INVESTIGATION OF POWER LOSSES OF TWO-STAGE TWO-PHASE CONVERTER WITH TWO-PHASE MOTOR

Michal PRAZENICA[1], *Jan KASSA*[1], *Jozef SEDLAK*[1]

[1]Department of Mechatronics and Electronics, Faculty of Electrical Engineering, University of Zilina, Univerzitna 1, 010 26 Zilina, Slovakia

prazenica@fel.uniza.sk, jan.kassa@fel.uniza.sk, jozef.sedlak@fel.uniza.sk

Abstract. *The paper deals with determination of losses of two-stage power electronic system with two-phase variable orthogonal output. The simulation is focused on the investigation of losses in the converter during one period in steady-state operation. Modeling and simulation of two matrix converters with R-L load is shown in the paper. 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 in application with high frequency voltage sources.*

Keywords

Investigation of power losses, two-stage two-phase converter, two-phase load.

1. Introduction

Present efforts in reducing size and increasing of the efficiency of equipment leading designers to constantly develop converters with new topology and of course to use ZVS and ZCS. One possibility is to use two-stage converter, which allows direct use of ZVS switching technique. If a two-phase motor (IM, or SM) is used as load, it will reduce the number of required switching elements and it will be possible to achieve more favorable characteristics (torque).

Two-phase system was used in the past [1], but later was replaced by a three-phase circuit. 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 use 3-phase low cost motors, which are supplied asymmetrically into two phases from the voltage converter [2].

Advantageous is to create a two-phase (orthogonal) system using a power electronic converter with battery supply for example. Two-phase system can be created directly from DC voltage receive DC/2AC, Fig. 1, or by using of the VF AC interlink (voltage level adjustment for the engine) receive DC/HF_AC/2AC, Fig. 2 [4].

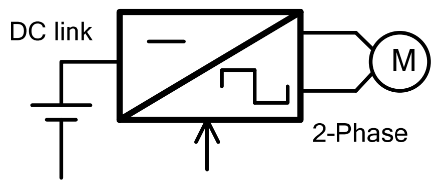


Fig. 1: Principle block diagram of DC/2AC converter (without HF interlink).

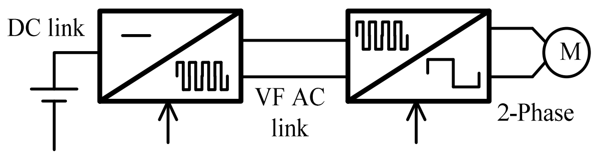


Fig. 2: Principle block diagram of DC/HF_AC/2AC converter (with HF interlink).

2. Two-Stage Two-Phase System

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. System with matrix converter and high frequency AC interlink can generate two-phase orthogonal output with variable voltage and variable frequency [5], [6]. Switching frequency of the converter is rather high (~tens of kHz). Since the voltages of the matrix converter system should be orthogonal, the second phase of converter is the same as the first one and its voltage is shifted by 90 degree.

The switches in first stage operate in hard switching condition (except for LLC converter, where soft switching is used) and create a rectangular voltage waveform (duty cycle 50 %) for HF AC Interlink. Inverter in second stage (matrix converter) creates required output voltage for motor load from the input voltage (voltage of HF_AC interlink). The switches of second stage operate in zero voltage switching condition (thanks to transition across zero of HF_AC interlink voltage).

Inverter in first stage can be connected as:

- full bridge converter,
- half bridge converter,
- LLC converter,
- boost converter.

Inverter in second stage can be connected as:

- full bridge converters connection,
- two half-bridge converters with central point of the source using HF transformer,
- half-bridge converter with central points of the motor load.

The best choice for first stage is LLC or Boost converter and for second stage is best choice using of Half-bridge matrix converter. 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, [2], [7], [8], [9] and others.

3. PWM Modulation Strategies

In the context of controlling the output voltage of the converter, we can use the following types of PWM regulation:

3.1 Standard Sinusoidal PWM Modulation

Standard sinusoidal PWM modulation is commonly used in unipolar, as shown in Fig. 3 and bipolar mode of control.

