

RESEARCH OF TWO-PHASE ELECTRONIC SYSTEM WITH ORTHOGONAL OUTPUT USING MATRIX CONVERTERS FOR TWO-PHASE APPLICATION

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Abstract

The paper deals with two-phase power electronic system with variable orthogonal output for industrial- and transport drives applications. Two-phase electronic system with 90 degrees between phases can be easily created using power electronic converters supplied from battery. 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. Modeling and simulation of two-phase power electronic converters with both R-L and motor load is shown in the paper. The simulation models are created in program Matlab-Simulink. Results of simulation are compared with experimental verification ones.

1 Introduction

In the early times of electrical engineering the uses of two-phase electric motors supplied from independent 4-wire network were obviously, Fig. 1 [1]. Today's classical manner of driving systems of energy conversion and AC motors uses indirect connections of converters with the interconnection via DC link. In the industrial and residential applications, where the 3-phase exists, it means: three-phase rectifier, DC link, three-phase voltage inverter and three-phase motor. Nowadays, the low-cost two-phase drives are 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. 2.

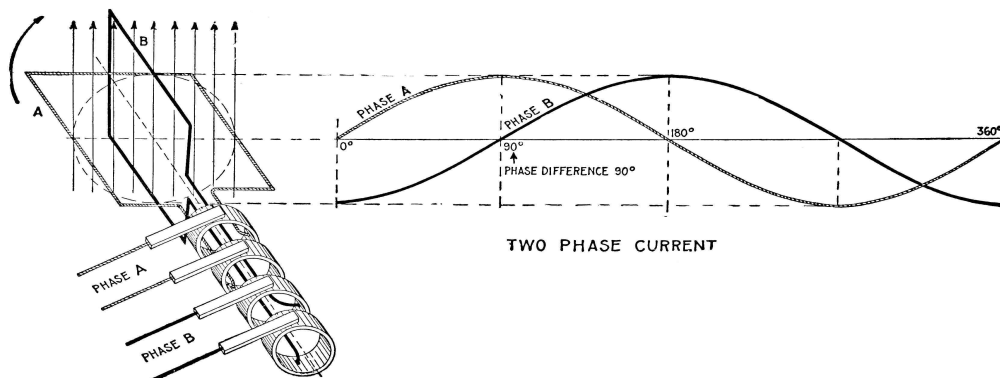


Figure 1: A simplified diagram of a two-phase power system [2]



Figure 2: Two-phase drive using voltage inverter and 3-phase low-cost motor [3]

2 Two-Phase System for Two-Phase Load

Two-phase system can be also easily create by using Single-Phase Induction Machines (SPIM). The most SPIMs have auxiliary winding. The auxiliary winding has mostly the same parameters as main winding and it is shifted in space by 90° . It is convenient to use this main winding as first phase and auxiliary winding as second phase. Then is possible consider SPIM as Two-Phase Induction Machines (TPIM). Two phase power system generate two-phase orthogonal output with variable voltage and frequency and 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. 3, and DC/HF_AC/2AC, Fig. 4. [4].

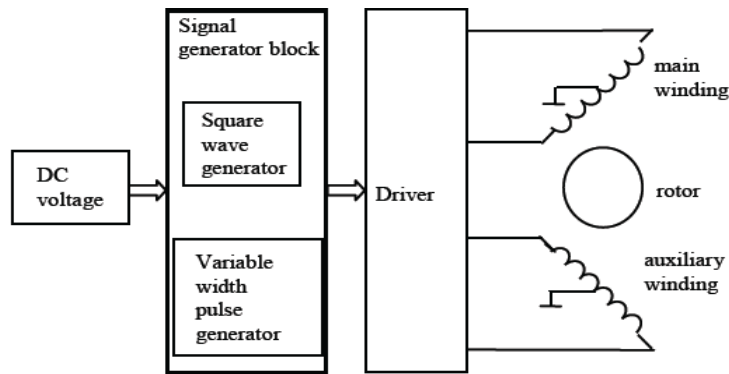


Figure 3: Block diagram for single-stage two-phase motor drive system supplied from DC source [5]

System with DC source is rather simply, however it has several drawbacks:

- DC voltage of battery (usually low) should be matched with nominal motor voltage (usually higher),
- DC source (usually low voltage) is not galvanic isolated from the motor load (usually middle/high voltage),
- there is no galvanic separation between individual phases of the AC motor (common DC link).

2.1 Two-Stage Two-Phase System

Such a system usually consist of single-phase voltage inverter, AC interlink, HF transformer, 2-phase converter and 2-phase AC motor. One of the possible schemes without transformer and using 2-phase direct matrix converter is depicted in Fig. 4.

