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Compact Matrix Converter Prototype

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Abstract:
Matrix converter belongs to direct frequency converter category. Output voltage is made by direct switching of input phases to output phases. This fact means that converter does not need DC-link capacitor which increases the costs and volume requirements of the converter. The absence of DC-link capacitor is one of the main advantages of the matrix converter. On the other hand it means that the output voltage amplitude is limited by 86.6% of the input voltage amplitude. Higher voltages can be achieved with overmodulation, which causes input current distortion. The other advantages of the converter compared to conventional indirect frequency converter are: power factor regulation, operation in all four quadrants, its high dynamic, sinusoidal current consumption, nearly sinusoidal output voltage waveform with low harmonic content, and high efficiency. To the main disadvantages belongs: amount of semiconductor devices, limited output voltage amplitude, and complicated control algorithm. The new prototype of the matrix converter equipped with modern sophisticated components (FPGA, one desk PC, etc.) in the converter's control part is being developed. Modulator of the converter is going to be realized in Field Programmable Gate Array. The hardware protection circuits against over voltage and current overload are going to be evaluated directly in the FPGA, therefore the reaction time of the control algorithm to the possible failure will be much shorter.

INTRODUCTION

The beginning of the matrix converter dates back to the 1970s. Nowadays, the name "Matrix Converter" is used to label any power topology that can be organized into sub blocks placed in a matrix shape. In this paper "Matrix Converter" refers to the symmetrical 3x3 topology provided by nine bidirectional switches. The converter belongs to the direct frequency converter category. The output voltage is produced by direct switching of the input phases to the output phases. This means that the converter has no DC-link and therefore it does not need an accumulation element in DC-link. Simplified block diagram of the most important parts of the converter is shown in Fig 1. The individual blocks will be described in following paragraphs.

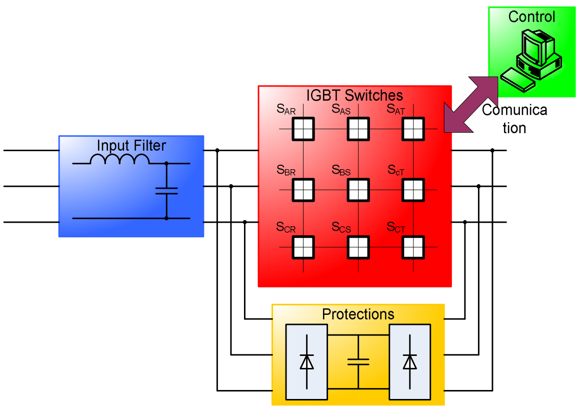

Fig. 1: Simplified Block Diagram of the Matrix Converter

The main advantages of the matrix converter compared to conventional indirect frequency converter are: power factor regulation, operation in all four quadrants, its high dynamic, sinusoidal current consumption, nearly sinusoidal output voltage waveform with low harmonic content, and high efficiency. The main disadvantages include: number of semiconductor devices, a complicated control algorithm, and also absence of the DC-link means that the output voltage amplitude is limited by 86.6% of the input voltage amplitude. Higher voltages can be achieved by overmodulation that causes input current distortion.

DESIGN OF THE POWER PART

The power part of the converter consists of 9 bidirectional switches that provide the power flow in both directions. Each switch is formed by two IGBT modules with antiparallel diodes. The modules are then connected anti-serially with common emitter. This means that the whole power part of the converter is carried out of 18 discreet IGBT transistors. We chose discreet transistor modules because in case of a transistor breakdown the discreet transistor can be easily replaced.
To design the transistor in power part of the converter it is necessary to know some of its basic characteristics. The converter is supplied from the ordinary 230/400V AC network and the output current is assumed to be circa 25A. In accordance with output current value we choose the IGBTs in the

SOT227 package that can be easily mounted to the radiator, and continuous current 70A. From the input voltage and current can be derived the approximate power of the converter 20kW.
Next step is to design the radiator that will cool the IGBTs. The power losses in IGBTs arise during current conduction and in the course of switching. Losses are approximately 4% of the power of the converter. This means that the radiator must conduct away approximately P_z = 800W. We chose the radiator of dimensions 125 x 135 x 300 mm. The length of the radiator was chosen with consideration of the compactness of the converter. This radiator can not conduct away all losses in natural way; therefore it will be equipped with fan on the side.
The placement of the transistors is shown in Fig. 2.

