DESIGN, MODELLING AND SIMULATION OF TWO-PHASE TWO-STAGE ELECTRONIC SYSTEM WITH ORTHOGONAL OUTPUT FOR SUPPLYING OF TWO-PHASE ASM

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Abstract. *This paper deals with the two-stage two-phase electronic systems with orthogonal output voltages and currents - DC/AC/AC. Design of two-stage DC/AC/AC high frequency converter with two-phase orthogonal output using single-phase matrix converter is also introduced. Output voltages of them are strongly non-harmonic ones, so they must be pulse-modulated due to requested nearly sinusoidal currents with low total harmonic distortion. Simulation experiment results of matrix converter for both steady and transient states for IM motors are given in the paper, also experimental verification under R-L load, so far. The simulation results confirm a very good time-waveform of the phase current and the system seems to be suitable for low-cost application in automotive/aerospace industries and application with high frequency voltage sources.*

Keywords

Matrix converter, two-stage system, two-phase system, orthogonal system, switching strategy.

1. Introduction

In the very early days of commercial electric power, some installations used two-phase four-wire systems for motors [1]. Two-phase systems have been replaced with three-phase systems. Two-phase supply with 90 degrees between phases can be derived from a three-phase system using a Scott-connected transformer. Two-phase circuits typically use two separate pairs of current-carrying conductors, alternatively three wires may be used, but the common conductor carries the vector sum of the phase currents, which requires a larger conductor.

Nowadays, the low-cost two-phase drives are again developed and produced. They are dedicated for industrial and residential applications when 3-phase system of electrical energy is missing. But they are used 3-phase low cost motors which are supplied asymmetrically into two phases from the voltage converter, Fig. 1, [4].

On the other side, it can be also easily created using power electronic converters e.g. from battery supply, with two-phase transfer of energy for zero distance. DC/2AC, Fig. 2, and DC/HF_AC/2AC, Figs. 3a, b and Fig. 4, converter system can generate two-phase orthogonal output with variable voltage and frequency [2], [3].

Fig. 1. Two-phase drive using voltage inverter and 3-phase low-cost motor [4]

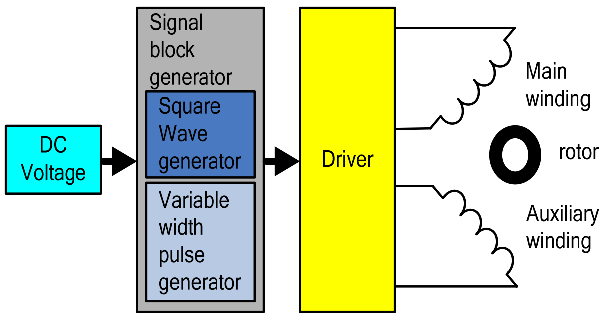
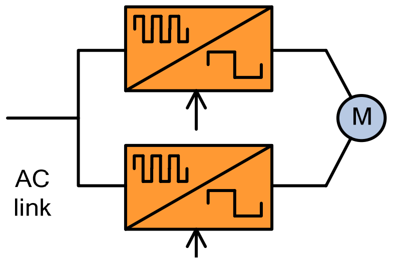


Fig. 2. Block diagram for two-phase motor supply



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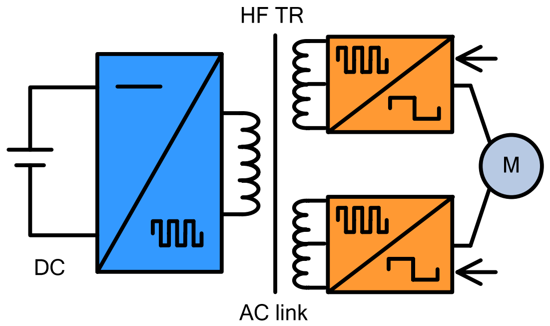

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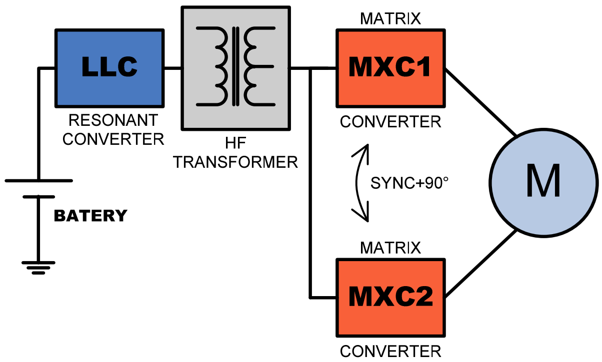
Fig. 3. a) principle diagram of full bridge converter with second phase shifted by 90 degrees, b) block diagram of half bridge converter with HF transformer and central points of the source