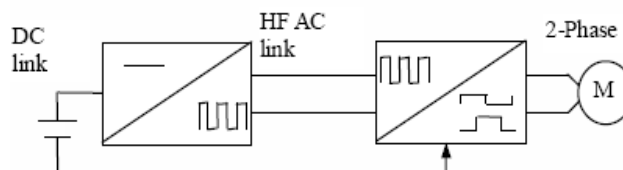


Figure 4: Principle block diagram of 2-stage DC/AC/AC converter (without HF transformer) and with 2-phase second stage

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° . Proposed scheme of two-stage two-phase converter system is shown in Fig. 4. Basically, it consists of single-phase fast IGBT inverter, and of two single-phase matrix converters. 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.

Each matrix- can be connected as:

1. full bridge converters connection, Fig. 4,
2. two half bridge ones with central point of the source using HF transformer, Fig. 5a,
3. half-bridge ones with central points of the motor load, Fig. 5b.

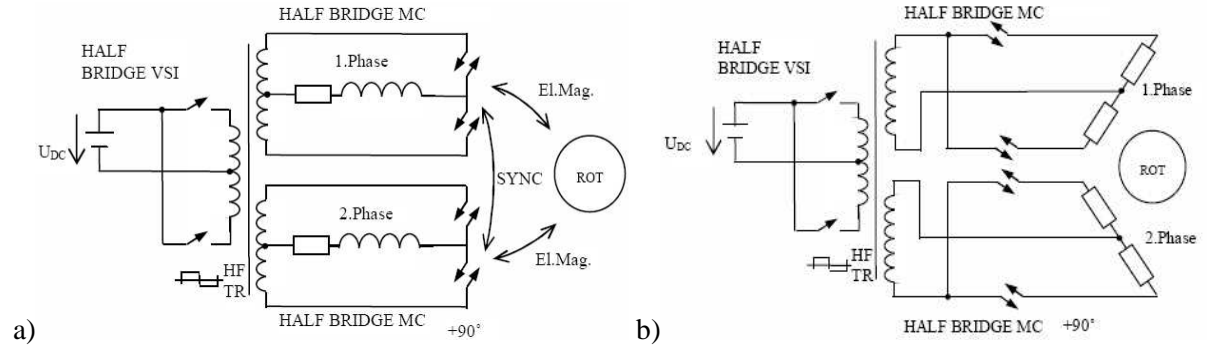


Figure 5: Circuit diagram of half-bridge converters system with a) central points of AC source; b) central points of motor loads

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.

3 PWM Modulation Strategies for Half-Bridge Matrix Converter

Theoretical analysis of single-phase matrix converter has been done, e.g. [6], [7]. Equivalent circuit diagram of half-bridge single phase converters two-phase system is depicted in Fig. 6.

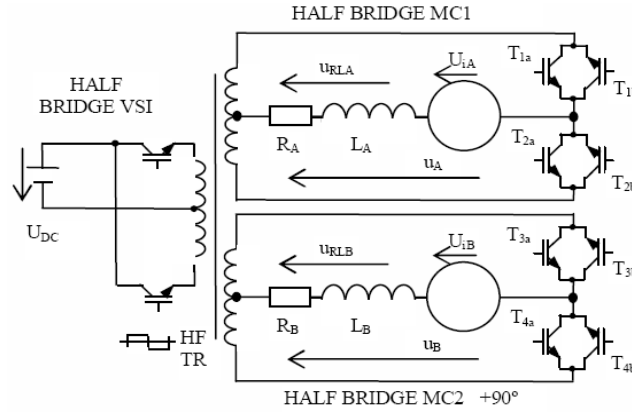


Figure 6: Circuit diagram of half bridge converters system with HF transformer and central points of the source

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 Figs. 7a and 7b.

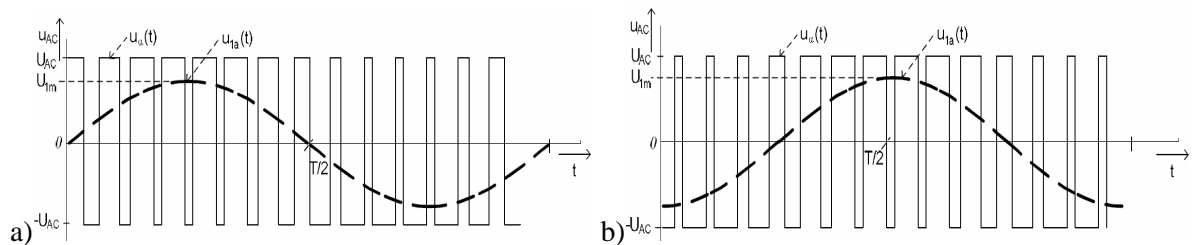


Figure 7: Output orthogonal voltages of the half-bridge matrix converter system with bipolar PWM: a) u_α ; b) u_β