The main parameters of sinusoidal PWM modulation are: amplitude modulation index - m_a <0, 1> - the ratio of amplitude reference sine function and DC interlink. Frequency modulation index m_f is ratio between switching and fundamental inverter frequency of inverter. With larger modulation index, higher quality (less harmonic distortion THD) of output controlled quantity is achieved.

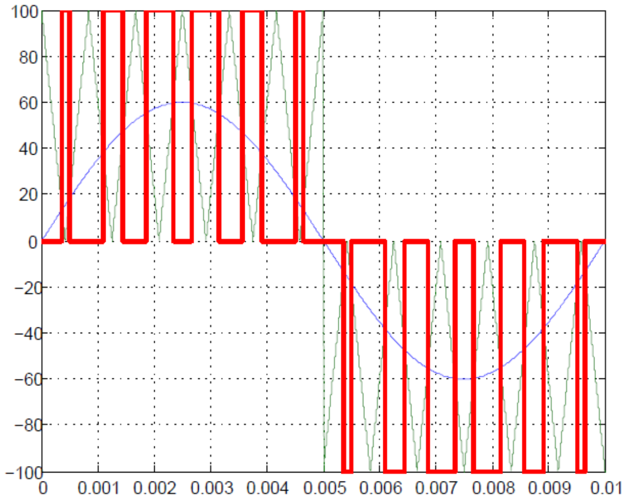


Fig. 3: Sinusoidal PWM output voltage of inverter with modulation index: $m_a = 0.6$ and $m_f = 12$.

3.2 Software PWM Modulation

Software PWM modulation is based on equation of areas between reference voltage sine wave and DC interlink, as shown in Fig. 4, and it is designed for applications with fast DSP control systems.

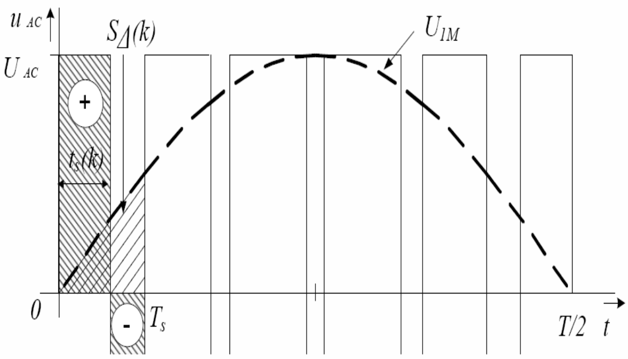


Fig. 4: Software bipolar PWM output inverter voltage with modulation index: ma = 1 and mf = 6.

3.3 Dimensional Vector PWM Modulation (SVM)

Dimensional vector PWM modulation (SVM) is one of the newest types of PWM modulation, especially designed for 3-phase electric drives. Its use for two-phase motors is not simple, because we have not two zero voltage vectors as in the case of 3-phase inverters. Hence, insertion of additional vectors is needed. This is described only in one magazine source [10]. Yet, there is not comparison with other PWM types. Proposal space vector PWM modulation (SVM) output voltage for two-phase inverter according to [10] is shown in Fig. 5.

