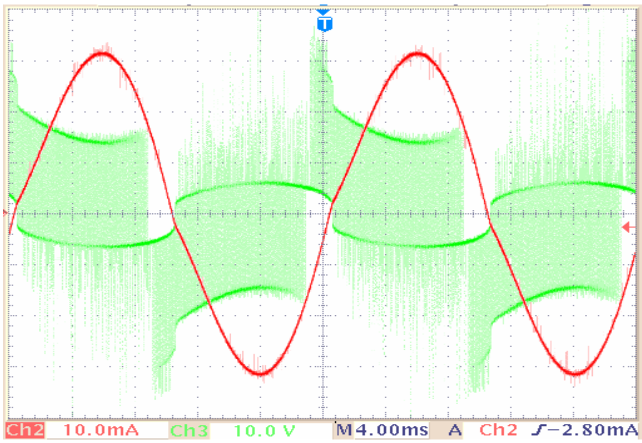

Figure 16: Output voltage (switched waveform) and current (continuous waveform) of single-phase matrix converter

7 Conclusions

There is shown in the paper the good results regarding to output quantities of matrix converters. Since the switches of the inverter operate with hard commutation, switches of full-bridge matrix converters are soft-commutated in the zero-voltage instants of the DC voltage interlink using unipolar PWM. Therefore, the expected efficiency of the system can be higher as usually by using of classical three-phase inverter. On the other side, the phase current will be higher at the same output power and output voltages, using two-phase AC motor.
Using of bipolar PWM half-bridge matrix converter is possible to obtain the same very good results as those by full-bridge connection. However the half-bridge connection have more power loss with comparing to full-bridge connection due to hard switching in one power switch. Number of power switching elements of half-bridge converter can be reduced and smaller then those of full-bridge connection which also reduce losses.

Experimental verification shown very good agreement between experimental results and the theoretical- and simulation analysis results. Based on this it is possible to provide the design and power dimensioning of the converter.

Acknowledgement

The authors wish to thank for the financial support to VEGA Agency for the project No. 1/0470/09, and R&D operational program Centre of excellence of power electronics systems and materials for their components No. OPVaV-2008/2.1/01-SORO, ITMS 26220120003 funded by European regional development fund (ERDF).

References

[1] Blalock, T.J.: The First Poly-Phase System - a Look Back at Two-Phase Power for AC Distribution. In: IEEE Power and Energy Magazine, March-April 2004, ISSN 1540-7977 pg. 63

[2] Two-Phase Power. Wikipedia the free encyclopedia, http://www.wikipedia.org, July 2009.

[3] Bala, S. and Venkataramanan, G.: Balanced Power Aggregation of Asymmetric Single-phase Systems. University of Wisconsin - Madison, 200x

[4] Dobrucky, B., Prazenica, M., Benova, M.: Converter Topology Design for Two-Phase Low-Cost Industrial and Transport Application. Paper in: *Monograph on Computer Systems Aided Science*, No. N, Publishing Office TU Radom (PL), Dec. 2009, ISSN 1642-5278, pp. (accepted paper).

[5] Dobrucky, B., Benova, M., Pokorny, M.: Using Virtual Two Phase Theory for Instantaneous Single-Phase Power System Demonstration. In: Electrical Review/ Przeglad Elektrotechniczny (PL), Vol.85 (2009), No. 1, pp. 174-178, ISSN 0033-2097.

[6] Dobrucký, B., Špánik, P., Kabašta, M.: Power Electronic Two-Phase Orthogonal System with HF Input and Variable Output. In: *Magazine of Electronics & Electrical Engineering*, Kaunas (LT), No. 1 (83), 2009, ISSN 1392-1215, pp. 9-14.

[7] 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.

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

[9] Luft, M., Szychta, E.: Commutation Processes in Multiresonant ZVS Bridge Converter. In: *AEEE - Advances in Electrical and Electronic Engineering,* University of Zilina (SK), No 1-2, Vol. 7/2008, pp. 84-91, ISSN 1336-1736.

[10] Prazenica, M.: Design of 2-Phase Switched Power Supply with Matrix Converters.Master Thesis, FEE University of Zilina (SK), 2009.

[11] 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.

[12] Phuc, N.: Single- and Two-Phase Motors, Chapter 9. OpenCourse Ware: http://vocw.edu.vn/content/m10681-/1.1/, Dec 2, 2007.

[13] 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.

[14] Bala, S.: Dynamics of Single/Two Phase Induction Motors. Department of Electrical and Computer Engineering, University of Wisconsin-Madison, 200x

[15] Záskalický, P., Záskalická, M.: Behaviour of the Two-phase Permanent Magnet Synchronous Motor Supplied by Rectangular Voltage. In: *Acta Technica CSAV 50 (2005)*, 195-206, Prague (CZ).

[16] Záskalický, P., Záskalická, M.: Behaviour of the Two-phase Permanent Magnet Synchronous Motor Supplied by Triacs from Single-Phase Voltage. In: *Acta Elec-trotechnica et Informatica, TU Kosice (SK)*, vol. 5 (2005), no. 3, pp. 1-5, ISSN 1335-8243.

[17] 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.

[18] Zuckerberger, A., Weinstock, D., Alexandrovitz, A.: Single – Phase Matrix Converter. *IEE Proc. on Electrical Power Applications*, vol.144, no. 4, 1997.

[19] Havrila, R.: Three-Phase Matrix Converter and Its Application in Power Semicon-ductor Systems (in Slovak). PhD Thesis, FEE University of Zilina (SK), 2000.

[20] Luft, M., Szychta, E.: Commutation Processes in Multiresonant ZVS Bridge Converter. In: *AEEE - Advances in Electrical and Electronic Engineering,* University of Zilina (SK), No 1-2, Vol. 7/2008, pp. 84-91, ISSN 1336-1736.

[21] M. Beňová, B. Dobrucký, E. Szychta, M. Praženica: Modelling and Simulation of HF Half-Bridge Matrix Converter System in Frequency Domain. Paper in: *Monograph on Computer Systems Aided Science*, No. N, Publishing Office TU Radom (PL), Dec. 2009, ISSN 1642-5278, pp. (accepted paper).

[22] Kragh, H.: *Modelling, Analysis and Optimisation of Power Electronic Circuits for Low-Cost Drives.* Ph.D. Thesis, Institute of Energy Technology, Aalborg University (DK), February 2000, ISBN 87-89179-28-5.

[23] Roy, M., Gonthier, L., Anceau, Ch.: The MBS (MOS Bidirectional Switch), a New MOS Switch with Reverse Blocking Voltage, ST Microelectronics, Proc. of EPE ´99 Int'l Conf., Lausanne (FR), Sep. 1999.

[24] Rahimo, M., Kopta, A., Schlapbach, U.: The Bi-mode Insulated Gate Transistor (BIGT) - A High Voltage Switch for Next Generation Megawatt Applications. *Journal of Bodo's Power Systems*, July 2009, pp. 16-19, ISSN 1863-5598.

[25] Chau, K.T., Chan C.C., and Wong, Y.S.: Advanced Power Electronic Drives for Electric Vehicles. *Electro-Motion 5 (1998)*, no. 2, pp. 42-53, ISSN 1223-057X

[26] *56F8013 Demonstration Board User Guide*, 56F8000 16-bit Digital Signal Controllers, Freescale Semiconductors, Rev. 0.