It deals with sinusoidal bipolar pulse-width-modulation contrary to unipolar regular PWM [8], [9]. 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. Considering bipolar PWM with switching frequency equal to even multiply of fundamental frequency, Fig. 8, the switching instant is equal to:

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

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

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

The total harmonic distortion of the current is given by [14]:

$$\begin{aligned} \frac{\sqrt{\sum I_v^2}}{I_1} &= \sqrt{\frac{I^2 - I_1^2}{I_1^2}} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} = \\ &= \sqrt{[(8.34822/8.34386)2 - 1]} = \sim 2\% \end{aligned} \quad (3)$$

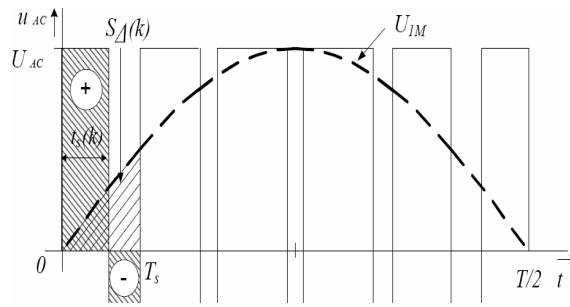


Figure 8: PWM with even multiply of f_1

Fourier analysis is useful and needed for determination of total harmonic distortion of the phase current of the matrix converter [6, 8, 10]. Switching strategy of one half-bridge matrix converter, based on ‘even’ bipolar PWM, can be explained using Figs. 9a and 9b in greater details.

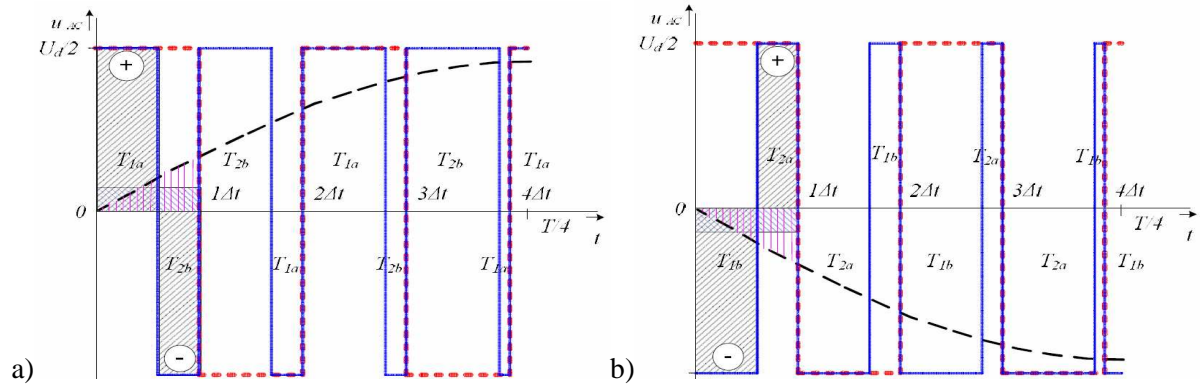


Figure 9: Switching strategy of half bridge converter for a) positive and b) negative half period of operation

It is important and clear visible from these figures that during switching at the end of the period of HF AC supply ($n \cdot T_s$) 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.

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 [11].

