Riga Technical University

Faculty of Power and Electrical Engineering

Institute of Industrial Electronics and Electrical Engineering

Alvis Sokolovs

Research and Development of Integrated AC Drive with Induction Motor and Matrix Converter

Summary of doctoral thesis

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Riga Technical University

Faculty of Power and Electrical Engineering

Doctoral student of program "Computer control of electrical technology"

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DOCTORATE WORK
PRESENTED TO OBTAIN THE DOCTOR'S DEGREE IN ENGINEERING SCIENCES

Doctorate work for the doctor's degree in the engineering sciences was publicly presented on the 21st of December 2010 at 12:00 o'clock in Riga Technical University, Kalku str. 1 – 119

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CONFIRMATION

Hereby I confirm that I have worked out the present doctorate work, which is submitted for consideration to the Riga's Technical University for the degree of Doctor of engineering sciences. Doctorate work has not been submitted in any other university for obtaining the Doctor's degree.

Alvis Sokolovs …………………………….

Date: ………………………

The doctorate work is written in English language, contains: 189 pages, introduction, 3 chapters, conclusions, 114 figures, 104 formulas, 29 tables, 130 references and 6 appendixes.

SIGNIFICANCE OF THE TOPIC

Nowadays in most electric drive systems DC motors are replaced with regulated AC drives. Due to simple and precise control of DC motors these machines were dominating in industry for many years. However with rapid advances of power semiconductors and digital computing technologies in last decades AC machines became more attractive in many industrial and household applications. Until recent years most AC drive systems consisted of three parts: AC machine, frequency converter and connection between them. Recent technological advancements allow integration of power semiconductors inside the AC machine that yields compact all-in-one solution. Such level of integration allows use of electric drives in places with restricted installation space. However due to bulk passive elements inside voltage source inverters this was not an easy task. Besides most power electronic converters implement uncontrolled diode bridge rectifier in the converter input. This yields high content of harmonic distortions that require large input filters, no regenerative braking is possible and input power displacement angle cannot be regulated. For integrated drives most attractive would be so called "all silicon device" such as a matrix converter. The matrix converter is a direct frequency converter that does not contain any passive elements, allows bi-directional power flow and input power factor modulation.

Another common problem in any power electronic converter is commutation process of high currents with high frequencies that cause dangerous overvoltages on semiconductor devices and are sources of electromagnetic interference. In most cases some sort of overvoltage damping circuit is added to the power device. This solution dissipates the energy stored in the parasitic inductances in the damping resistor. Such solution is energy inefficient and space consuming and cannot be considered as a solution in integrated drives. This is why other methods of overvoltage reduction are quested. The most direct way to deal with this problem is elimination of the source of the problem by reducing parasitic inductances in the commutation loop. An indirect way is to influence commutation process without additional circuitry in the power part.

OBJECTIVE OF THE WORK AND FULFILLED TASKS

The ojective of this doctoral work is to research and develop power part of integrated AC drive system with matrix converter. Because whole AC drive is a complex system consisting of an induction motor, power converter, control unit and other elements, several specific tasks are defined:

- analysis and comparison of matrix converter with other frequency converter for integrated drive applications;
- analysis of overvoltage reduction methods by means of bus bars in three phase matrix converter;
- analysis of overvoltage reduction by means of power switch gate signal manipulations;
- development of integrated three phase matrix converter power board for integrated AC drive;
- analysis of experimental results and conclusions of system potential;
- economical potential estimation of matrix converter integrated drive system.

METHODS AND MEANS OF RESEARCH

In order to estimate the effectiveness of the proposed idea of active gate drive circuits and bus bar implementation in matrix converters Matlab mathematical analysis software is used, simulation of particular components and circuit parts as well as filter analysis is performed in PSpice Schematic and Matlab Simulink.

Numerical analysis of conductor inductances and bus bar structure is done in Matlab.

Parasitic inductance influence on matrix converter commutation is simulated in PSpice. To obtain practical results of bus bar influence on overvoltage reduction, bus bar system was constructed and experimentally tested.

Gate drive circuit performance as well as active gate drive commutation is simulated in PSpice and experimentally tested in laboratory of Power Electronics.

Electric machine parameter extraction experiments were carried out in Riga Techinincal university Department of Power and Electrical engineering Laboratory of Electrical Machines and Laboratory of Electrical Drives on HPI test bench.

Experiments with matrix converter drive are carried out with Siemens induction motor, matrix converter and a control unit developed in the University of Nottingham, Power Electronics and Motion Control Department.

Economic analysis and estimation of potential product is based on an existing expenses calculation in a metal working factory in Valmiera.

SCIENTIFIC ORIGINALITY

A novel method of matrix converter bi-directional switch power interconnection has been elaborated and verified by means of analytical calculations and experiments;

A novel power IGBT commutation active gate current control method for overvoltage reduction as well as short circuit detection has been implemented and tested;

Design of power converter is described for further ready-for-marked development;

An economical assessment of matrix converter integrated drive production is done;

Comparison of matrix converter integrated drive and other drive systems available on the marked is done to evaluate its competitiveness.

PRACTICAL APPLICATION OF THE WORK

The elaborated prototype of the integrated drive system can be further developed to commercial product and launched on the market for industrial, household or other applications. Typical application of such system can be considered in conveyor lines, fans, pumps and other areas where speed or torque control is a key factor.

WORK APPROBATION

The approbation of work has been realized participating the following international conferences:

1. 3rd International conference on “Topical problems of education in the field of electrical and power engineering”, Tallin University of Technology, Kuressaare, Estonia, 2006;
2. 12th Power Electronic and Motion Control Conference EPE-PEMC, Portoroz, Slovenia, 2006;
3. 10th biennial Baltic Electronics Conference BEC 2006, Tallinn, Estonia, 2006;
4. 47th Riga Technical university International Scientific Conference, Riga, Latvia, 2006;
5. Doctoral school of energy- and geo-technology 2007, Kuressaare, Estonia, 2007;
6. IEEE International Symposium on Industrial Electronics ISIE 2007, Vigo, Spain, 2007;

7. 9th International Conference on Electric Power Quality and Utilization EPQU 2007, Barcelona, Spain, 2007;
8. 5th International Conference on Compatibility in Power Electronics CPE 2007, Gdansk, Poland, 2007;
9. 16th International Conference on Electrical Drives and Power Electronics EDPE 2007, Podbanske, Slovakia, 2007;
10. Doctoral school of energy- and geo-technology 2008, Kuressaare, Estonia, 2008;
11. 11th biennial Baltic Electronics Conference BEC 2008, Tallinn, Estonia, 2008;
12 Doctoral school of energy- and geo-technology 2009, Kuressaare, Estonia, 2009;