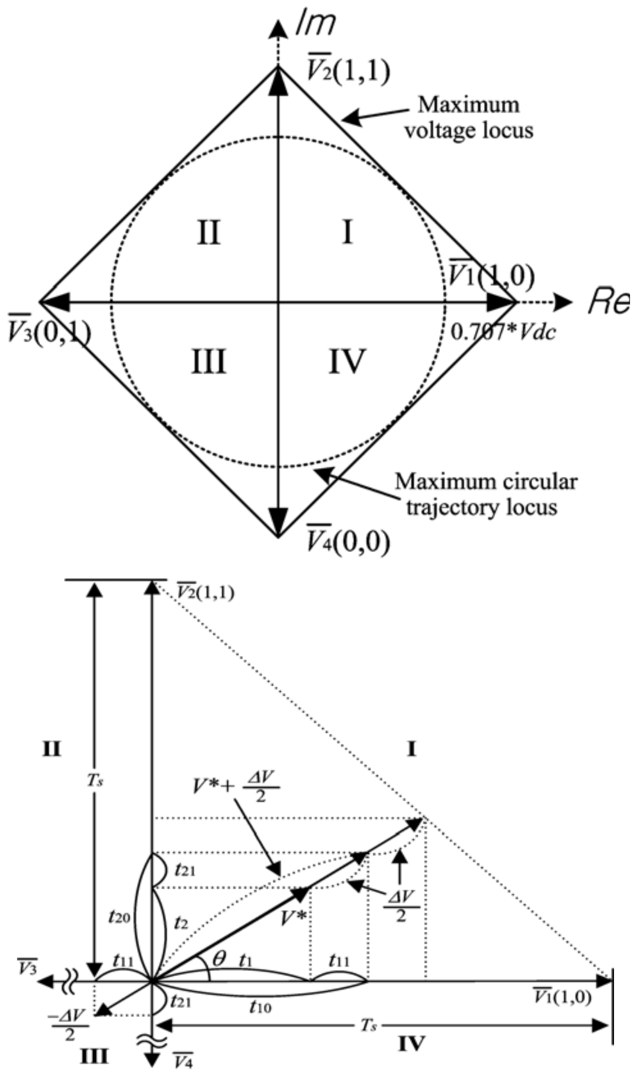


Fig. 5: Proposal space vector PWM modulation (SVM) output voltage for 2-phase inverter [10].

Since there are no zero vectors (half-bridge inverter connection), it is necessary to work with additional voltage vector ΔV. Thanks to this vector, it is possible to determine the relative length of the switch in α, β axes.

3.4 Switching Strategy for Two-Stage Two-Phase Converter System with AC Interlink

Theoretical analysis of single-phase matrix converter has been done, e.g. [15], [17]. Equivalent circuit diagram of Half-bridge single phase converters for two-phase system is depicted in Fig. 6. 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 shown in Fig. 7. Switching strategy of one half-bridge matrix converter, based on 'even' bipolar PWM, can be explained using Fig. 8, in greater details. Fourier analysis is useful and needed for determination of total harmonic distortion of the phase current of the matrix converter [15], [16]. 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.

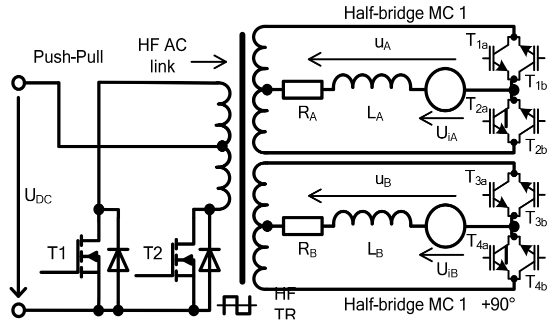


Fig. 6: Circuit diagram of half bridge converters system with HF transformer and central points of the source.

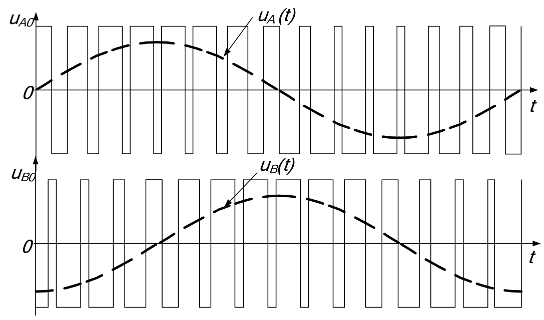
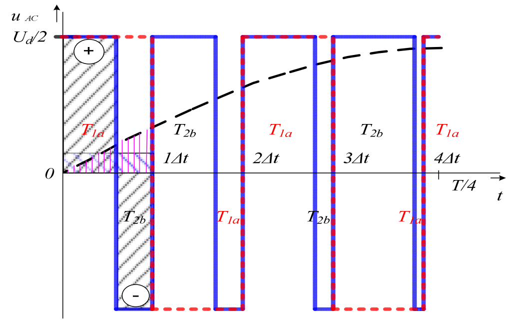


Fig. 7: Output orthogonal voltages of the half-bridge matrix converter system with bipolar PWM.