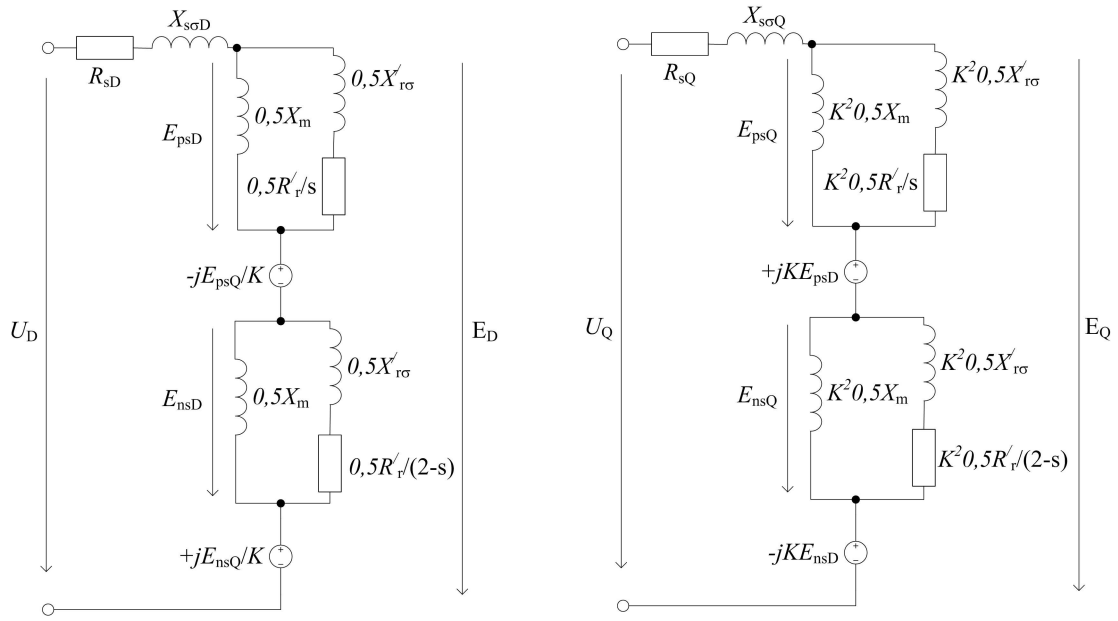


Figure 10: Equivalent circuit of TPIM

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

$$v_{Ds} = \frac{d\psi_{Ds}}{dt} + R_{Ds}i_{ds} \quad (4)$$

$$v_{Qr} = \frac{d\psi_{Qr}}{dt} + R_{Qr}\dot{i}_{qr} - K\omega_r\psi_{Dr} \quad (5)$$

$$v_{Dr} = \frac{d\psi_{Dr}}{dt} + R_{Dr}\dot{i}_{dr} + K\omega_r\psi_{Qr} \quad (6)$$

Flux linkages can be written as:

$$\psi_{Qs} = L_{sD}i_{Qs} + L_{mD}(i_{Qs} + i_{Qr}) \quad (7)$$

$$\psi_{Ds} = L_{sQ}i_{Ds} + L_{mQ}(i_{Ds} + i_{Dr}) \quad (8)$$

$$\psi_{Qr} = L_r\dot{i}_{Qr} + L_{mD}(i_{Qs} + i_{Qr}) \quad (9)$$

$$\psi_{Dr} = L_r\dot{i}_{Dr} + L_{mQ}(i_{Ds} + i_{Dr}) \quad (10)$$

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

$$v_{Qr} = v_{Dr} = 0 \quad (11)$$

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

$$\omega_r = \frac{d\vartheta_r}{dt} \quad (12)$$

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:

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

where p is a number of pole-pairs.

The real TPIM was used with name-plate:

TABLE 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:

TABLE 2: PARAMETERS OF TPIM

	R_s [Ω]	R'_r [Ω]	$X_{\sigma s}$ [Ω]	Method	X_m (Ω)	L_m (H)
D winding	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
	21.37	0.0679	0.0679	Two-phase	452	1.4388
	R_s [Ω]	R'_r [Ω]	$X_{\sigma s}$ [Ω]	FEM	398.5	1.2599
Q winding	21.32	51.1	22.3			
	X'_r [Ω]	L_s [H]	L'_r [H]			
	22.3	0.0709	0.0709			

5 PC Simulation of Two-Phase Power Electronic Drive with TPIM Motor

For analysis of two-phase power electronic system with TPIM motor was created model in MATLAB Simulink.

Simulation of half-bridge matrix converters with bipolar PWM modulation has been done and its results for R-L load are shown in Fig. 11.

Parameters for simulation of R-L load are:

$U_{ISQUARE} = 650$ V, $f_{in} = 10$ kHz, $U_{OUT} = 230$ V, $f_{sw} = 20$ kHz, $f_{OUT} = 50$ Hz, $R = 20$ Ω , $L = 70$ mH