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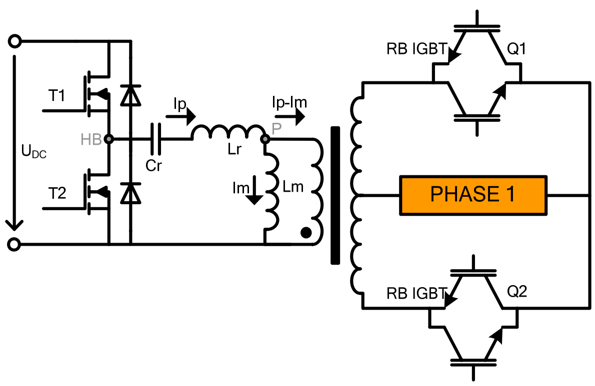

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Fig. 4. Principle diagram of two-stage converter with using LLC converter, HF transformer and half-bridge matrix converter a) block scheme of two-phase system, b) circuit diagram of single branch of the system

2. Two-stage Two-phase systems with HF AC interlink matrix converters (DC/HF_AC/2AC)

This DC/HF_AC/2AC 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 or matrix converter) is the best choice. System with matrix converter and high frequency AC interlink can generate two-phase orthogonal output with both variable voltage and frequency [4] - [6]. 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. 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 bridge converter,

2) half bridge converter

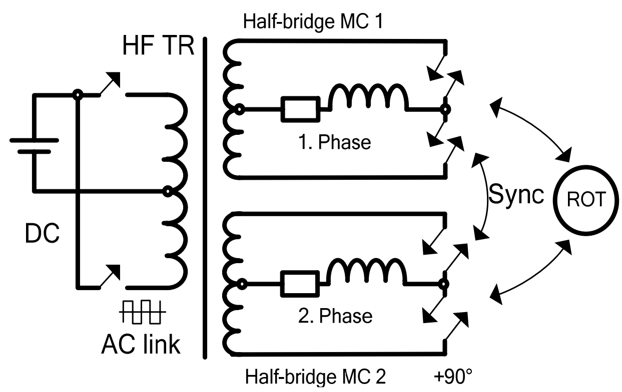
3) LLC converter, Fig. 4.

Inverter of second stage can be connected as:

1) full bridge converters connection, Fig. 3a,

2) two half bridge ones with central point of the source using HF transformer Fig. 5a or

3) half-bridge ones with central points of the motor load Fig. 5b.



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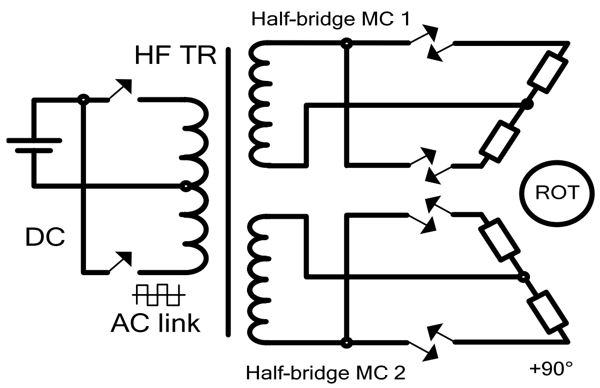

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Fig. 5. Circuit diagram of half-bridge converters system with a) central points of AC source; b) central points of motor loads

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, [4], [7] - [9] and others.

3. PWM modulation Strategies for Half-Bridge Matrix Converter

Theoretical analysis of single-phase matrix converter has been done, e.g. [10], [11]. Equivalent circuit diagram of Half-bridge single phase converters two-phase system is depicted in Fig. 6.