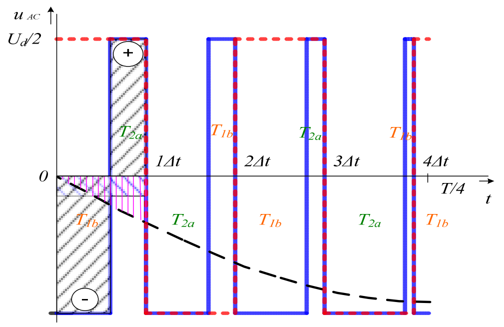


Fig. 8: Switching strategy of half bridge converter for a) positive and b) negative half period of operation.

Switching-pulse-width can be determined as equivalence of average values of reference waveform and resulting average value of positive and negative switching pulses area during switching period, Fig. 9.

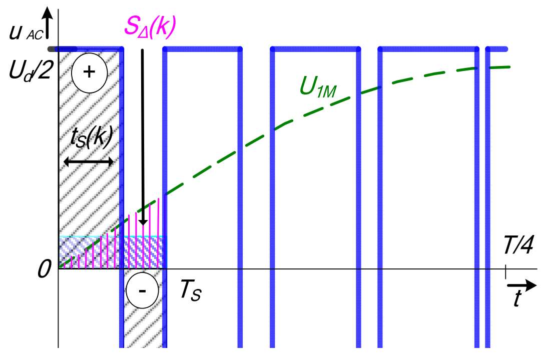


Fig. 9: PWM with even multiply of f_1.

4. Simulation Analysis and Example of Losses Calculating

According to paper [11] assume that the efficiency in a two-stage inverter compared with one-stage inverter decreases slowly with increasing switching frequency, Fig. 10 and Fig. 11.

The equation of the switching losses P_{SV} of a VSC with sinusoidal ac line current and with IGBT switching devices is given by eq. (1) from [13].

$$P_{SV} = \frac{6}{\pi} \cdot f_s \cdot \left(E_{ON,I} + E_{OFF,I} + E_{OFF,D}\right) \cdot \frac{V_{DC}}{V_{ref}} \cdot \frac{\hat{i}_L}{i_{ref}} . \quad (1)$$

Here f_S is the switching frequency, $E_{ON,I}$ and $E_{OFF,I}$ are the turn-on and turn-off energies of the IGBT respectively, $E_{OFF,D}$ is the turn-off energy in the power modules' diode due to reverse recovery charge current, V_{DC} is the dc link voltage and $\hat{\imath}_L$ is the peak value of the ac line current assumed to be sinusoidal. The values of switching energies provided by data sheets are given for a certain reference voltage V_{ref} equal to the blocking state voltage of the IGBT occurred before the corresponding commutation and a reference current I_{ref} which is the on-state current after this commutation [12].

Conduction losses $P_{CV,I}$ of a single semiconductor IGBT are expressed by equation (2). Likewise the conduction losses that appear in one diode $P_{CV,D}$ can be written as in eq. (3). The sum gives the total conduction losses P_{CV} in eq. (4) for n used semiconductors [12].