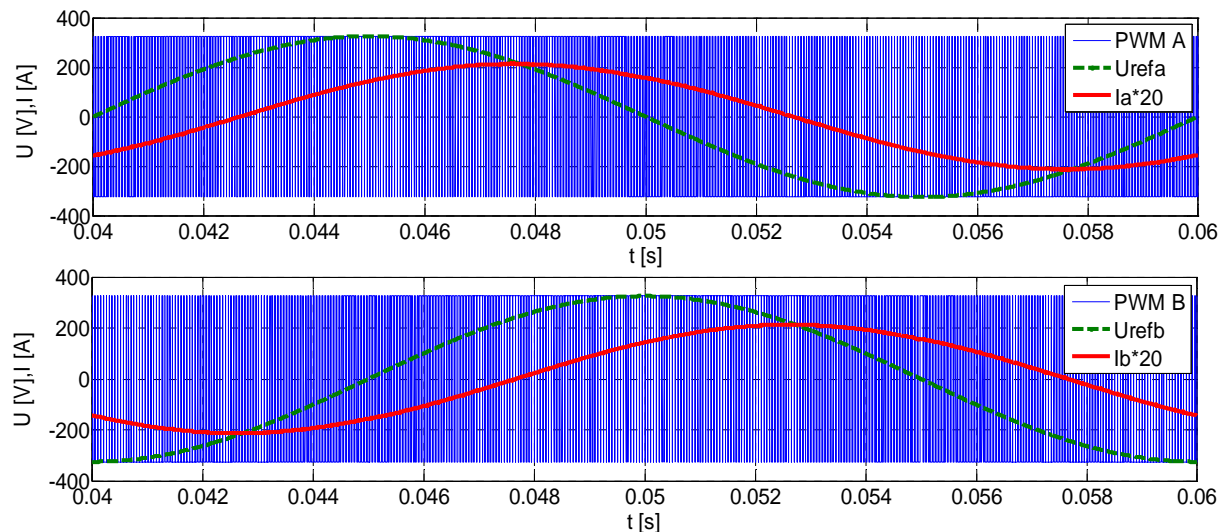


Figure 11: Simulated waveforms of output voltages and currents of the converter under R-L load

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. 12.

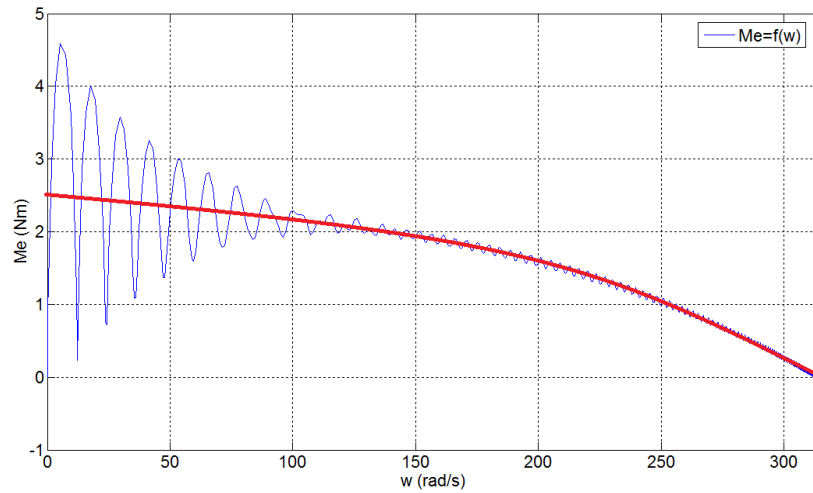


Figure 12: Simulated torque-speed characteristic (and its approximation) for two-phase harmonics supply of TPIM

Simulated waveforms during start-up of the two-phase induction machine (TPIM) supplied by two-phase square-wave voltage shifted by 90 degree are depicted in Fig. 13.

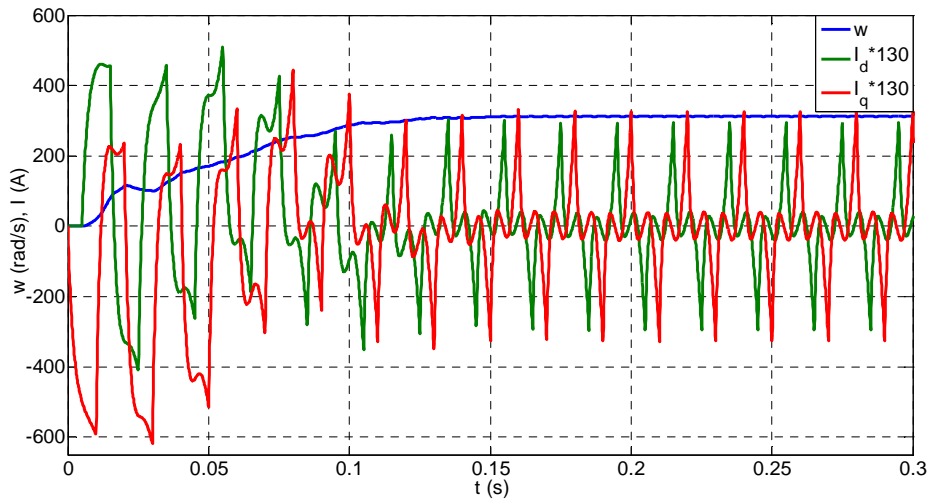


Figure 13: Time-waveforms currents and speed of two-phase induction motor during start-up supplied by two-phase square-wave voltage

Simulation model, created in Matlab-Simulink for analysis of two-phase power electronic system with TPIM motor is depicted in Fig. 14.