AUTHOR'S PUBLICATIONS

1. "Simulation of a simple control strategy for a common 3x3 Matrix Converter", A. Sokolovs, I. Galkins, J. Laugis, 3rd International conference on "Topical problems of education in the field of electrical and power engineering", 40. lpp, Tallin University of Technology, Kuressaare, Estonia, 2006;
2. "Simulation Methods for 3x3 Matrix Converter", A. Sokolovs, I. Galkins, O. Krievs, J. Laugis, Power Electronic and Motion Control Conference EPE-PEMC 2006, pp. 822 – 827, Portoroz, Slovenia, 2006;
3. "Bus bar test bench development for common 3x3 matrix converter", A. Sokolovs, I. Galkin, J. Laugis, 10th biennial Baltic Electronics Conference BEC 2006, Tallinn, Estonia, 2006;
4. "Development of bus bar EMI reduction test bench for matrix converter", A. Sokolovs, I. Galkins, 47th RTU international scientific conference, Riga, Latvia, 2006;
5. "Problems related with use of bus bars in matrix converters", A. Sokolovs, I. Galkin, Doctoral school of energy- and geo-technology 2007, Kuressaare, Estonia, 2007;
6. "Comparison of Bus Bar constructions for Matrix Converters", I. Galkin, A. Sokokovs, IEEE International Symposium on Industrial Electronics, pp 49-49, Vigo, Spain, 2007;
7. "Possible construction of bus bars for matrix converter", A. Sokolovs, I. Galkin, International Conference on Electric Power Quality and Utilization EPQU 2007, pp. 1 – 5 Barcelona, Spain, 2007;
8. "Bus Bar construction consideration for Matrix Converters in Integrated AC drives", A. Sokolovs, I. Galkin, Compatibility in Power Electronics CPE 2007, pp. 1 – 4, Gdansk, Poland, 2007;
9. "Bus Bar construction for Matrix Converters", A. Sokolovs, I. Galkin 16th Int. Conference on Electrical Drives and Power Electronics EDPE 2007, Podbanske, Slovakia, 2007;
10. „Cost and Space Effective IGBT Gate Drive Circuit for Bi-directional Switch of Matrix Converter", A. Sokolovs, I. Galkin, 11th biennial Baltic Electronics Conference BEC 2008, Tallinn, Estonia, 2008;
11. „Alternative Constructions of Bus Bars for 3x3 Matrix Converter in Integrated Drives", A. Sokolovs, I. Galkin, Doctoral school of energy- and geo-technology 2008, Kuressaare, Estonia, 2008;
12. „800 V DC-DC power supply for gate driver of a common two transistor leg of VSI", A. Sokolovs, I. Galkin, Doctoral school of energy- and geo-technology 2009, Kuressaare, Estonia, 2009;
13. „High frequency sine wave PWM generation – programmable logic, microprocessor and analogue approach", Doctoral school of energy- and geo-technology 2009, Kuressaare, Estonia, 2009;

Publication in Scientific Journal

1. Galkins I., Sokolovs A. Bus bar construction considerations for matrix converters in integrated AC drives, PRZEGLĄD ELEKTROTECHNICZNY, ISSN 0033-2097, pp. 108.-111, Poland, 2007.

CONTENTS OF DOCTORAL THESIS

INTRODUCTION

It can be said that most of the advancements in electronics were introduced during the second half of the 20th century, however the unstoppable technological evolution began much earlier with the Industrial Revolution in the 18th and 19th centuries. Since then humanity has been searching for more and more efficient ways to use energy and never before this issue has been so important as nowadays. With growing population, production and energy consumption, yet high use of nonrenewable natural resoures, efficiency is the most important issue in any industry.

Nowadays the field of industrial electronic is closely related to electric drives and control hence the new term – mechatronics appears. For a long time DC machines dominated in industrial applications due to their simple and precise speed control possibilities. However because of their main drawback, meaning collector and brushes that wear off and relatively decrease safety, induction machine is more attractive. This is a simple and robust machine that dominates in the world marked and industrial applications. With advances of power electronics and digital control techniques AC machines become more attractive since they can provide wide speed and torque control techniques.

As technological progress goes on, the minimization and integration of electronic components becomes possible. Not only high power density modules implemented in power electronic converters are now available on the market, but also all-in-one solutions can be found at several developer homepages. These solutions assume high integration level of power electronic converter, power switch driver and control signal isolation in one package. Such advancements give possibility of even higher integration levels – when motor, power electronic converter and its control can be integrated in one unit, hence reducing size and costs of the system and increasing reliability of the system.

This thesis is dedicated to research of modern electric drive system which integrates mechanical part – the motor, power electronic part – the matrix converter and control part all in one unit. Main attention is drawn to efficient minimization of parasitic phenomenon – overvoltage that occurs across the switching device when inductive current is commutated. The aim of the work is to build basis for further product development of integrated drive with induction motor and matrix converter.

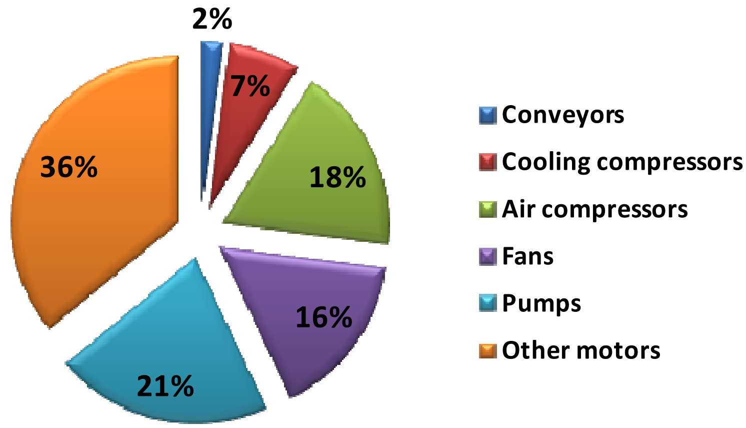
Thesis is written in Engilsh and it contains: 185 pages, introduction, three chapters, conclusions, 114 figures, 104 formulas, 29 tables, 130 references and 6 appendixes.

1. ENERGY EFFICIENCY OF ELECTRIC DRIVES

Electric motors are electromechanical devices that are responsible for the conversion of electrical power into the mechanical one. In the European Union (EU) motor driven systems account for approximately 69% of the electricity consumed by industry and 38% of the electricity consumed by the tertiary sectors [1].

Table 1.1. Total motor electricity annual consumption in industry by end-use application in EU, year 2000[2]

End-use application	TWh
Conveyors	13.0
Cooling compressors	45.5
Air compressors	117.0
Fans	104.0
Pumps	136.5
Other	234.0
TOTAL	**650.0**



In year 2000 on European market integral motor shares were dominated by AC motors. The trend of DC motor market share declines every year due to three-phase induction machine possibilities when fed from voltage-source-inverters, moreover induction machine price and maintenance costs are much lower.