$$P_{CV,I} = \frac{V_{CE,0} \cdot \hat{i}_L}{2.\pi} \cdot \int_0^{\pi} \sin(\omega t) \cdot \frac{1+M(t)}{2} \cdot d\omega t + \frac{r_{CE} \cdot \hat{i}_L^2}{2.\pi} \cdot \int_0^{\pi} \sin^2(\omega t) \cdot \frac{1+M(t)}{2} \cdot d\omega t , \quad (2)$$

$$P_{CV,D} = \frac{V_{F,0} \cdot \hat{i}_L}{2.\pi} \cdot \int_0^{\pi} \sin(\omega t) \cdot \frac{1-M(t)}{2} \cdot d\omega t + \frac{r_F \cdot \hat{i}_L^2}{2.\pi} \cdot \int_0^{\pi} \sin^2(\omega t) \cdot \frac{1-M(t)}{2} \cdot d\omega t , \quad (3)$$

$$P_{CV} = n \cdot \left(P_{CV,I} + P_{CV,D}\right). \quad (4)$$

In these equations, ω is the load current-angular frequency, $M(t)$ is the modulation function, $V_{CE,0}$ is the IGBT's threshold voltage, r_{CE} is the IGBT's differential resistance, $V_{F,0}$ and r_F are the diode's threshold voltage and differential resistance respectively [12].

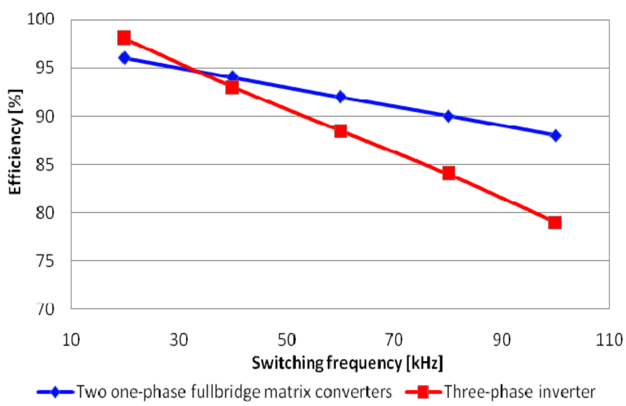


Fig. 10: Efficiencies of investigated inverter topologies depending up switching frequency. With RL load [14].

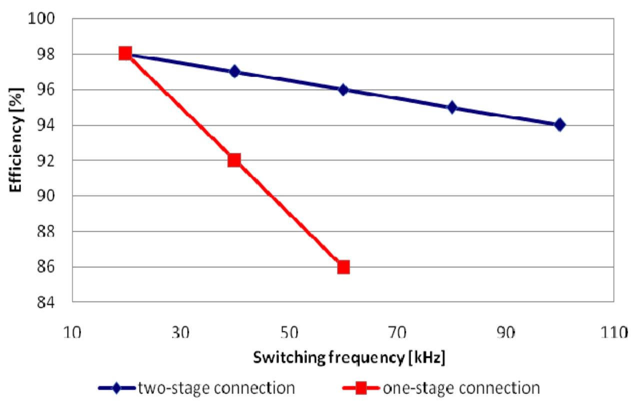


Fig. 11: Efficiencies of two-stage three-phase inverter with AC-interlink and of classic three phase inverter depending up switching frequency. With RL load [11].

Example of losses calculating:

- IGBT switching losses = 0,47 W,
- commutation energy of antiparallel diodes = 0,07 W,
- conduction losses of serial connection IGBT and diode = 1,5 W,
- total loss on one switching element (block) = 2,04 W,
- total loss of a matrix converter = 4,08 W,
- total loss of two-phase converter = 8,16 W.

The next parts of the total losses are created from losses of the first-stage converter and the losses of HF transformer.

Adjusting that turn-off losses of IGBT's in two-stage matrix converter are minimal (technically zero, because voltage across IGBT goes by into negative values by natural manner, thanks to AC interlink) is shown in Fig. 12. and Fig. 13.