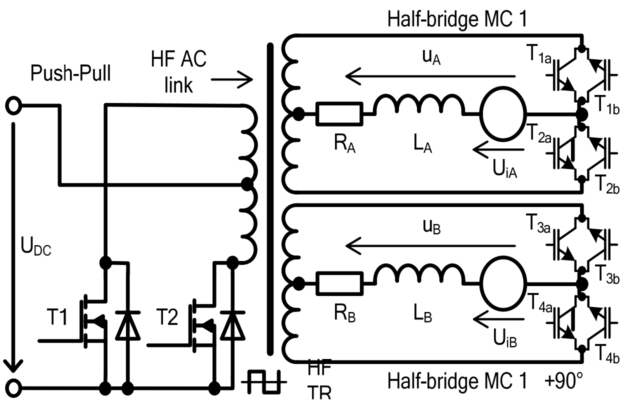


Fig. 6. Circuit diagram of half bridge converters system with HF transformer and central points of the source

Contrary to bridge-matrix converter the half-bridge connection doesn't provide unipolar PWM control, so the bipolar pulse switching technique should be used. The orthogonal voltages with bipolar PWM control are depicted in Fig 7.

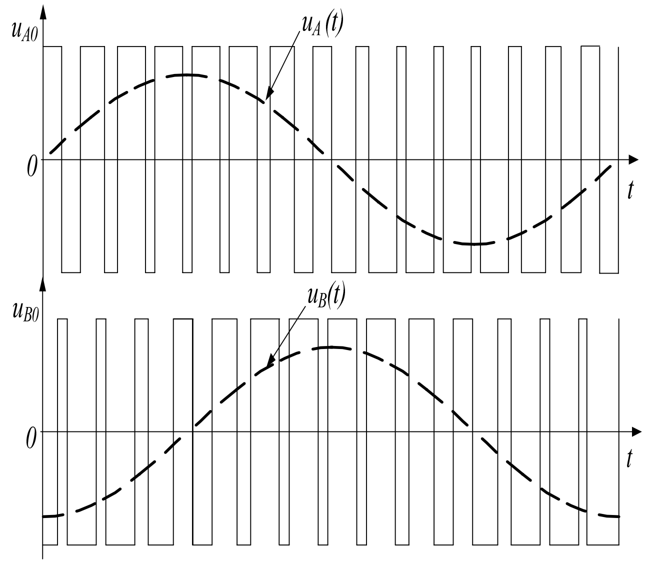
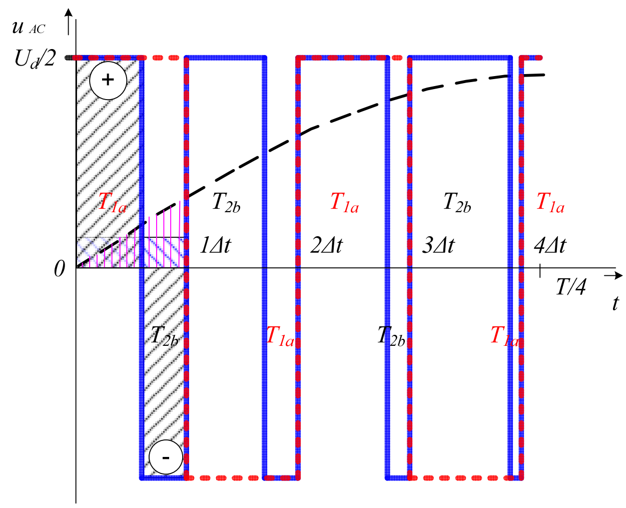


Fig. 7. Output orthogonal voltages of the half-bridge matrix converter system with bipolar PWM

Switching strategy of one half-bridge matrix converter, based on 'even' bipolar PWM, can be explained using Figs. 8, in greater details. Fourier analysis is useful and needed for determination of total harmonic distortion of the phase current of the matrix converter [10], [12].



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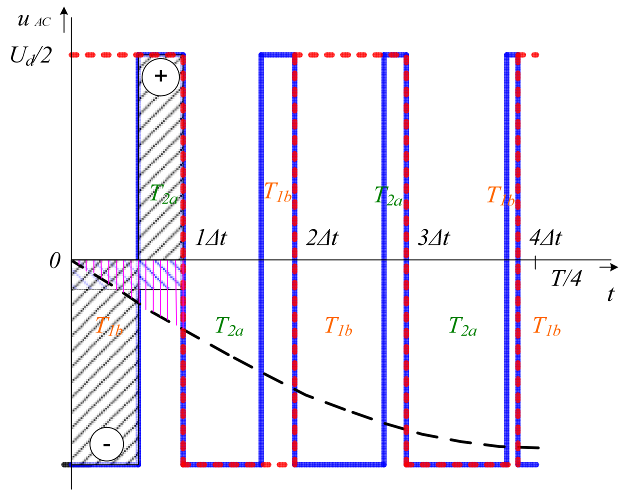

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Fig. 8. Switching strategy of half bridge converter for a) positive and b) negative half period of operation

It is important and clear visible from these figures that during switching at the end of the period of HF AC supply ($n.T_s$) the switching losses will be zero due to zero value of commutation voltage. Switching frequency can be set from some kHz for high power applications up to several tens of kHz for low power applications. It deals with sinusoidal bipolar pulse-width-modulation contrary to unipolar regular PWM [13]. Switching-pulse-width can be determined based on equivalence of average values of reference waveform and resulting average value of positive and negative switching pulses area during switching period, Fig. 9.

