# Realized Matrix Converter PWM Strategy for Hybrid Drive System

JIRI LETTL
Department of Electric Drives and Traction
Faculty of Electrical Engineering
Czech Technical University in Prague
Technicka 2, 166 27 Prague 6
CZECH REPUBLIC

*Abstract:* - Matrix converters have attracted an amount of interest over the past 25 years already, but they find time after time once again new utilisation. The presented paper deals with the recent concept of hybrid and power splitting traction drive systems. Special attention is paid to electric power splitting. In the investigated system a traction induction motor is employed. The matrix converter realised on the base of new progressive semiconductor elements is used to treat the electrically transmitted part of the whole drive energy. This solution is advantageous with regard to the reactive component reduction. The special digital control system consisting of two personal computers is used for the realised test bed. The matrix converter IGBTs are controlled by means of the designed indirect pulse width modulation method.

*Key-Words:* - Matrix converter, digital control system, PWM strategy, hybrid drive, electric power splitting, traction induction motor

## 1 Introduction

The matrix converter is a very popular topic today. Until now it has attracted mainly academic attention, with investigation in this field begun in seventies. The very first attempts to establish the matrix converter technology was presented by Gyugyi and Pelly [1]. A significant contribution was given in the late seventies when professor Venturini published a paper presenting the topology and some improved control algorithms. By that time the converter was mainly named after the author as the "Venturini-converter". After decades of spontaneous evolution, ten years ago, the tendency went towards using the names "direct converter" and "matrix converter". At the time of Venturini's first publication, the control algorithms only allowed a voltage transfer ratio of 50 %. The input current quality was better than for traditional drives, but still the input power factor was low. In the eighties an improved control strategy was proposed by Venturini [2]. The voltage transfer ratio was now raised to 87 %, which was proven to be the theoretical maximum without overmodulation. The input current quality was also improved. In the late eighties space vector modulation schemes were introduced by different authors [3]. Especially Hubert and Borojevic [4] were very active in this field. The space vector modulation of the matrix converter offers the full theoretical voltage transfer ratio and sinusoidal input current with adjustable phase angle. So the matrix converter switch topology has the cycloconverter advantage of lacking a DC link, and hence lacks an energy store, while offering a potentially unlimited frequency range. The paper deals with the recent concept of hybrid and power splitting traction drive systems, whereas a special attention is paid to electric power splitting.

## 2 Matrix Converter as an Alternative Component of Hybrid Drive System

Enormous expansion of automobile traffic brings new problems in environmental load and fuel resources accessibility. Gas emissions of car combustion motors create ecological problems especially in big cities. Unfortunately development of alternative car drives based only on electric energy stored in a battery brings a solution only for short distances. Energy density of modern hi-tech batteries is too low in comparison with a full fuel tank of internal combustion motors. It is possible to ecologically solve the problem of internal combustion motor emissions and low action radius of electric vehicles by using hybrid drive systems. The hybrid drive is a complex system resulting from the combination of two or more simple systems that can operate simultaneously. Hybrid electric vehicles combine electric and other drive or generating systems, such as internal combustion engines, gas turbines, and fuel cells. Hybrid electric vehicles combine the zero pollution and high efficiency benefits of electric traction with the high fuel energy density benefits of an energy source or thermal engine.

There are various types of hybrid drives [5]. Promising is propulsion with electric power splitting based on internal combustion engine power splitting into two parts. One part is converted into electric power in a generator, which supplies a traction motor, mechanically connected to vehicle wheels, and the remaining part is transmitted by electromagnetic forces in the air gap to the wheels mechanically without losses in electric machines. The splitting devices can be realized mechanically by a planetary gear or electrically by a special electric generator. Such system with electric power splitter furnished with a DC motor was used for the Czech traction express train unit ”Slovenska strela” in the year 1936 [6]. The electrical torque split device (see Fig. 1) consists of a special electric generator with both stator and rotor rotating. The rotor is connected to internal combustion engine and its torque is via air gap electromagnetic forces transmitted to the stator. The torque and the output shaft angular speed constitute the mechanically transmitted power. The remaining part of the internal combustion engine power is transformed into the electric power and represents the input power of electrical transmission. To treat the electrically transmitted part of the whole hybrid drive power, the matrix converter can be employed.