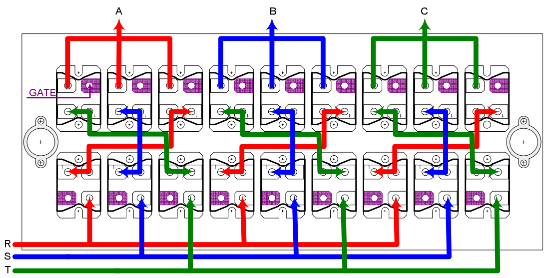

Fig. 2: Disposition of the Modules on the Radiator

It was decided to connect the modules according to Fig. 2. First, the links are traversed due to the symmetry of the phases and to suspend the parasite inductances in the links. The connections are realized by 4 layer printed circuit board and each output phase has its own board. This solution was chosen because of the modularity of the converter, and also because the IGBTs protection circuits are realized on the board. There are snubber capacitors, varistors, and a clamp circuit. The manufactured board is shown in Fig. 3.

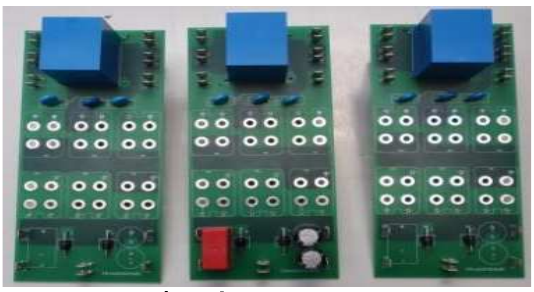

Fig. 3: Connection of Boards

DESIGN OF THE INPUT FILTER

Nowadays the input filter is an important part of electronic devices. The advantages offered by modern controlled electric drives need not to be mentioned here; however on the other hand semiconductor converters belong among the worst polluters of the supply network. Therefore we decided to equip the converter with two filters. The first of these is a commercial filter with a frequency range from 150 kHz to 30 MHz.

The low frequency filter is designed as a simple LC filter. The filter is supposed to protect the supply network against the negative effects of the converter like produced harmonics and distortions caused by switching of the power modules.
The important properties of the filter are cutoff frequency and output impedance of the filter. The cutoff frequency of the filter must have enough distance from the switching frequency because the filter must already have sufficient attenuation in the range of converter's switching frequency. The output impedance of the filter must be in safe distance from the input impedance of the converter in order to avoid the oscillations of the filter.

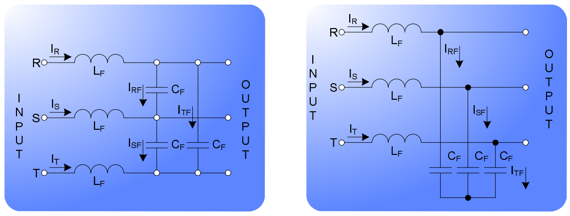

Fig. 4: LC Filter Configuration

The filter is mostly being designed according to Fig. 4. These simple configurations are easy to design and work mostly without problems. The second order filter provides 12dB per octave of attenuation after the cutoff frequency f_0. It has no gain before f_0, but it presents a peaking at the resonant frequency f_0, see Fig. 6.
The own design of the filter is compromise between the value of the capacity and inductance. The high capacity on the input of the converter has positive effect on the input voltage quality. On the other hand higher inductance value is required to achieve demanded cutoff frequency of the filter. In our case the cutoff frequency of the filter was chosen to be 1kHz. The inductance of the filter was chosen L_f = 1mH. From these two values can be calculated the capacitor value as C_Y = 25.4µF or C_Δ = 8.43µF. Here the advantage of the capacitors connection to triangle is obvious; the value of the capacity is 3 times smaller. The real cutoff frequency of the filter can be calculated as (1).

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{1e^{-3} x27e^{-6}}} = 986.7Hz \qquad (1)$$

The transfer function of the filter can be calculated according to the equation (2).

$$F(s) = \frac{1}{1 + s \cdot L_F + s^2 \cdot L_F \cdot C_F} \qquad (2)$$

We made simulations of the both filters connected to the input of the matrix converter with help of the simulation software Matlab/Simulink. The model of the converter with the filter was made by help of the special Simulink toolbox PLECs. The results of the simulations emerges that the filter works properly when the converter is loaded. The problems came out when the converter worked unloaded. Oscillations of the filter and of the protection circuit appeared in this case. In order to avoid the oscillations the damping circuit was added to the filter. The schemes of the filters with added damping are in Fig. 5.