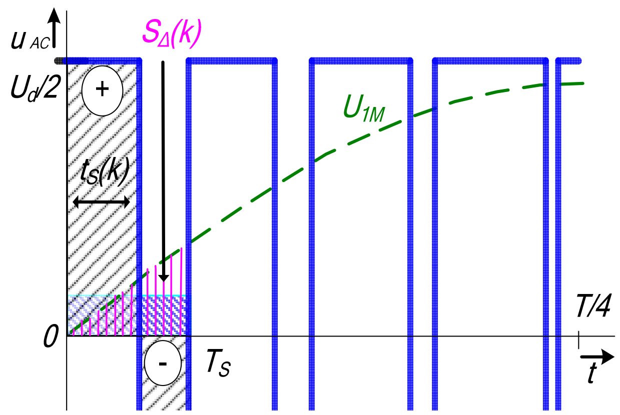


Fig. 9. PWM with even multiply of f_1

The switching instant is equal to:

$$t_s(k) = \frac{1}{2U_{DC}} \cdot S_\Delta(k) + \frac{T_s}{2} \tag{1}$$

and the area under sine wave during k-switched interval $S_\Delta(k)$ is:

$$S_\Delta(k) = U_m \cdot \frac{m_f}{2\pi} \cdot \left[\cos\left(\frac{2\pi}{m_f} \cdot k\right) - \cos\left(\frac{2\pi}{m_f} \cdot (k+1)\right)\right] \tag{2}$$

The total harmonic distortion of the current is given by [10]:

$$\frac{\sqrt{\sum I_v^{\,2}}}{I_1} = \sqrt{\frac{I^2 - I_1^{\,2}}{I_1^{\,2}}} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} = \sqrt{[(8.34822/\ 8.34386)2\ \ -1]} = \sim 2\ \%. \tag{3}$$

4. Two-Phase Induction Motor

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 [14].

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.

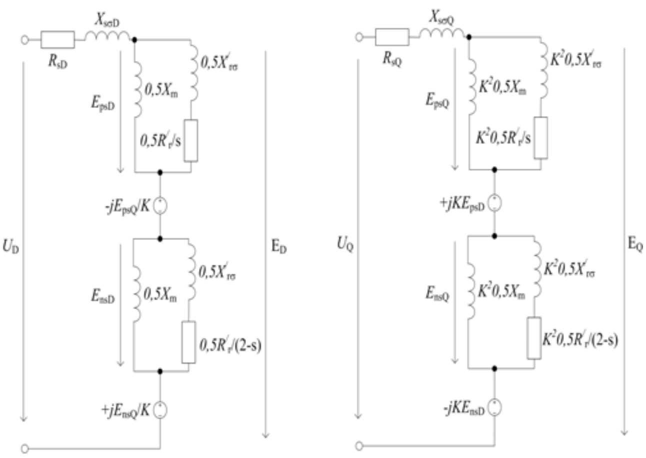


Fig. 10. Equivalent circuit of TPIM

The equivalent circuit, Fig. 10, can be described by following formulas:

$$v_{Ds} = \frac{d\psi_{Ds}}{dt} + R_{Ds} i_{ds} . \tag{4}$$

$$v_{Qr} = \frac{d\psi_{Qr}}{dt} + R_{Qr}' i_{qr} - K\omega_r \psi_{Dr} . \tag{5}$$

$$v_{Dr} = \frac{d\psi_{Dr}}{dt} + R_{Dr}' i_{dr} + K\omega_r \psi_{Qr} \; . \qquad (6)$$