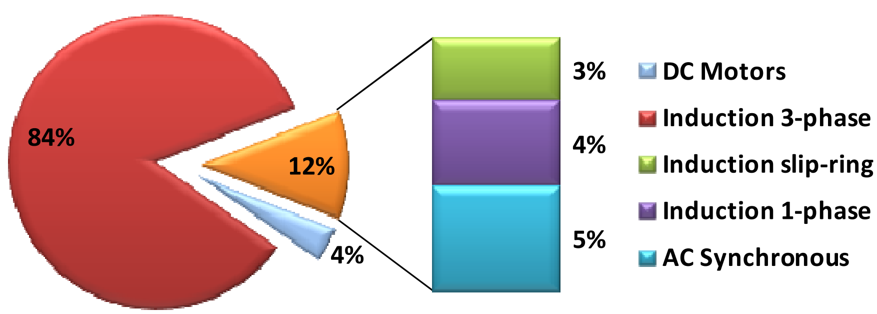


Fig. 1.1. Motor type shares in Europe in 2006

Future assumption of motor electricity consumptions in EU by year 2015 is 721 TWh in industry and 224 TWh in tertiary sector. For the assessment of electricity saving potential several scenarios are introduced. In [1] four energy saving scenarios are presented by introducing of new electric motor market policies which state reduction of class 3 and 2 motor sales. However in [3] three different scenarios with application of VSDs have been considered: technical saving potential, economic saving potential assuming constant VSD prices as well as economic saving potential assuming VSD price decrease of 5% per year. From obtained statistical data it is evident that most electric energy is consumed by pump, ventilation, refrigeration and air compressor systems. These systems are mostly driven by three phase induction motors, which can be fed form frequency converters. Variable speed drives give an opportunity to implement more efficient control strategies that allow speed regulation of induction motors and hence efficient regulation of flow or pressure is achieved. Result is the energy saving of up to 100TWh in industrial sector and up to 40TWh in tertiary sector each year in European Union.

This is why three phase induction motor is selected as the target in this particular thesis for integrated drive system development with matrix converter.

2. CHALLENGES OF ELABORATION OF INTEGRATED DRIVE

This section is dedicated to the integrated drive development. Reasons for the electric drive integration are stated and drive integration benefits and problems are analysed. Most common existing frequency conversion techniques are described. Choice of matrix converter for particular application is stated. Matrix converter switch realisation, power IGBT commutation and regarding problems are studied as well as possible commutation overvoltage reduction methods are investigated and experimentally confirmed. Description and calculation of other drive elements such as auxiliary power supplies and electrical parameter measurement circuits is given. In the end of this section induction motor scalar and vector control methods are described and experimental results of induction motor drive with matrix converter are presented.

2.1. ELECTRIC DRIVE INTEGRATION

Evolution of power electronics and electric drives has now reached the point of integration. There are cases when motor drive installation in separate locations is not possible or difficult to achieve, and fixed speed motors are still used. The purpose of integration is to achieve variable speed motor drive with the same dimensions as usual motor. Another reason is to simplify the drive system by introducing a one drive unit. This tendency is stimulated by high level power electronic converter integration – not only power electronics, but also drivers, control and power supplies are integrated into one unit resulting in a smaller device, higher power density and higher efficiency.

However such advancement is not an easy task to achieve due to natural challenges: electrical and thermal issues are the main conflicting entities. When electrical performance is improved by placing components closer to each other, thermal performance worsens. With reduction of power electronic system volume the power density increases, thus increasing the temperature inside the components. Surface that is exposed to the surrounding environment becomes smaller which means that the ability to facilitate heat exchange is reduced. Trade off between these facts must be found to achieve well performing and reliable drive system. However, nowadays some high-frequency power conversion technologies have reached the fundamental limits that cannot be overcome unless radical change in the design and implementation of the system is done.

The concept of integrated AC drive system is mentioned in 1988 in [5] and there are several integrated drive solutions available on the marked nowadays, most of them are servo or low-power high-speed drives. However some manufacturers such as Lenze offer induction motor with addable voltage source inverter, this solution thou is not what might be called *fully integrated* drive. Viability study of fully integrated induction motor drive with matrix converter is done in [6]. Authors of this paper approve that design, construction and operation of 30kW integrated induction motor drive with matrix converter technology is viable. Keeping the same space envelope as original motor the advantages of MC power topology are demonstrated. Main challenges of such system development are described in [6], [7], [8] and [9].

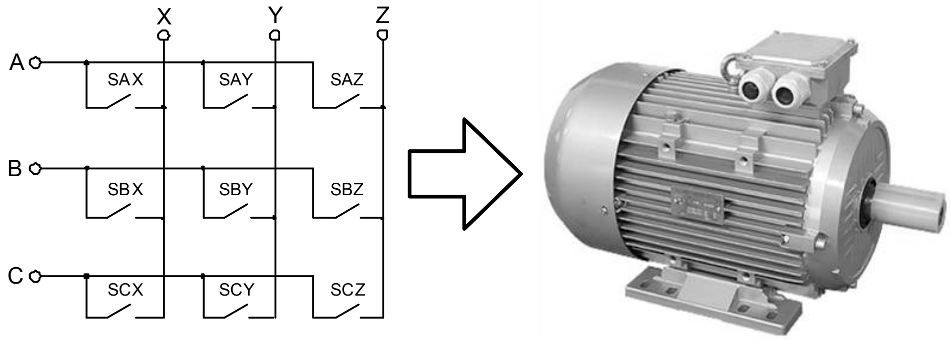


Fig. 2.1. Induction motor integrated drive concept with matrix converter

In this thesis the high level of device integration is not considered due to the existing technical and financial limitations of the research, yet the integration of power converter module of inside an induction motor (Fig. 2.1.) is considered.

2.2. CHOICE OF VOLTAGE AND FREQUENCY CONVERSION TECHNIQUE

The most significant task during the drive system development is the choice of frequency converter. Since this work is dedicated to integrated induction motor drive an appropriate frequency converter must be chosen from several well known converters. Most common frequency conversion techniques such as indirect or two-stage and direct are discussed in this section.

The most common technique in modern electrical drives is the indirect frequency conversion by implementation of voltage source inverters (VSI) shown in Fig. 2.2. These converters utilize two stage energy conversion: first, a rectification stage, that is, AC-DC conversion by implementation of a diode bridge (in case of one way energy flow) or a transistor inverter (in cases of bi-directional power flow) in the input; the second, DC-AC conversion by implementing voltage source inverter that utilize power transistors.