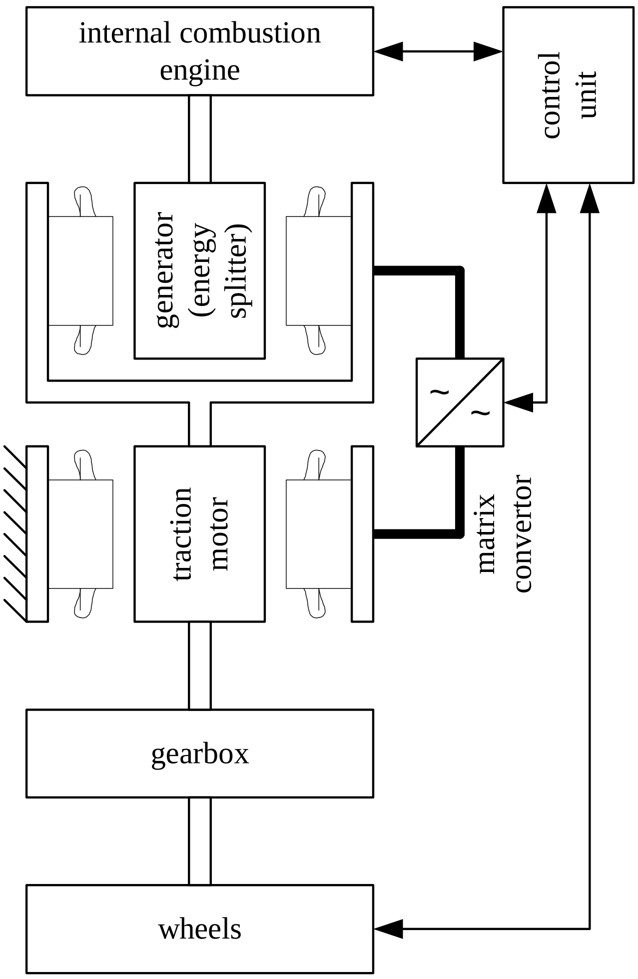



Fig. 1. Hybrid drive system with electric power splitting generator

## 3 Realized Experimental Test Bed

Block diagram and real implementation of the realized test bed are shown in Fig. 2. In the considered case the hybrid drive with electrical power splitter is investigated. On the realized test bed the internal combustion engine (ICE) is substituted by induction motor controlled by frequency converter. Similarly the wheels and traction load are substituted by induction motor controlled by frequency converter with energy recuperation. The traction motor is of the asynchronous type. Power splitter is special machine with two rotors. One rotor is with permanent magnets, second one is with winding and rings.