Flux linkages can be written as:

$$\psi_{Qs} = L_{sD} i_{Qs} + L_{mD}\left(i_{Qs} + i_{Qr}\right). \qquad (7)$$

$$\psi_{Ds} = L_{sQ} i_{Ds} + L_{mQ}\left(i_{Ds} + i_{Dr}\right). \qquad (8)$$

$$\psi_{Qr} = L_r' i_{Qr} + L_{mD}\left(i_{Qs} + i_{Qr}\right). \qquad (9)$$

$$\psi_{Dr} = L_r' i_{Dr} + L_{mQ}\left(i_{Ds} + i_{Dr}\right). \qquad (10)$$

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

$$v_{Qr} = v_{Dr} = 0 \; . \qquad (11)$$

If □$_r$ is angular displacement between stator and rotor axes, then

$$\omega_r = \frac{d\vartheta_r}{dt} \; . \qquad (12)$$

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:

$$T_e = p\left(\frac{N_a}{N_m}\psi_{qr} i_{dr} - \frac{N_m}{N_a}\psi_{dr} i_{qr}\right). \qquad (13)$$

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]	$X_{σs}$ [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]	$X_{σs}$ [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			

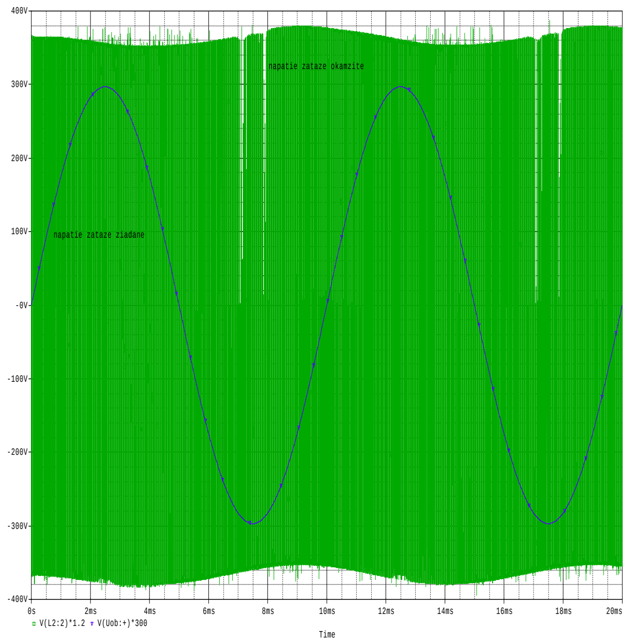
5. PC simulation

Simulation model for R-L load has been modelled in OrCAD programming environment and simulation model for PMSM motor load has been modelled in MatLab programming environment.

Simulation results of single-phase half-bridge matrix converter with R-L load are shown in Fig. 11 and the output voltages (in different topologies of converter) in detail are depicted in Fig. 12.

Parameters for simulation of R-L load are:

U_{inDC} = 350 V, $U_{iSQUARE}$ = 350 V, $f_{iSQUARE}$ = 50 kHz, $U_{outACmax}$ = 300 V, f_{outSW} = 100 kHz, f_{outAC} = 100 Hz, R = 10 Ω, L = 30 mH.



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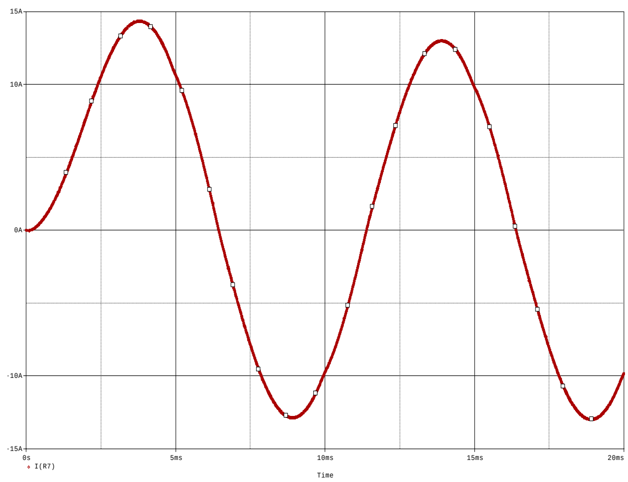