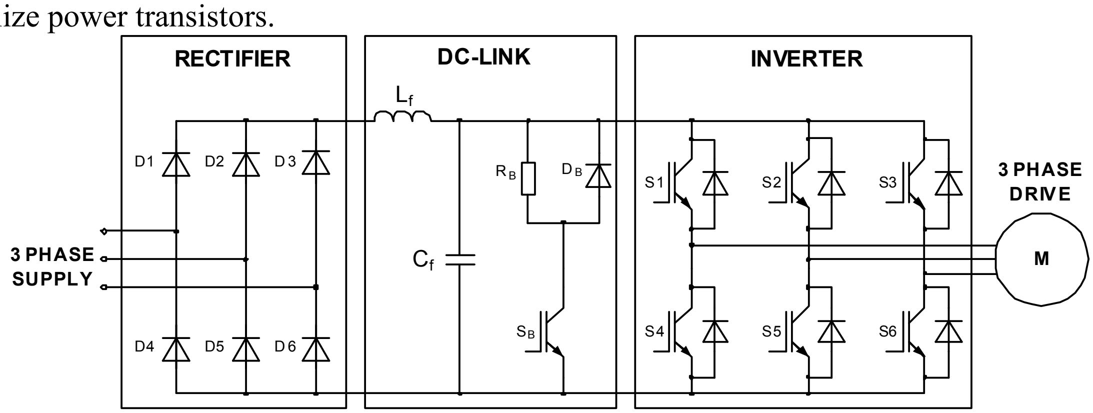


Fig. 2.2. Voltage source inverter schematic diagaram

In electric drive applications sinusoidal PWM (SPWM) is used to create sinusoidal output voltages. Typically bipolar SPWM is used when output voltage is modulated as discreet pulses of positive and negative DC-link voltages according to a neutral point. Output voltage and current waveforms of one phase of VSI are presented in Fig. 2.3.

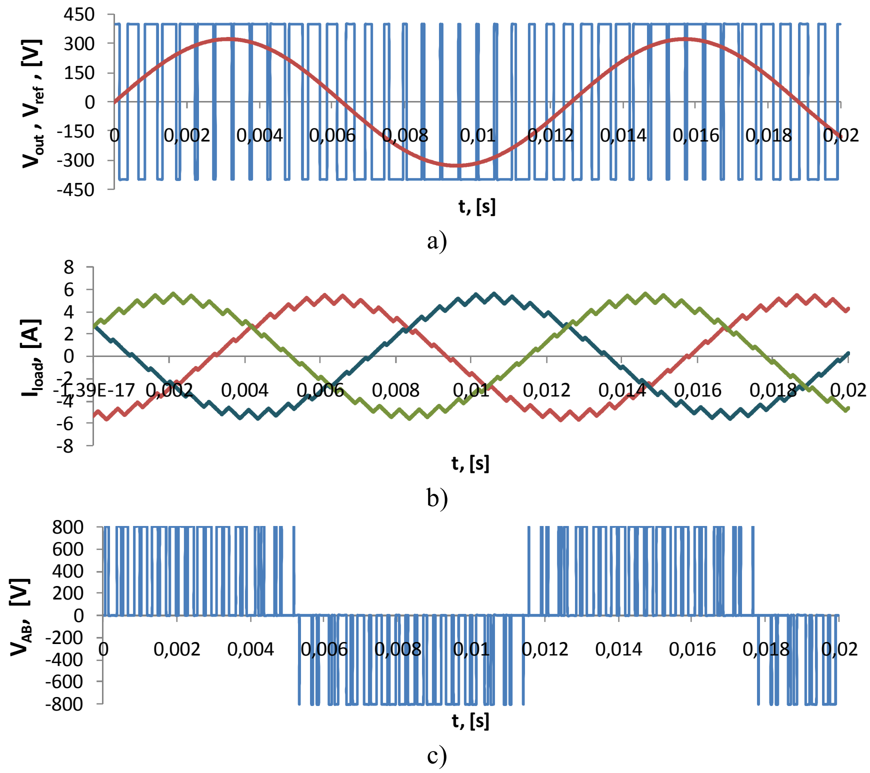
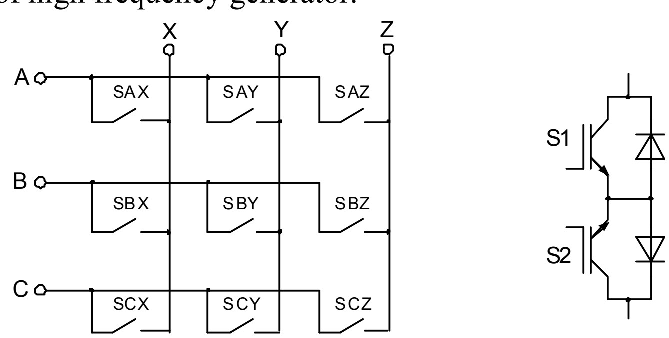


Fig. 2.3. VSI a) bipolar phase voltage (blue – SPWM, red – reference); b) three phase current; c) output line-to-line voltage

Basic structure of direct frequency converters (DFC), sometimes referred to as static direct frequency converters, consists of static power switches that allow direct connection of input terminals to any output terminal. The operation of DFC is based on usage of input waveform segments to create output waveforms with the desired fundamental frequency component. From a variety of DFCs, probably the most known is the classic cycloconverter.

Cycloconverters can be divided into naturally commutated cycloconverters (NCC) and forced commutated cycloconverters (FCC).

In NCC switches such as thyristors are naturally turned-off by the input AC voltages, this yields an output frequency control form 0 to 40% of the input frequency, which is a serious limitation in electric drive applications. A solution to this constrain is increase of input voltage frequency by use of high frequency generator.



a) b)

Fig. 2.4. Matrix Converter a) three-phase to three-phase topology, b) typical bi-directional switch

A typical forced commutated cycloconverter is a matrix converter (MC). The main element in matrix converter is a fully controlled bi-directional power switch.

Common three-phase to three-phase matrix converter (3x3 MC) consist of nine bi-directional switches, that allow connection of any input phase to any of the output phases (Fig. 2.4.). It is assumed that the MC operates with voltage sources on the input and current sources on the output. Because of bi-directionality of the converter it also can be supplied with current source on the input and voltage source on the output. Theoretically nine bi-directional switches give 2^9=512 state combinations.