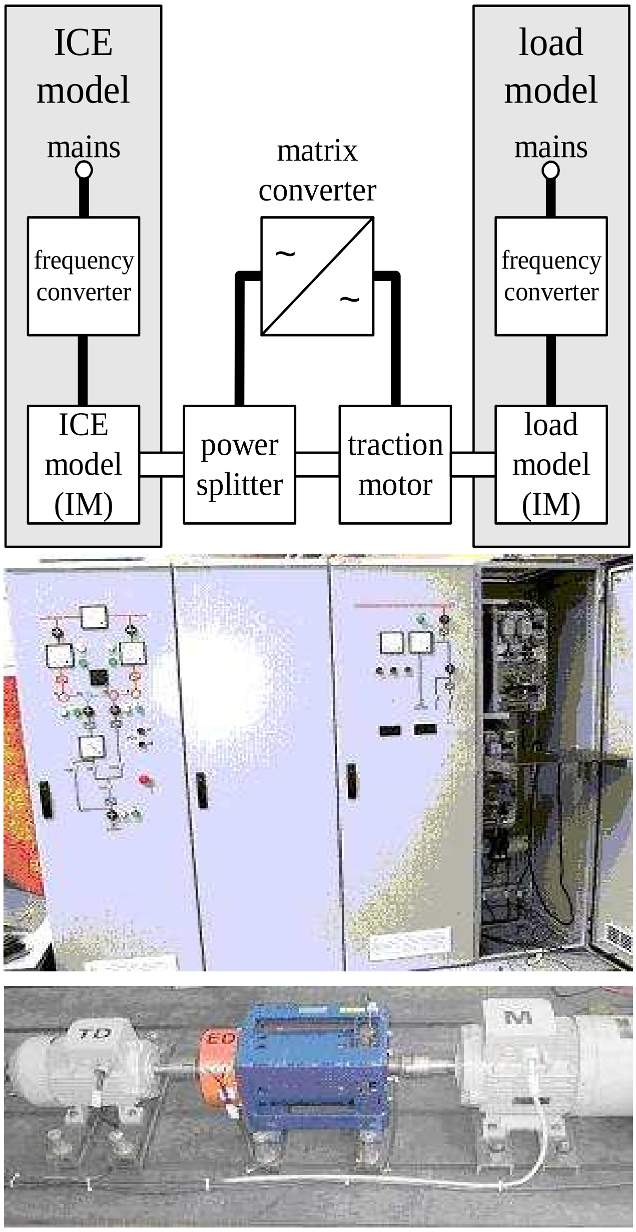



Fig. 2. Block diagram and real implementation of the test bed for hybrid drives research

### 3.1 Power Part

The power part of the realized matrix converter is installed into an iron frame (see Fig. 3). The proposed rated power is about 12 kW. On the left top side, the switching logic and protection and circuit breakers are placed. The current and voltage sensors can be found on the left side in the middle.

The input filter is placed in its bottom part. It consists of three coils and star-connected capacitors. The cut-off frequency can be adjusted by selecting of the number of capacitors used and / or by selecting a branch outlet of the inductor in the range from about 1 up to 4 kHz.

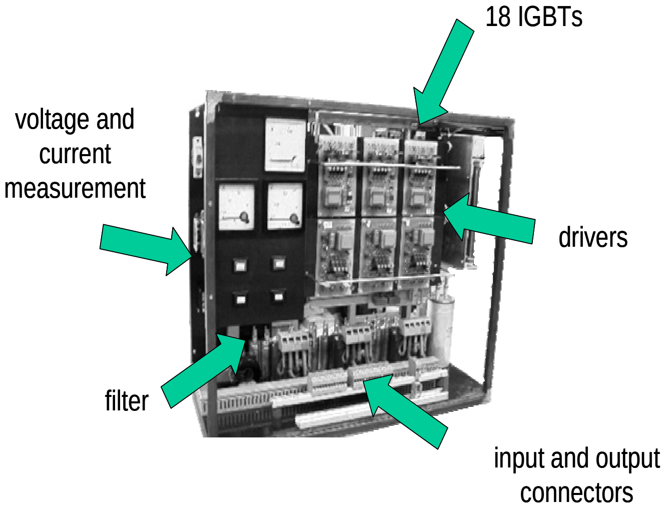



Fig. 3. Realized matrix converter power part.

The heat sink is mounted in the middle upper part on the back side of the frame. In the middle of the heat sink six diode modules (each made up of two diodes) have been placed in order to assemble the capacitor based clamp circuit (see black modules in Fig. 3).

Fig. 4. Configuration of the semiconductor elements on the heat sink

The bidirectional switches are constructed from two anti-serial connected IGBTs in the common collector configuration. The transistors are split into six groups according to their emitter potential and into two groups according to whether they are connected to the input or output side of the converter. The row of transistors connected to the output can be seen in the upper part of Fig. 3. The first three of these on the left side are connected with their emitters to the output phase A, the middle group to the output phase B, etc.

For each group of three transistors one driver unit is used. It has an optical interface (three inputs for switching pulses, one input for an enabling signal and finally one output for an error signal). The error signals are collected in the control rack and in the case of any error pulses are disabled on all units. The most recent version of the driver unit can be seen in Fig. 5.