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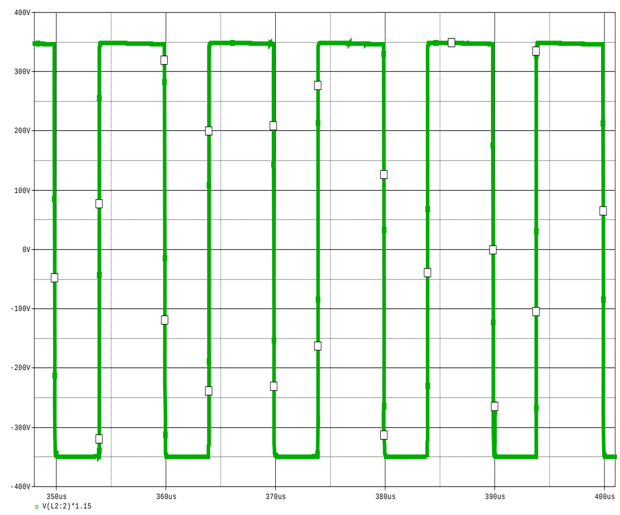
Fig. 11. Simulated waveforms of the single-phase converter under R-L load a) output voltage, b) output current



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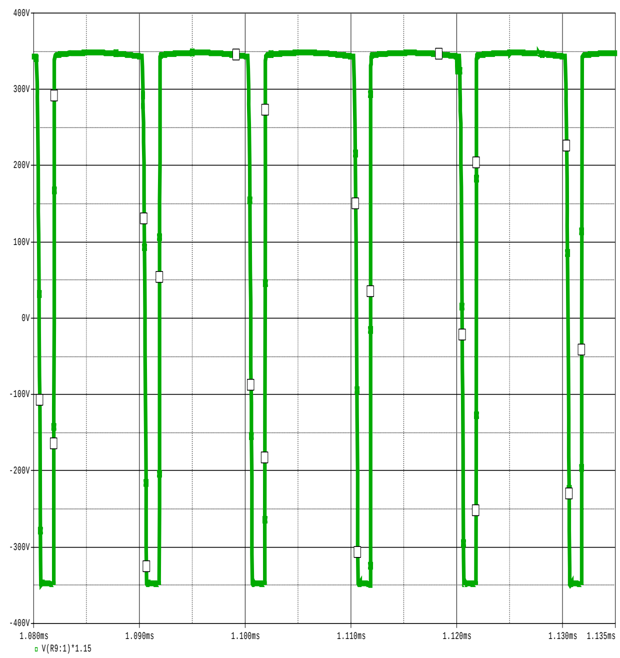

b)

Fig. 12. Output voltages of two-stage converter in detail with using a) Push-pull converter b) LLC converter

Simulated waveforms during start-up of the two-phase induction machine (TPIM) supplied by two-phase switched (PWM, U_{DC} = *350 V*, f_{sw} = *50 kHz*, U_{outAC} = *230 V*, f_{out} = *50 Hz*) voltage shifted by 90 degree are depicted in Fig. 13.

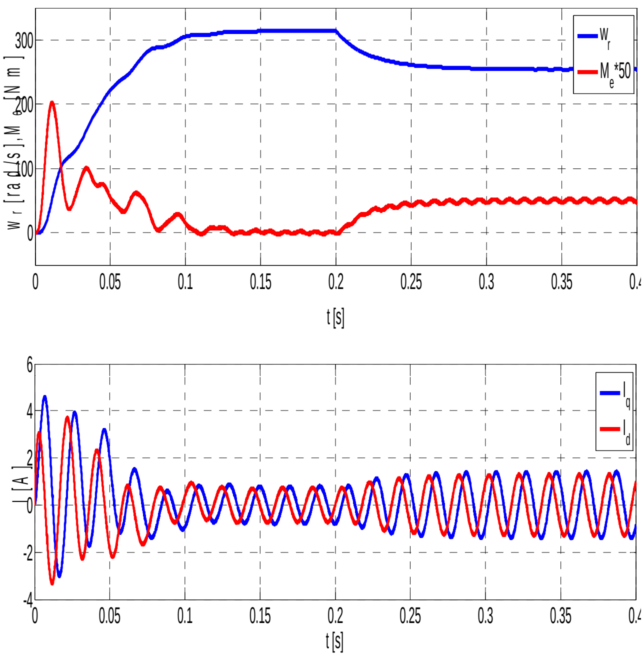

Fig. 13. Time-waveforms speed, torque and currents of TPIM during start-up

Simulation results of torque-speed characteristic of two-phase induction machine (TPIM) supplied by two-phase harmonics voltage shifted by 90 degree are shown in Fig. 14.