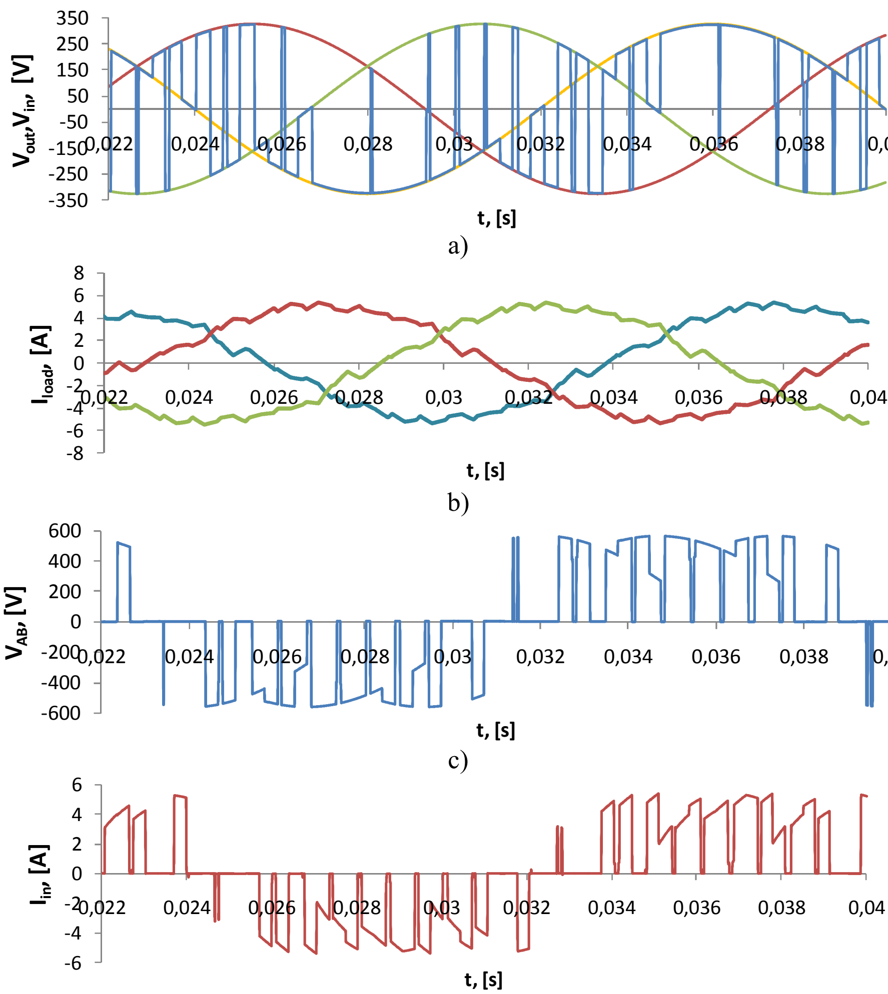


Fig. 2.5. Matrix converter a) output PWM phase voltage; b) three phase load current; c) output PWM line-to-line voltage; d) input current

Regardless control strategy two basic commutation rules state possible switch combinations. Since the converter is fed with voltage sources the input phases may never be shorted, that is, two switches of matrix converter may never be turned-on at the same time. Because MC feeds inductive load, the output current should never be interrupted due to the lack of static freewheeling path, that is, one switch per output phase should be turned-on at any time instant. Taking into account these rules, there are only 27 valid switch state combinations.

Main advantages of matrix converter over a conventional voltage-source inverter are: sinusoidal input current and output voltage with minimal harmonic distortions, full range input power factor control, inherent bi-directional power flow capability and there is no requirement for reactive energy storage elements that makes MC a compact device.

MC has also several disadvantages: it requires more power switching devices than conventional AC-DC-AC inverters, the voltage transfer ratio is limited to 0.866 and matrix converter is sensitive to the input voltage disturbances due to the lack of the energy storage elements.

Because of lack of energy storage elements in MC the output voltage is generated directly form the input voltages (Fig. 2.5). Voltage waveform in each phase is synthesized by sequential sampling of the input voltage. Likewise the input currents are directly generated by the output currents.

Converter Comparison

To make the right choice of power converter it is necessary to make several topology performance comparisons. The doctoral thesis covers several studies that regard different parameter comparison of matrix converter and other converter topologies. The main aim of is to introduce matrix converter as a potential solution in integrated drives.

Utilization of power semiconductor switches, power diodes, DC-link capacitors and clamp circuit estimation has been done. It can be concluded that despite the large number of semiconductor devices matrix converter is comparable to back-to-back converter in terms of reliability and output performance. Compared to three-level converter matrix converter has similar output results. The most significant privilege of matrix converter is a compact design without bulk passive components. Hence several studies [6], [27] – [37] approve that the matrix converter is suitable and can be implemented in integrated drive applications.

2.3. POWER SWITCHES IN MATRIX CONVERTER

Bi-directional switch topologies

One of the main problems of the MC is realisation of bi-directional switch. The key feature of a bi-directional switch is its capability of conducting current and blocking voltage in both directions.

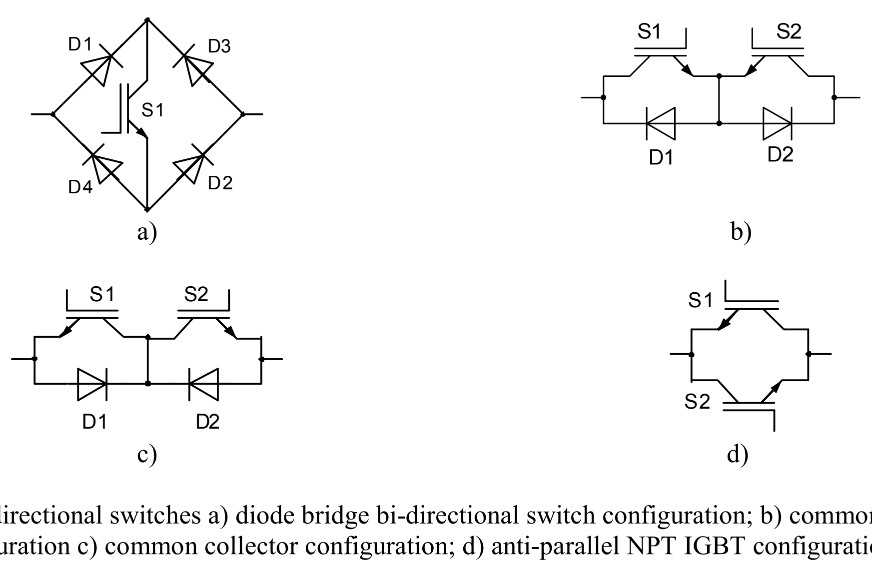


Fig. 2.6. Bi-directional switches a) diode bridge bi-directional switch configuration; b) common emitter configuration c) common collector configuration; d) anti-parallel NPT IGBT configuration

As bi-directional switch is still unavailable on the market, conventional unidirectional discreet devices are combined as a solution.

There are several possible topologies of bi-directional switch realisation. All of them have their advantages and disadvantages. However the most common bi-directional switch topology – common emitter is considered.

This arrangement implements two series connected IGBTs with anti parallel diodes (Fig. 2.6.b.) that ensure higher reverse voltage blocking capability of IGBTs. Its main advantage over diode bridge configuration is lower conduction losses due to lack of one diode in the conduction path configuration and it is possible to independently control current direction that allows safe commutation of load current and reduce commutation losses. It also has some disadvantages like higher number of gate drivers compared to common collector configuration and higher conduction losses compared to anti-parallel configuration. Despite that this configuration is considered in particular application and is built of discrete IGBTs with integrated anti parallel diode.

Bi-directional Switch Commutation Features and Techniques

Switch commutation in MC is more difficult to achieve than in conventional voltage source inverters due to the lack of natural current freewheeling paths. Since the main load is targeted to be active-inductive, the commutation process between switching elements must be controlled every time instant with respect to the two basic commutation rules mentioned before.