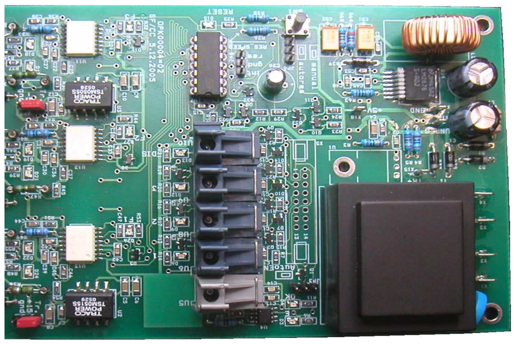


Fig. 5. The driver unit for three transistors at the same collector voltage potential

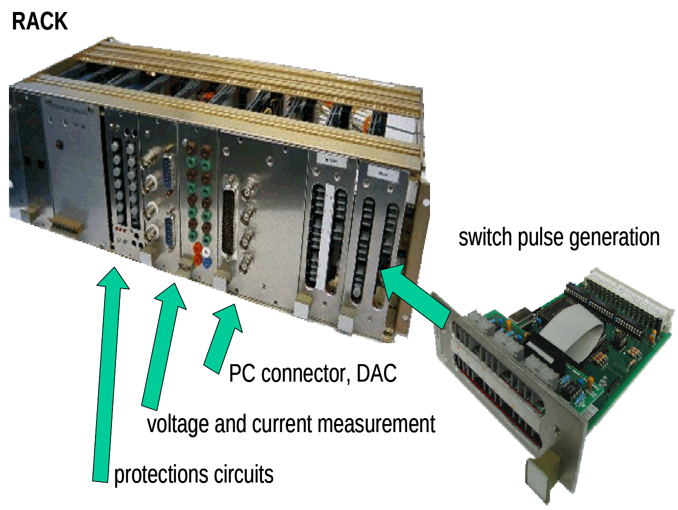



Fig. 6. The control rack.

The realized converter is connected with an induction motor, which is one part of a machine set. The set consists of the induction motor, the DC machine and the small DC machine excited by permanent magnets, which is used for speed measurements.

### 3.2 Control Hardware

The employed control system is based on two common personal computers (see Fig. 7). The first one (Host PC) is equipped with any multitasking operating system as is usual nowadays. It serves for compilation of the target real-time applications and for monitoring purposes only. The latter PC is equipped with a multi I/O PCI card Meilhaus ME-2600i containing 16 A/D and 4 D/A converters and a 32 bit bidirectional digital I/O port. This card is connected with an external rack that deals first of all with signal adjusting, pulse generation, and error signal management.

A special unit has been developed for the generation of switching pulses. It is connected to the digital output from the I/O card. A kind of 24 bit parallel bus is implemented, which enables the connection of two switching units. Some of the signals are used for control and synchronization purposes, 12 signals define desired states of the output bits (switch word bus) and 12 the relative times corresponding to particular switching words. It is possible to define up to 16 switch events on average for every period. The switching unit has to be able to generate exact switching patterns and to be programmed for the next regulation cycle simultaneously. This is done with a help of the dual port memory which is implemented in the FPGA which is employed in the switching unit. The controller of the switching unit assures that programmed switching events are saved one after the next to the correct positions in the dual port RAM. In this way a FIFO structure with flexible length is actually created. The value of the last not yet used time part of the programmed event is continuously compared with the value of the internal timer which is reset at the beginning of every regulation period and when they match, the switching words are applied to drivers of the optical outputs of the switching unit. Two pieces of these switching units are employed in the matrix converter version of the control system.