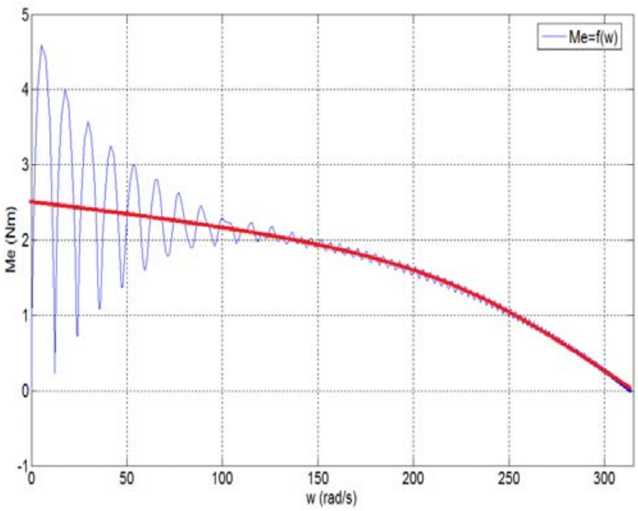

Fig. 14 Simulated torque-speed characteristic for two-phase harmonics supply of TPIM (and its approximation)

Torque-speed characteristics were investigated by several methods of calculation and modeling [14], [16]. The obtained characteristics are shown in the next section (Experimental Verification, Fig. 17) due to comparison possibility with measured values.

6. Experimental Verification

Experimental verification (measurement) of torque-speed characteristic has been done using two-stage two-phase power electronic converter consists of single-phase full-bridge voltage inverter and two single-phase full-bridge matrix converters (switching frequency f_{sw}= 5kHz) for test rig system. There is shown test rig in Fig. 15. All system is controlled by Freescale DSP 56F8013DEMO. Measured output waveforms of voltage and current of the two-phase power electronic system with TPIM motor are presented in Fig. 16. The *Q* winding is supplied by voltage of converter U_Q , equal in magnitude to *D* winding and shifted by 90 electrical degrees of the *D* winding [15].

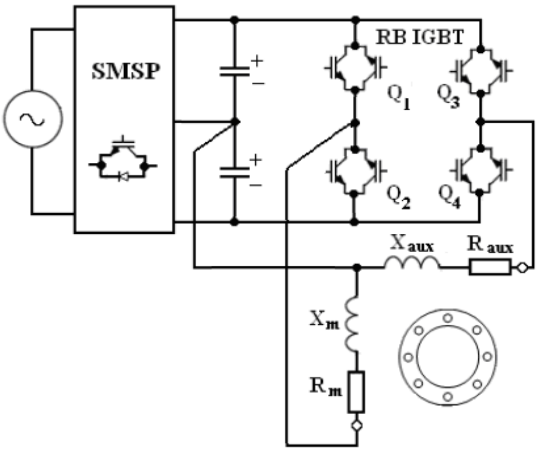

Fig. 15. Circuit diagram of investigated of two-phase induction machine

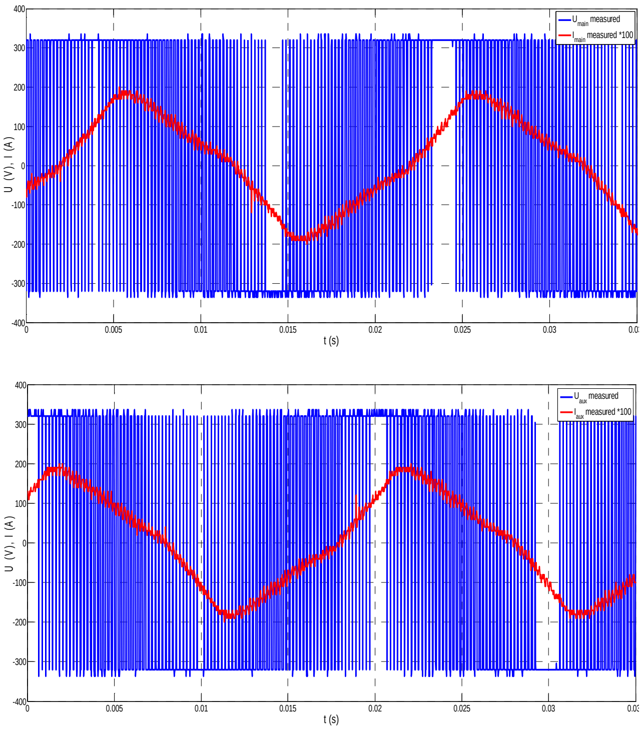

Fig. 16. Measured output voltages and currents of the physical model of two-phase power electronic system (f_{SW} = 5 kHz)