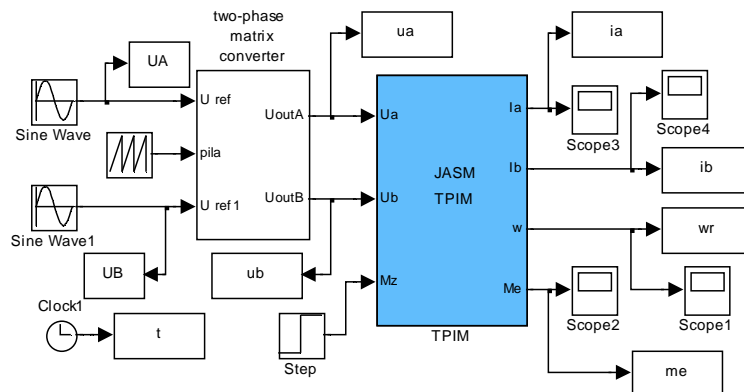


Figure 14: MatLab-Simulink model for two-phase power electronic system with TPIM motor

Simulation experiment of torque-speed characteristic of two-phase induction machine (TPIM) supplied by two-phase switched (PWM) voltage shifted by 90 degree are shown in Fig. 15.

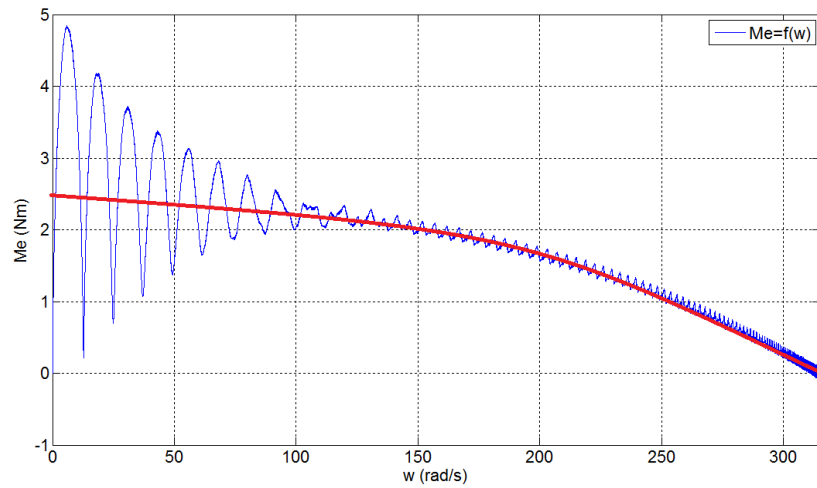


Figure 15: Simulated torque-speed characteristic (and its approximation) for two-phase switching (PWM) supply of TPIM

Simulated waveforms during start-up of the two-phase induction machine (TPIM) supplied by two-phase switched (PWM) voltage shifted by 90 degree are depicted in Fig. 16.

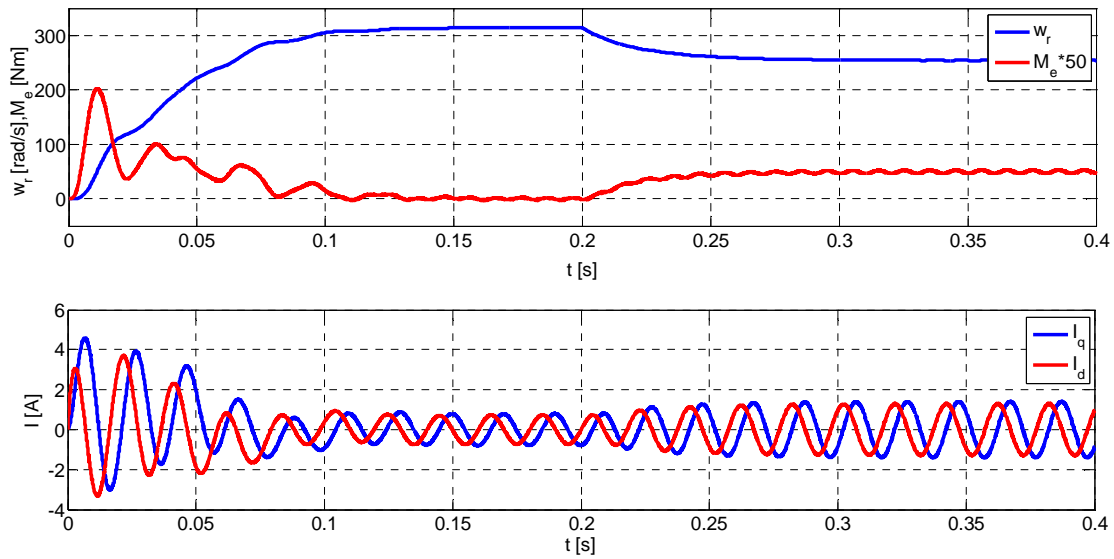


Figure 16: Time-waveforms speed, torque and currents of TPIM during start-up

Torque-speed characteristics were investigated by several methods of calculation and modeling [11], [13]. The obtained characteristics are shown in the next section V. due to comparison possibility with measured values.