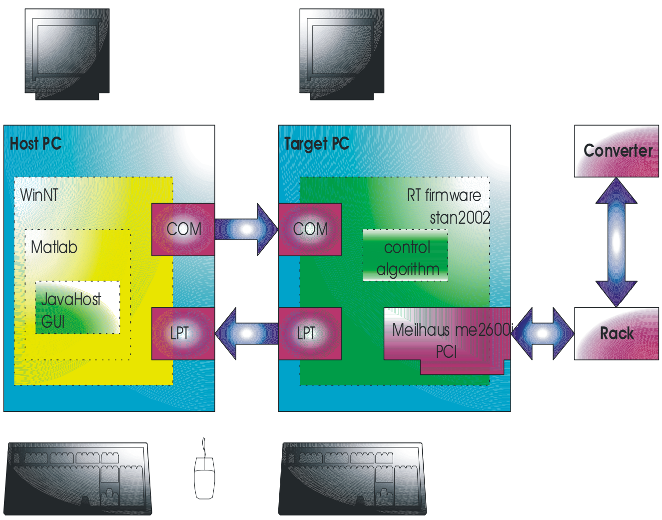



Fig. 7. Host PC – Target PC concept

### 3.3 System Software

The realized system software serves to shield the user from the PC and I/O card hardware. This is done by exact determination of the place where the user should write his algorithms and by defining variables that serve as gates between application and system software. The kernel of the system software serves for synchronization of the control loop with an externally generated synchronizing signal, which is connected with one of the special purpose inputs of the I/O card. The frequency of the synchronization signal can be adjusted in the control rack. According to this signal the kernel repeatedly starts particular system processes (data conversion, communication with the monitoring software, keyboard service routine, etc.) as well as the actual control algorithm. The user application can according to the results of the measurement undertake any necessary counting and fills to the table of switching events for the regulation period. These tables are then again used by the system software as input data for routines programming the switching units. The remaining time is used for communication with the host system.

### 3.4 Monitoring Software

The monitoring program consists of the set of mutually communicating programs programmed in the MatLab, JAVA, and C languages. However, from the user's perspective it seems to be only one application. The monitoring software enables changing the parameters in the target system even while the target system is running in real time operational mode. It is also possible to download the saved waveforms. The main disadvantage of this implementation is the limitation of data transfer speed caused by communication between the monitoring program and MatLab. Thus, a version running outside of MatLab was also successfully tested.

## 4 Matrix Converter Control Strategy

Great number of sophisticated strategies of pulse width modulation methods, and control algorithms for induction motor control in terms of various optimization criteria are known in case of indirect frequency converters, whereas both the inverter and the rectifier can be operated with pulse width modulation. The instantaneous state of both the output and the input converter waveforms depends at any time on the switch state of the converter power switches S. Suitable switch states sequence of the nine matrix converter switches can be indirectly derived from the given switch states sequence of the twelve switchers of the indirect frequency converter as can be seen in Fig. 8 and Fig. 9.

The matrix converter instantaneous switch state matrix **S** can be afterwards determined by means of the instantaneous switch state vectors $\mathbf{s}_{ABC}$ and $\mathbf{s}_{RST}$ in form given by the simplified equation (1).

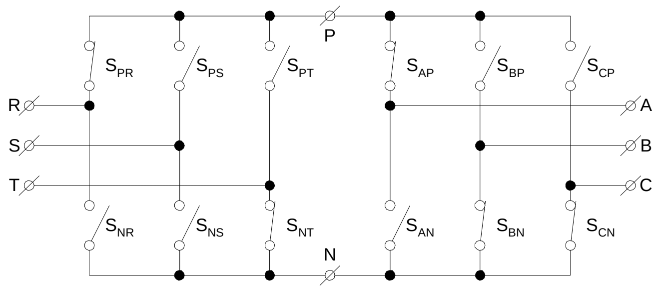



Fig. 8. Indirect frequency converter power switches instantaneous switch state

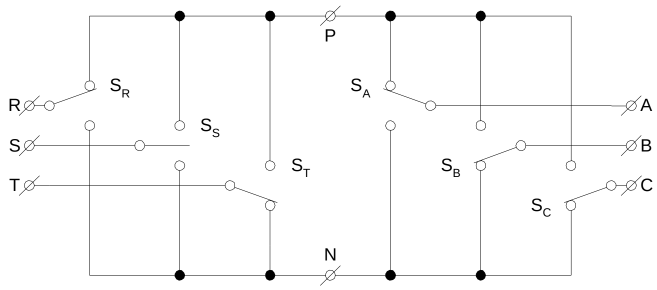



Fig. 9. Indirect frequency converter simplified instantaneous switch state schema