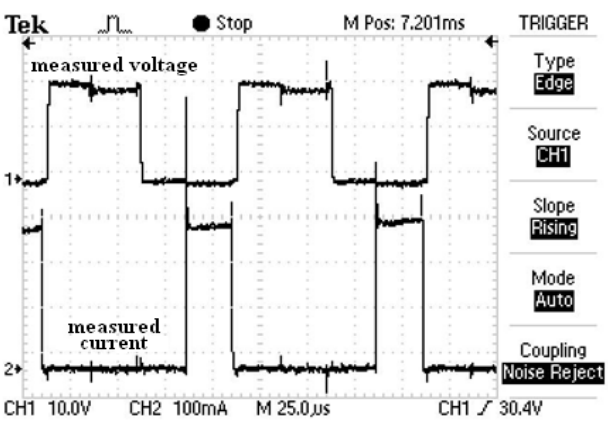


Fig. 12: Measured voltage across IGBT and current through IGBT in matrix converter.

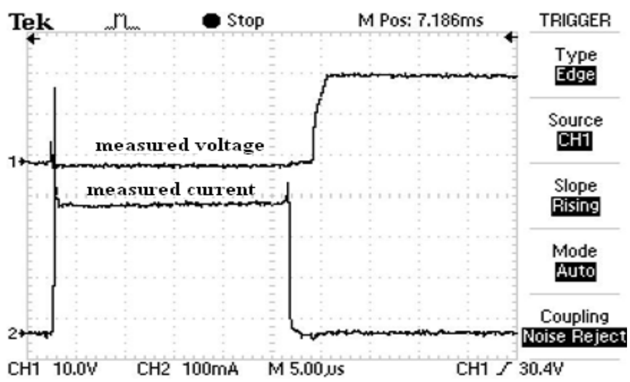


Fig. 13: Detail of measured voltage across IGBT and current through IGBT waveforms.

5. Experimental Verification

Involvement of the test system is shown in Fig. 14. The test system consists of two stages - single-phase voltage inverter and two single-phase matrix converters. Switching frequency was f_{sw} = 5 kHz. All system is controlled by Freescale DSP 56F8013DEMO. Involvement of two-phase motor test stand is depicted in Fig. 15.

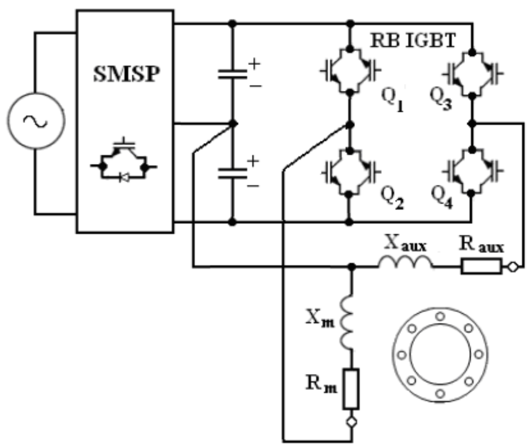


Fig. 14: Circuit diagram of investigated of two-phase induction machine.

Fig. 15: Motor test stand.

Waveforms of voltages and currents from measurements are shown in Fig. 16. Measured data (input and output power, speed and generated torque of motor) and calculated data (efficiency) are shown in Tab. 1.

Tab.1: Values obtained from measurements and calculating.

n (rpm)	T (Nm)	P el. (W)	P mech. (W)	Efficiency (%)
2694	0,24	84	67,7	80,5
2624	0,3	101	82,4	81,6
2513	0,4	125	105,2	84,2
2414	0,48	140	121,3	86,6
2273	0,58	160	140	86,2
2036	0,7	182	158	85,2
1934	0,79	188	160	85,1
1593	0,87	205	150	73,2
1176	0,97	233	119,4	51,2
930	1	250	97,4	38,8