6 Experimental Verification of Torque-Speed Characteristic of Two-Phase Power Electronic System

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 $f_{sw} = 5\text{kHz}$) for test rig system. There is shown test rig in Fig. 17. All system is controlled by Freescale DSP 56F8013DEMO.

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 [12].

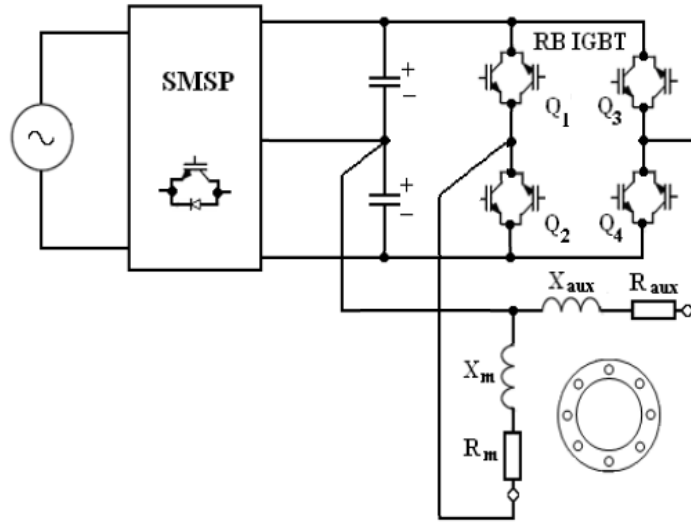


Figure 17: Circuit diagram of investigated of two-phase induction machine

Measured output waveforms of voltage and current of the two-phase power electronic system with TPIM motor are presented in Fig. 18.

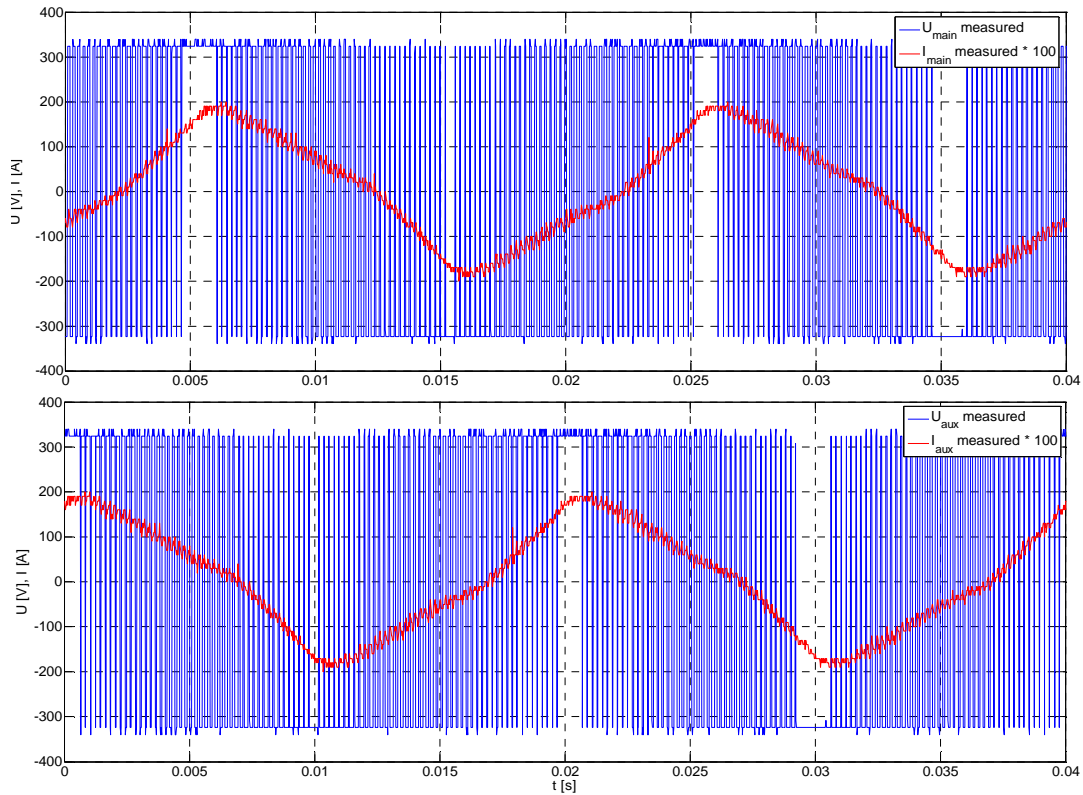


Figure 18: Measured output voltages and currents of the physical model of two-phase power electronic system

Experimental measurements of torque-speed characteristics, Fig. 19, 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 $f_{sw} = 5\text{kHz}$)

Resulted torque-speed characteristics carried-out by the measured on real machine, Fig. 20, at steady-state conditions are presented in Fig. 19 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.