$$\boldsymbol{S} = \boldsymbol{s}_{\mathrm{ABC}}\boldsymbol{s}_{\mathrm{RST}}^{\mathrm{T}} = \begin{pmatrix} S_{\mathrm{A}} \\ S_{\mathrm{B}} \\ S_{\mathrm{C}} \end{pmatrix} \begin{pmatrix} S_{\mathrm{R}} & S_{\mathrm{S}} & S_{\mathrm{T}} \end{pmatrix} = \begin{pmatrix} S_{\mathrm{AR}} & S_{\mathrm{AS}} & S_{\mathrm{AT}} \\ S_{\mathrm{BR}} & S_{\mathrm{BS}} & S_{\mathrm{BT}} \\ S_{\mathrm{CR}} & S_{\mathrm{CS}} & S_{\mathrm{CT}} \end{pmatrix} \tag{1}$$

## 5 Simulation and Measured Results

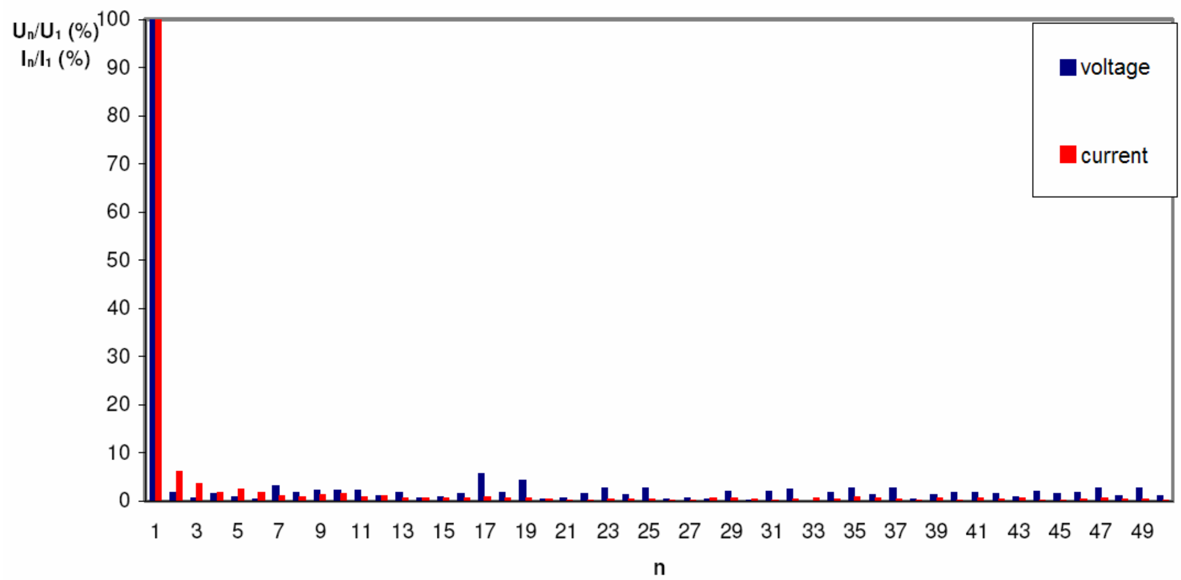
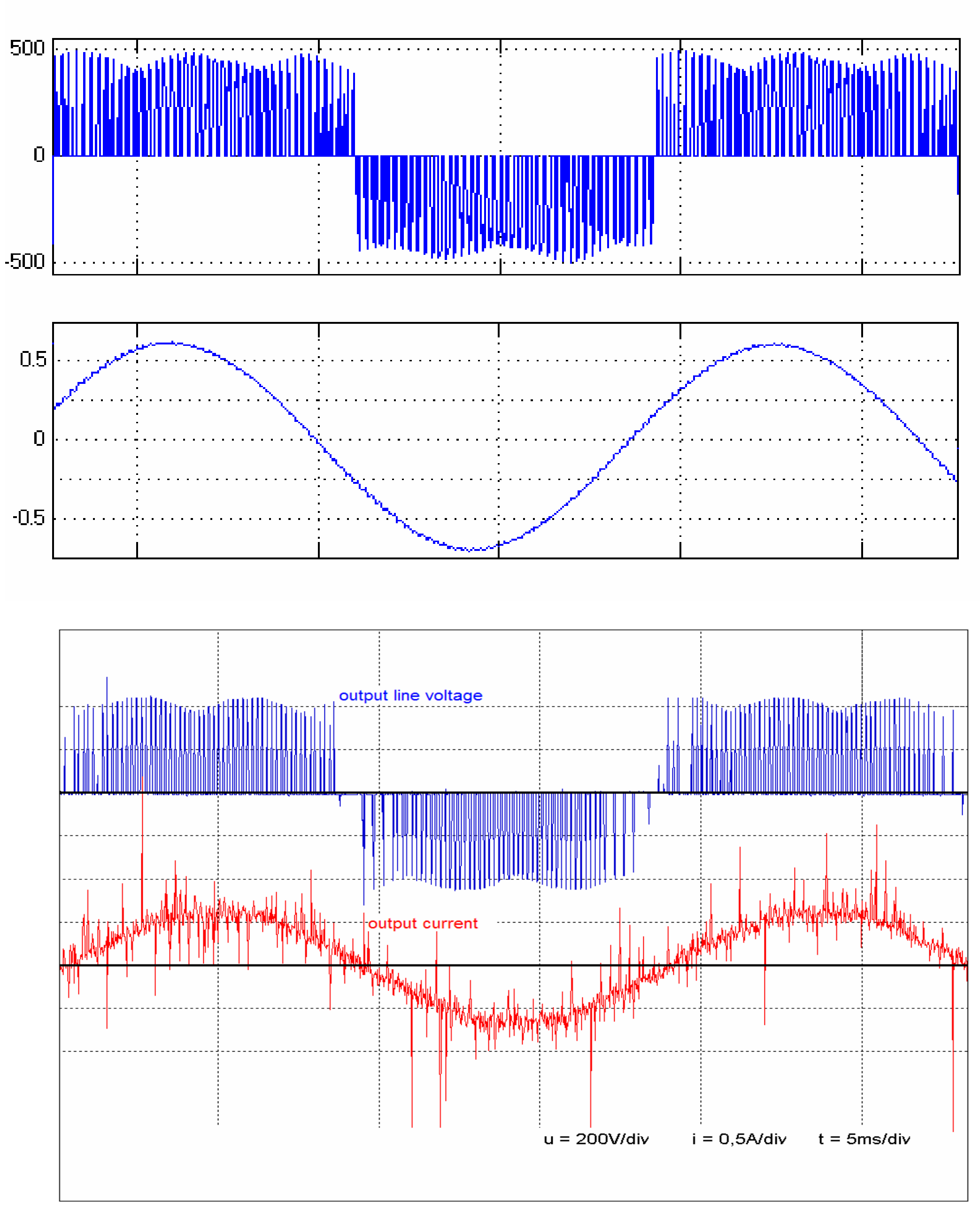



Fig. 10. Typical output voltage and current waveforms harmonic analysis for indirect vector modulation at 20Hz

## 6 Conclusion

The developed matrix converter control hardware and software system makes it possible to achieve greater throughput of the digital control system and its variability. The matter consists in the processor throughput. While in case of the digital signal processors it can be as far as 100 MIPS at 16 bit DSP with fixed point, 200 MIPS at 32 bit DSP with fixed point, 20-200 MIPS/MFLOPS at DSP with floating point only, in case of processors for PC it can reach e.g. 9000 MIPS and 2600 MFLOPS. The results obtained on the built-up experimental test bed have proved proper function of the designed conception of the matrix converter control system and implemented PWM strategy. The proper function of the matrix converter control system is illustrated also by the matrix converter voltage and current waveforms shown in Fig. 11.




$U_{in}$ = 310 V, $U_{out}$ = 140 V, $f$ = 55 Hz, $T_{reg}$ = 150 μs

Fig. 11. Comparison of simulated and measured output waveforms for indirect vector modulation

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