There are two simple commutation techniques – dead-time and overlap commutation, however they do violate commutation rules are require additional hardware components in order for the matrix converter to operate. More sophisticated commutation techniques do not violated these rules and take in to account either input voltage magnitude or output current direction. There is also commutation technique that takes into account both – input voltage magnitude and output current direction.

The idea of this method is to turn-on all switches conducting in the same direction as the load current flow. Commutation between phases can be achieved in one step by turning-off one or two switches simultaneously depending on the required switching state and the input voltage relative magnitude.

Despite the advantages from both voltage magnitude and output current direction commutation methods, it also inherits disadvantages form both, such as, input current disturbances caused by inaccuracies in input voltage measurement and commutation to the wrong input phase at zero crossing points of line currents; distortions of output waveforms at zero crossing points of the load current since only the switches that conduct in one direction are turned-on and there is no path for the current to reverse [46].

There are other commutation techniques such as soft commutation that involve resonant, zero voltage or zero current switching in matrix converter to reduce the losses and increase switching frequencies. These methods have their advantages and disadvantages and are well described in [16] and [47] – [50] and will not be discussed here.

Gate Drive Circuits of Power IGBTs

IGBT switching is determined by the rate of change of the gate-emitter voltage. Therefore the gate capacitance charge and discharge currents are essential. In order to make the commutation of power IGBT efficient and to reduce commutation losses, the gate current must reach the highest possible value. To amplify the logic signal a gate drive circuit (GDC) is required.

The GDC in this chapter are viewed in the context of development of integrated matrix converter drives. In this kind of drive solutions it is essential to keep dimensions of all devices as small as possible at the same time ensuring maximum efficiency and reliability. Several circuits are proposed in [51], [55] – [58]. Here the best solution that provides most gate charge and discharge current is quested. Potential GDC topologies are simulated in PSpice and then experimentally tested.

For particular application a double-fed half bridge topology is proposed. This circuit implements two voltage levels according to common node: +Vcc and –Vcc (Fig. 2.7.). In this case same output voltage levels are used for control source Vin. This usually is solved by use of an optocoupler with three terminal output.

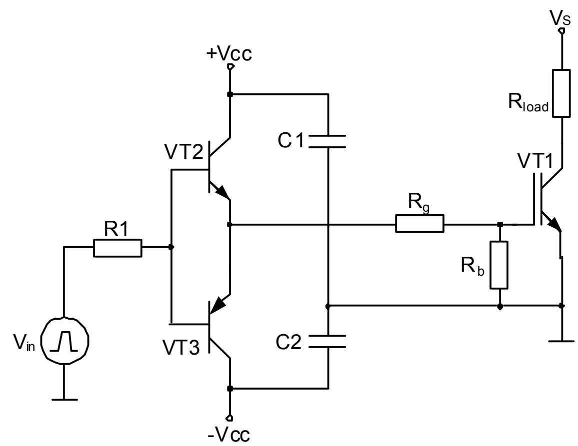


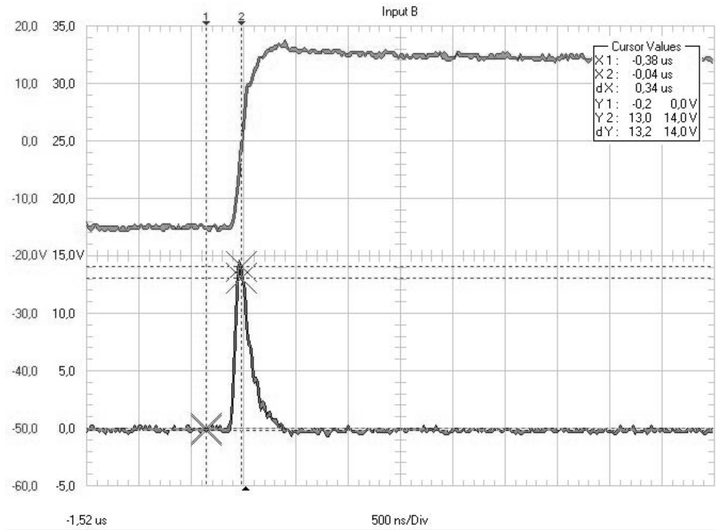
Fig. 2.7. Double-fed Half-Bridge topology

The operating principle relies on opposite switching of transistors VT2 and VT3 that connect VT1 base to positive or negative voltage according to neutral. This configuration requires minimum additional components: voltage dividing capacitors C1 and C2 and a balancing resistor Rb (usually of 10kΩ order), that is used to provide symmetrical voltage on C1 and C2 in each commutation period.

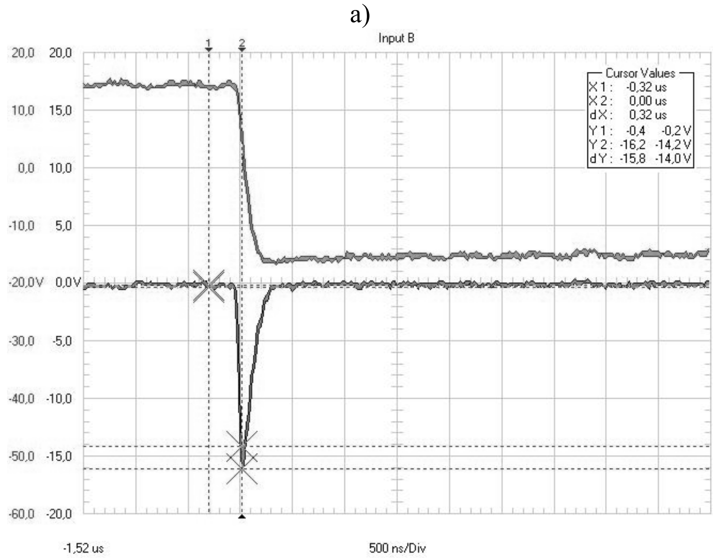
Main disadvantage is the two-level voltage that is necessary for this circuit operation that is not always convenient, but low number of active components and high gate current makes this circuit most attractive for driving power IGBTs.

From experimental results (Fig. 2.8.) it can be seen that this circuit provides 1.4A for approximately 600ns at turn-on and -1.6A for approx. 400ns at turn-off.

Simulation and experimental results as well as complexity of described GDC and other topologies are compared in Table 2.1. From this table it is obvious that the double-fed half-bridge GDC is not more complex than single-fed half-bridge topology. At the same time it provides as much gate current as the full-bridge one. Therefore the double-fed half-bridge GDC topology is preferable for particular use and will be used as a basis for further experiments.



a)



b)

Fig. 2.8. Experimental results of double-fed half bridge GDC a) at turn-on, b) at turn-off; from top gate-emitter voltage, gate current

Table 2.1.