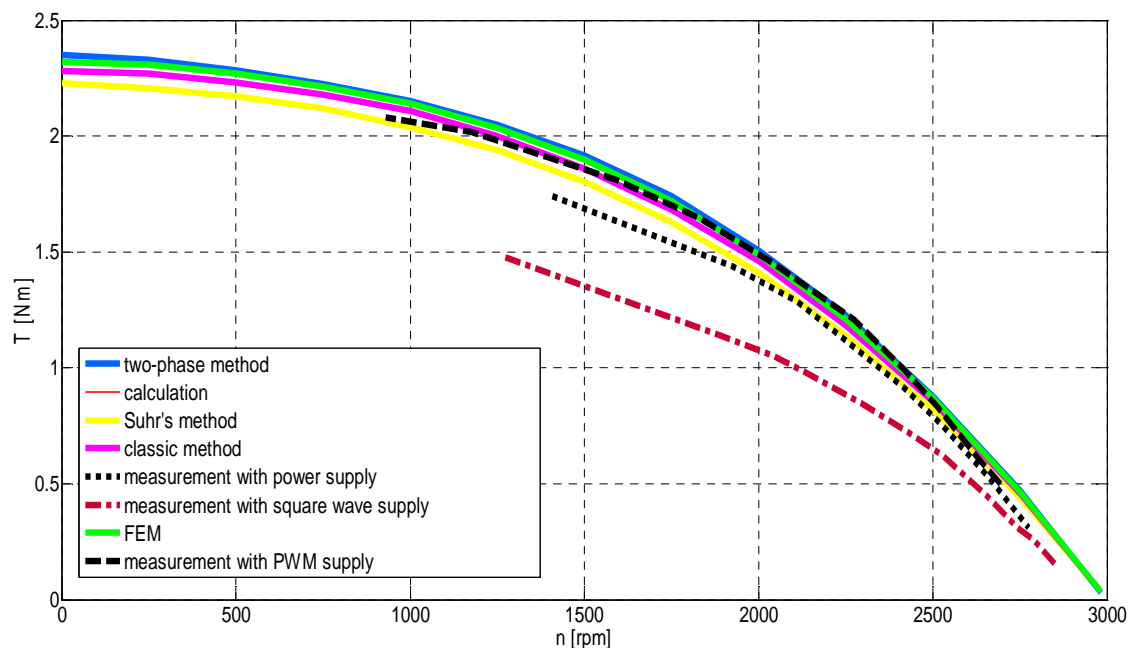


Figure 19: Comparison between measured and simulated torque-speed characteristics of TPIM with two-phase supply

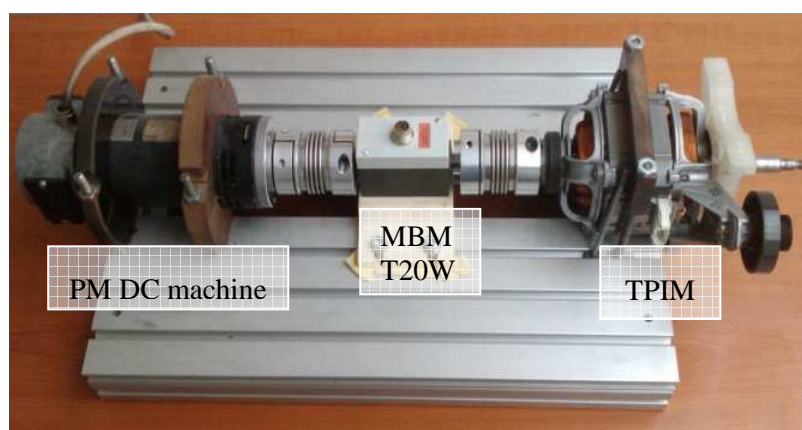


Figure 20: Motor test stand

7 Conclusion

The simulated results was compared with real measurement and the results give good coincidence, Fig. 19. 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 5kHz switching frequency than in case of simply rectangular supply. It is seen that 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 [11].

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