Experimental measurements of torque-speed characteristics, Fig. 17, have been done at full nominal supply voltage with this type of control:

- the voltage of matrix converter was overmodulated - the converter was operated with full width of the voltage pulses
- the voltage of matrix converter was controlled by PWM (switching frequency f_{sw}= 5 kHz)

Resulted torque-speed characteristics carried-out by the measured on real machine, Fig. 18, at steady-state conditions are presented in Fig. 17 together with those obtained by various methods of calculation and modelling. The torque-speed characteristics given in the figure can be compared between each to other. As can be seen the error between theoretical obtained characteristics is very small what can be justified by neglected imperfections in simulation model.

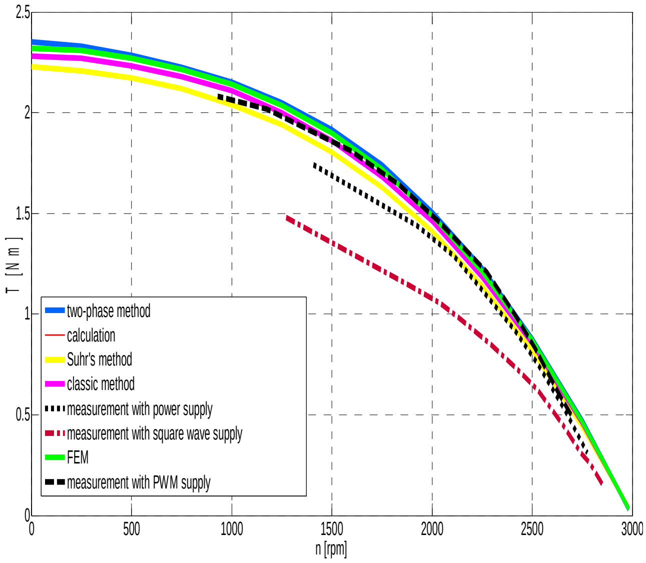

Fig. 17. Comparison between measured and simulated torque-speed characteristics of TPIM with two-phase supply

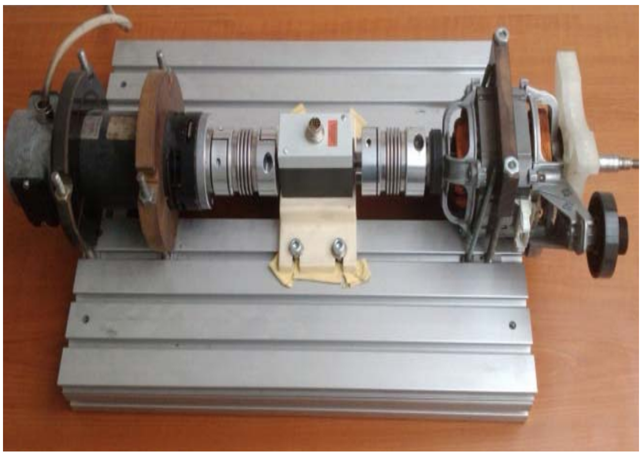

Fig. 18. Motor test stand

7. Conclusion

The simulated results was compared with real measurement and the results give good coincidence, Fig. 17. The parameters used in simulation model of TPIM have been calculated by several methods and majority once give good real results. It was found out that torque of TPIM is higher by PWM supply by 5 kHz switching frequency than in case of simply rectangular supply (the no-harmonic rectangular voltage supply decreases the TPIM performance, because of high harmonic spectrum). The torque by sinusoidal supply is lower than in case of PWM supply. It is caused by not regular phase shift, due to complicated supply aparature [14]. Using chosen half-bridge connection for both inverter and matrix converters with bipolar PWM the number of power switching elements of the two-stage converter can be reduced and smaller then those of classical three-phase voltage inverter.

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Michal Praženica was born in 1985 in Žilina (Slovakia). He is a PhD student at the University of Žilina - Faculty of Electrical Engineering - Department of Mechatronics and Electronics in the study programme "Power Electronics". The topic of his PhD thesis is: Research of the new electronic system based on direct single-phase inverters in matrix connection with orthogonal output with variable output voltage and variable frequency (0-U_N, 0- 2 f_N) with voltage shifted by 90 °el.

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