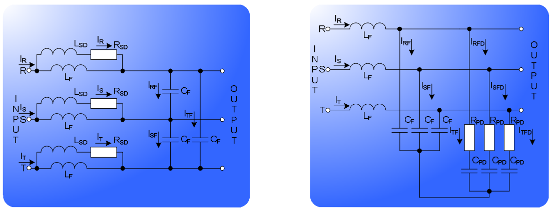

Fig. 5: LC Filter Variants with Damping

The parallel damped filter is complemented with resistor R_{PD} in series with capacitor C_{PD} and they are connected parallel with the filter's capacitor C_F. The purpose of resistor R_{PD} is to reduce the output peak impedance of the filter at the cutoff frequency. The capacitor C_{PD} blocks the DC component of the input voltage and avoids the power dissipation on R_{PD}. The values of the damping components are calculated according to (3) and (4).

$$R_{PD} = \sqrt{\frac{L_F}{C_F}} = \sqrt{\frac{1mH}{25.4\mu F}} = 6.28\Omega \qquad (3)$$

$$C_{PD} = 4xC_F = 4x25.4\mu F = 101.6\mu F \qquad (4)$$

Another way to obtain a damped filter is a resistance R_{SD} in series with an inductor L_{SD}, all connected in parallel with the filter inductor L_F. At the cutoff frequency the resistance R_{SD} has to have a higher value of the L_{SD} impedance. The disadvantage of this damped filter is that the high frequency attenuation is degraded, see Fig. 6. The values of the components in damping circuits were calculated according to equations (5) and (6).

$$R_{SD} = \sqrt{\frac{L_F}{C_F}} = \sqrt{\frac{1mH}{8.43\mu F}} = 10.89\Omega \qquad (5)$$

$$L_{SD} = \frac{2}{15} xL_F = \frac{2}{15} x1mH = 133.3\mu H \qquad (6)$$

Transfer functions of the all three filters without damping, with series damping circuit, and with parallel damping circuit are shown in Fig. 6.

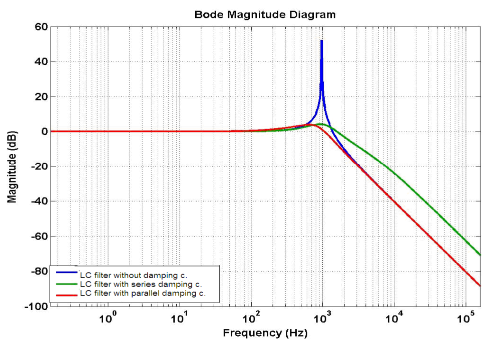

Fig. 6: Transfer Functions of the Proposed Filters

Blue waveform represents the filter without damping. The peek in the area of the cutoff frequency is clear. The red waveform corresponds to the filter with parallel damping. The parallel damped filter has better attenuation in comparison with the green waveform which belongs to the series damped filter.

The simulations of the filter behaviour with matrix converter obtained from Simulink are in Fig. 7 and Fig. 8. The right half of the figures shows the point when the capacitor in DC-link of the clamp circuit was loaded and the oscillations with the input filter started.

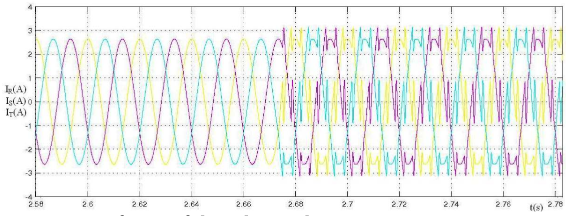

Fig. 7: Waveforms of the Filter with Series Damping

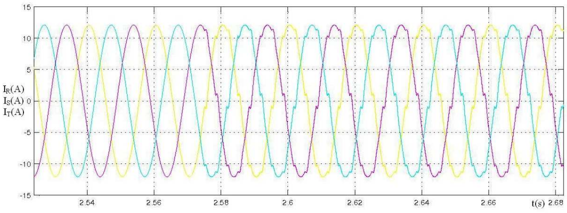

Fig. 8: Waveforms of the Filter with Parallel Damping

We have compared the results of both simulations. The current consumed by the converter with parallel damped filter looks more sinusoidal. On the other hand the current that flows in parallel damping circuit is bigger then the current in serial damping circuit. The components for the filter with parallel damping have also bigger values, for example the value of the filter capacitor C_{FY} = 25µF is very bulky. Therefore the filter with series damping circuit was chosen.