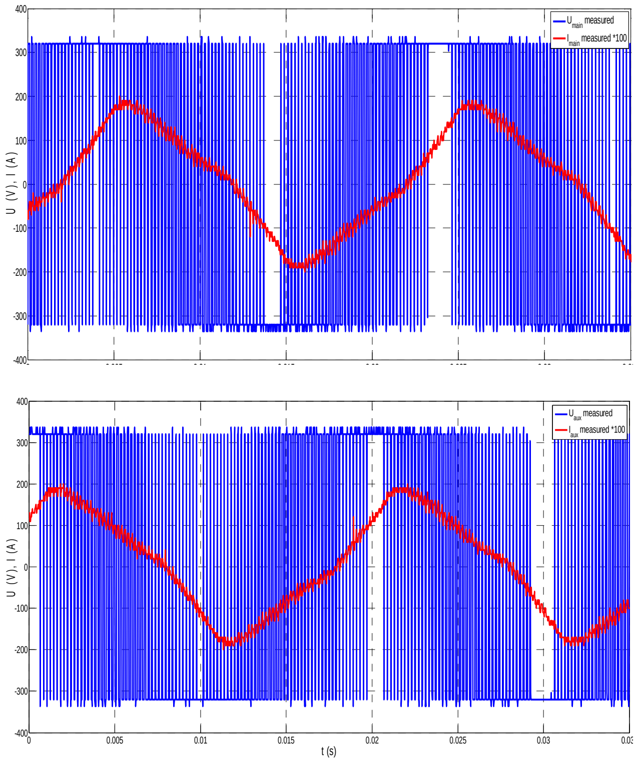


Fig. 16: Measured output voltages and currents of the physical model of two-phase two-stage power electronic system (f_{SW} = 5 kHz).

Waveforms of input power (electric) and the generated output power (mechanical) of motor are shown in Fig. 17. The resulting efficiency is displayed in Fig. 18.

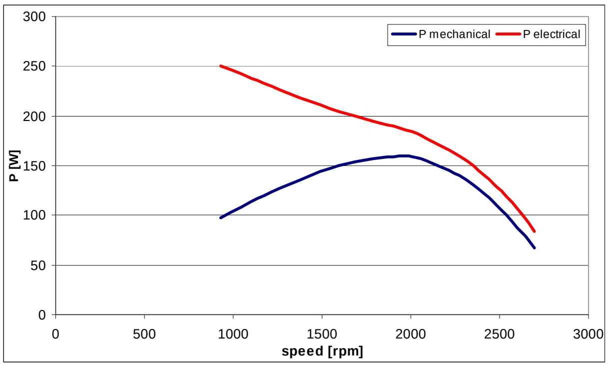


Fig. 17: Waveforms of electrical power of DC/AC/AC converter and mechanical power from 2-phase ASM motor.

Fig. 18: Efficiency waveforms of DC/AC/AC converter and 2-phase ASM motor system.

6. Conclusion

New concept of electric propulsion system for electric vehicle is shown. It consists of two-stage converter created by two single-phase matrix converters commutated by HF-AC input voltage, and two-phase induction TPIM or synchronous motors with PM. With using of two-stage converter, overall system losses can be reduced [11], Fig. 12 and Fig. 13. If this type of inverter is used to supply two-phase drive, high efficiency and very good mechanical parameters can be achieved (by two-phase - orthogonal supply of two-phase motor - TPIM, drive develops maximum torque). With using of higher switching frequency, it is possible to achieve not only higher efficiency, but also smaller harmonic distortion (THD) of output current.

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About Authors

Michal PRAZENICA was born in 1985 in Zilina (Slovakia). He is a Ph.D student at the University of Zilina - Faculty of Electrical Engineering - Department of Mechatronics and Electronics in the study programme "Power Electronics". The topic of his Ph.D. 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.

Jan KASSA was born in 1984 in Lucenec (Slovakia). He is a Ph.D student at the University of Zilina - Faculty of Electrical Engineering - Department of Mechatronics and Electronics in the study programme "Power Electronics". The topic of his PhD. thesis is: Design analysis and optimization of efficacy parameters of two-stage converters with HF AC interlink.

Jozef SEDLAK was born in Revuca in 1987. College graduation completed in 2010 at the University of Zilina in Faculty of Electrical Engineering in Department of Mechatronics and Electronics in the field of Power Electronics. Since September 2010 he is a Ph.D. student in Faculty of Electrical Engineering at project: Mechatronics structure of public-transport vehicles hybrid drives.