Gate drive circuit comparison

Topology	Supply voltage	Complexity	Simulation		Experimental			
	VCC [V]; ΔVG [V]	% of max	Turn-on IG [A]	Turn-off IG [A]	Turn-on		Turn-off	
					IG [A]	t [ns]	IG [A]	t [ns]
Single-fed Half-bridge	+15; 15	53 (8)	0.9	-1.0	0.5	~300	-0.7	~300
Single-fed Full-bridge	+15; 30	100 (15)	1.70	-1.90	1.3	~500	-0.8	~750
Double-fed half-bridge	+/-15; 30	73 (11)	1.80	-2.20	1.4	~600	-1.6	~400

Active Gate Drive

Due to some parasitic inductances in commutation loop, that store energy, fast IGBT commutation can cause a dangerous overvoltage stress onto the power device that can sometimes destroy semiconductor junctions and permanently damage power transistor. In many cases sunubber circuits are used to damp excessive energy in snubber resistor. In context of integrated drive snubbers are not considered since require additional space and cooling.

In this section an alternative to snubber circuits is presented. This principle is based on specific IGBT commutation that on one the hand slows down commutation process but on the other hand improves commutation process by means of reduction of dangerous overvoltage spikes at power device turn-off. This of course yields higher commutation losses in the transistor itself. However these losses are transferred from external resistor of snubber circuit to transistor that dramatically reduces size, weight and cost of the converter.

Several papers have been published on active gate drivers [60] – [62] to mention some. Active gate drive principles are proposed, described simulated and experimentally in [63].

Passive gate current commutation technique influences gate current by reduction of gate current or increase of gate resistance. The comparison was done with 300V, 10A, 20kHz simulation test bench. The control voltage is applied to the power transistor directly through the gate resistor. This fixes the maximal value of the gate current at certain level.

Control simulation is done at given parameters and typical gate resistance of 10Ω. This yields overvoltage of 155V. Smaller negative supply voltage or bigger value of gate resistance will produce just slightly smaller overvoltage of 145V but at the cost of much slower switching process and, hence much bigger commutation losses.

Since the passive gate current control does not influence the turn-off process in any way except the level of the current magnitude, it does not give any considerable result. For this reason an active gate control is introduced.

Two-Level Active Gate Voltage and PWM Gate Voltage Commutations show better results since, turn-off process of power IGBT is influenced. However it is difficult to implement voltage controlled gate driver.

Principle of active gate current commutation technique is based on control of turn-off gate current during the active charge re-combination of IGBT p-n junctions. The difference from previous method is that this time gate voltage is not the key factor – instead the gate current is controlled (Fig. 2.9.) since it is the gate current that determines the gate capacitance charge and discharge rate. The first negative current pulse initiates the transistor turn-off. The length of this pulse is determined by the beginning of the turn-off process, current is reduced back to zero when collector-emitter voltage starts to rise. The second stage can be called “zero gate current” stage and it is similar to two-level gate voltage control when transistor turns-off naturally. However, here the gate voltage command is negative and not limited to threshold value. The third stage – final shut down – here another negative current pulse is generated to safely turn-off the transistor.

The result of such commutation control is reduction of overvoltage by 81% compared to passive gate current control at 10Ω gate resistance, yet maintaining the same commutation time.

This commutation method is easier to implement by means of digital control and discrete elements than by two-level voltage control.

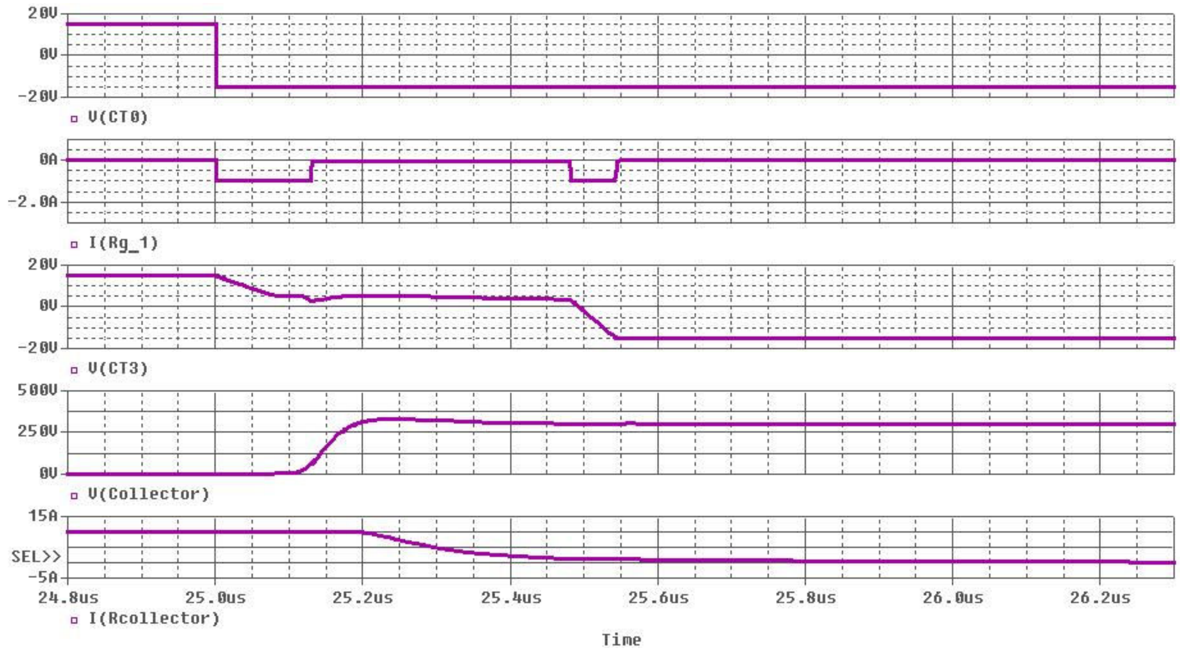


Fig. 2.9. Simulation results of IGBT turn-off with two-level gate current control

For better overview simulation results are summarised in Table 2.2. As it is obvious active commutation control has a significant influence on power loss in the transistor. This is the main issue when compactness is the key factor – compact design and higher commutation losses versus increased volume by snubber circuits. Besides snubbers too must be effectively cooled.

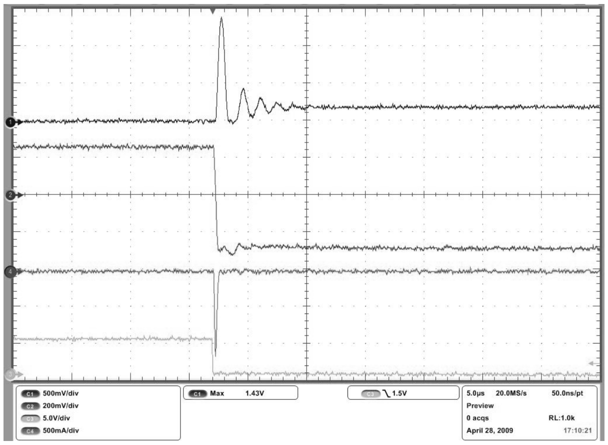
Table 2.2.