STRUCTURE OF THE CONVERTER CONTROL SYSTEM

The control system of the converter is realized by driver boards, switching pattern generators, and a pilot controller, see Fig. 9.

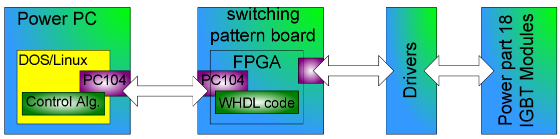

Fig. 9: Design of the Controller Structure

Each bidirectional switch requires two control signals (two IGBTs) and puts out 4 signals indicating its state and current direction. This means that there are 54 signals handled by the controller at any moment. The control system has to work in real time in order to generate the switching pulses and to receive information at maximum frequency. On the other hand the control system should be as simple as possible for reasons of reliability, and should be compatible with standard industry interfaces. To fulfil these requirements and to enable direct communication between the pilot controller unit

and the driving pulse generator, it was decided to connect the generator directly to a standard system bus. The ISA is the oldest bus, easy to handle and its throughput is sufficient for this application. Many producers offer industrial PC boards with PC104 bus, and EBX format for embedded applications. For the matrix converter controller a combination of a custom EBX main board and a PC104 processor board was selected.
The switching pattern board (Fig. 10) works as a modulator. The board was designed specially for this converter; therefore it contains interfaces that we thought they are important for the converter. Among digital interfaces are PC104, speed sensor, ISP, JTAG, RS232, PS2, switching pulses, error lines, and analogue interfaces including sigma-delta and voltage-frequency converters. All digital signals are handled by a core FPGA device (Cyclone II) which is situated on a board. FPGA has stored in it the code for switching pulse generation, basic error detection, diagnostics, and also the service routines for all peripheries including the PC 104 bus. A great advantage of this solution is that in the event of a breakdown the whole converter is stopped in nanoseconds by a change to one input pin of FPGA. A pilot controller is connected via the PC 104 bus. The one Desk PC module from RTD acts as the controller here. As far as the system is concerned, DOS will run for the initial testing in one Desk PC. Linux that has become very popular in recent years will be employed in the final implementation.

Fig. 10: Realized Switching Pattern Generation Board

It is necessary to be informed about 2 input voltage levels and 2 output current levels for simplest modulation algorithm execution. Therefore the converter is equipped with 5 LEM current sensors on the input and output, and 3 LEM voltage sensors on the input. The output voltages are measured with use of a resistor voltage divider. All signals will be transmitted to the control system. For this purpose the control system is equipped with 4 galvanic insulated U/f A/D converters and 4 galvanic insulated sigma/delta A/D converters. The one Desk PC module will be extended with measure card - Smart HighRel PCI-104 1.25 MHz 16 Channel 12-bit Analogue Module from RTD. That means we will have 24 A/D converters altogether.

THE PROTECTIONS

The converter will be used for design and testing of new control algorithms and commutation methods. After experiences with similar converter we decide to equip the converter with several protection circuits. IGBT modules will be protected with varistors against surges. Each bidirectional switch will have varistor connected parallel to it.
There is also software protection. Each IGBT module has its own driver circuit. The role of the driver is to amplify the switching signal and it is also used for monitoring the transistor states. This information is sent back to the switching pattern board. So when an error occurs, the switching pattern generator will immediately block all pulses.
Last protection will be the clamp circuit. The clamp circuit in Fig. 11 is made of two diode rectifiers connected to the input and output phases. Between these rectifiers is connected the capacitor and varistor. The task of these two elements is to accumulate and dissipate the energy, which is stored in the load inductances in a failure state.

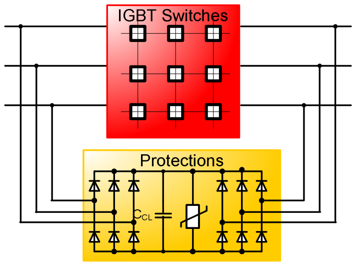

Fig. 11: The Clamp Circuit

The capacitor C_{CL} in the clamp circuit is charged to a voltage according to the amplitude of the line voltage after connecting the matrix converter system to the mains. Moreover, this voltage level is continuously boosted due to the converter's leakage inductance. That is why discharging of the capacitor must always be secured. The first option is to put a resistor R_{CL} in parallel and to set its resistance according to the requested time constant of the clamp circuit. It is connected with additional power-losses in the converter and it decreases its efficiency. Too small resistance value can also excite filter oscillations.
It was decided to replace the resistor with varistor in order to reduce these effects, so the capacitor is not discharged continuously but only when the voltage on the capacitor exceeds the breakdown voltage of the varistor.
When we consider that converter will be used as a supply for induction machine, the energy stored in its inductances can be calculated according to (7). The full derivation of the equation (7) is in [2]:

$$\Delta E_M = \frac{1}{2} \frac{P_N}{i_k \omega_s \cos \varphi_N \eta_N} \qquad (7)$$

Where P_N is the nominal power of the motor, the power factor $\cos\varphi$ of the motor is between 0.7 – 0.85, the efficiency η of the motor is between 0.7 – 0.9 and i_k is the coefficient of the motor run-up multiple of 3.5 – 7.5 times. So the equation (7) can be transformed to equation (8) from which the approximate energy can be estimated.

$$\frac{P_N}{3805} \leq \Delta E_M \leq \frac{P_N}{1077} \qquad (7)$$

THE MATRIX CONVERTER REALIZATION

The main task is to make the converter as compact and modular as possible. Many parts of the converter, e.g. driver boards, connection boards, switching pattern generation board, board for measurements and sensor signal adjustments have been specially developed for this converter. The placement of the boards fulfils the requirements on modularity and the boards are easy to remove. Because from the photo documentation can not be clearly seen the space alignment of the individual converter components, the position of the control part boards is schematically shown in Fig. 12. On the radiator are directly mounted the IGBT modules and temperature sensor. To the transistors are screwed the connection boars and above them the driver boards are placed. The rest of the control part is mounted to the framework that is screwed to the radiator, too. Current transducers are also mounted on the radiator. The connections between the boards are made by demountable joints like connector FASTON or common signal connectors DIN, PSH, etc. The radiator with the whole construction on is mounted to the chassis's back. Beside the radiator on the back of the chassis are mounted circuit breaker and contactors. At the bottom of the chassis are mounted filters, supply board, and 24V supply Traco. In the front part of the chassis are placed switches and connecting blocks. The realized converter is shown in Fig. 13.

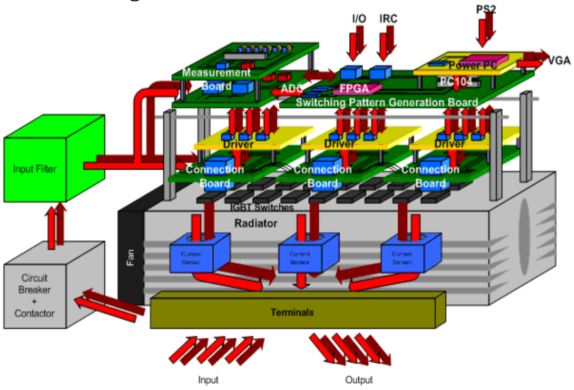

Fig. 12: Emplacement of the Control Part

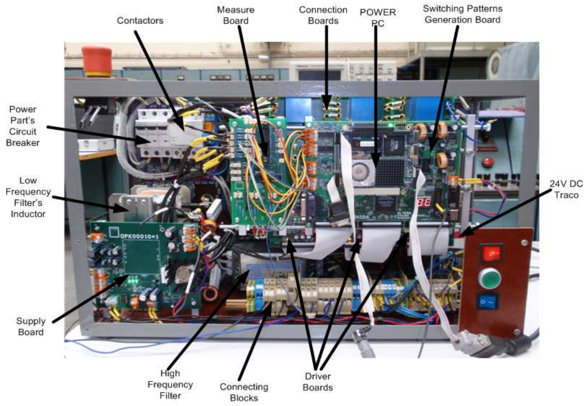

Fig. 13: The Realized Converter

CONCLUSIONS

The proposed new matrix converter system configuration promises many improvements. However, the real impact of the proposed system will be evaluated when the whole system is completed.
First step will be implementation of a simple control algorithm like indirect space vector modulation.
The selection of the commutation method is essential for the modulation method. We suppose that two step commutation method and the four step commutation method will be realized and tested on the converter.
Also the operation system in converter's controller should be improved. Today the DOS is being used in the controller. Recently the Real Time Linux is being very popular; therefore it is supposed to be used in final realization of the converter's controller.

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