IGBT turn-off commutation comparison

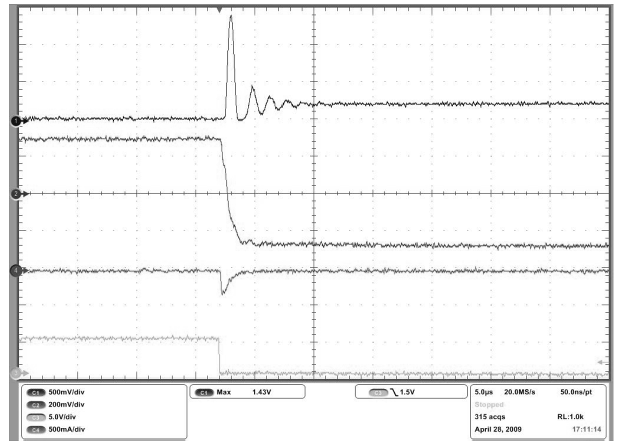
Approach	ΔV [V]	ΔT [ns]	ΔP [W]
Passive gate voltage @RG=10Ω	155	800	18
Passive gate voltage @RG=50Ω	145	1200	20
Two level gate voltage	55	700	26
Gate voltage PWM @100MHz	50	1000	27
Gate voltage PWM @40MHz	60	1300	27
Two level gate current	30	800	25

Laboratory test bench has been built for experiments with active two-level gate current control GDC. Experiment conditions: load resistance of 100Ω, load inductance – 56mH, input voltage – 100V, commutation frequency – 5kHz.

Control tests were done with double-fed half-bridge GDC at two different gate resistance values. First R_G = 10Ω was chosen. Second control test was done with R_G = 50Ω̃ Experiments are done at active-inductive load without freewheeling diode of power IGBT.



a)



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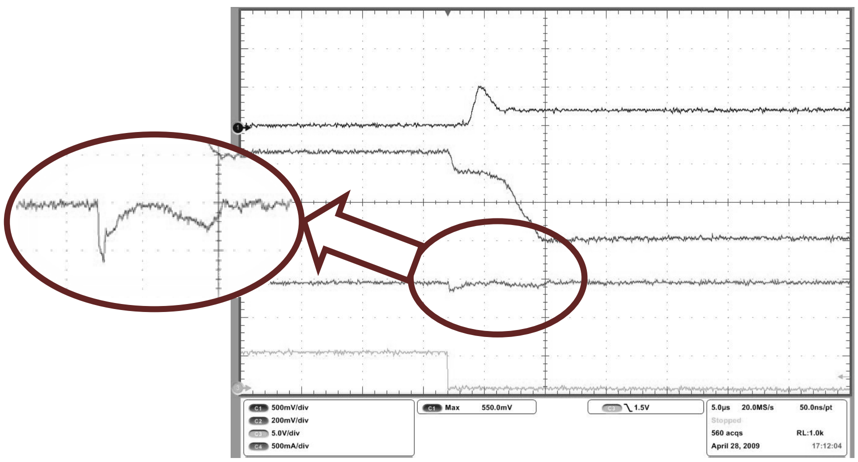


c)

Fig. 2.10. Experimental results of a) passive gate current control commutation at $R_G = 10\Omega$; b) passive gate current control commutation at at $R_G = 50\Omega$; c) active two-level gate current control commutation
From top: collector-emitter voltage, gate-emitter voltage, gate current, control comand

Experimental results approve the inefficiency of increase of gate resistance to minimize the overvoltage (Fig. 2.10.a and b.). In both cases the overvoltage ΔV reaches 650V. Though, active gate current control has shown considerable results (Fig. 2.10.c) – the overvoltage spike is reduced by 85% to 100V level. As it was mentioned before this improvement is achieved at the cost of much slower commutation. The improvements in system speed must be done in order to implement it in any converter with commutation frequency higher than 5kHz. However this method is more space efficient since it does not implement any power devices. Instead the control of power IGBT gate current is implemented in low power side. Compared to snubber circuits this is much more convenient reduction method since other (short circuit and emergency shutdown) protections of power transistor can be implemented.

2.4. CONDUCTOR SYSTEM IN MATRIX CONVERTER

The best way to reduce undesired effects of fast commutation is a proper design of power converter topology. In this section overvoltage occurrence is stated and basic principles and calculation of inductances are given. The most promising bus bar conductor configurations are analyzed. Special attention is paid to implementation of bus bars in matrix converters and to integrated induction motor drive.

Generalized Configuration of Conductors

By definition bus-bars (sometimes busbars) are thick strips of copper or aluminium that conduct electricity within a switchboard, distribution board, substation or other electrical apparatus [64] or as in [65] bus bar is an electrical conductor that makes a common connection between several circuits.

In this work term bus bar refers to low inductive laminated copper plates that are insulated one form another with thin insulation material that withstands maximum voltage that is possible between bus-bars. Such bus-bar system can be used in voltage source inverters in DC-link [66] to minimize the parasitic inductance of the conductors.

If the current changes, an EMF is generated within the wire causing currents that oppose the change. Although numerically small, inductance of a straight conductor is not always negligible. For example, in the hard-switching converters high values of load current must be commutated at high frequencies – reduction of current to zero in a short time. Since the energy stored in the magnetic field of the conductor must be dissipated, a dangerous overvoltage can occur across the semiconductor device. The self induced voltage is proportional to the rate of change of current [70] – [73]:

$$V=L(di/dt). \qquad (2.1)$$

To avoid this, the stray inductance of wires in the commutation loop must be reduced. This can be achieved by reduction of the length or change of the shape and layout of the conductors.

Usually any electrical circuit produces a current loop that consists of at least two wires – positive and negative or ground. This must be taken into account when calculating wire inductances.

The numerical estimation of coupled conductors was done in MatLab. The inductance of different conductor configuration as function of conductor dimensions versus distance between conductors is shown in Fig 2.11. Dashed line shows analytical values of inductance of given shape conductors when distance between conductors is much larger than conductor width. It is also common that lowest possible inductance can be achieved when distance between conductors is much smaller than dimensions of conductors. First, inductance of two round conductors (red line) was analyzed. This kind of electric system has logarithmic character, minimal value of inductance at d/a = 1.72 is over 5.95µH/m. Second, two flat conductors placed one next to other (Fig. 2.11. blue line). In this case inductance has linear character, and minimal value of inductance that can be achieved at d/a = 0.067 is 5.56µH/m. Third, coaxial conductor (Fig. 2.11. magenta line) was analysed and in this case, as in round conductor case, the inductance has logarithmic character, and the lowest possible value of 0.99µH/m is achieved at d/a = 1.52.

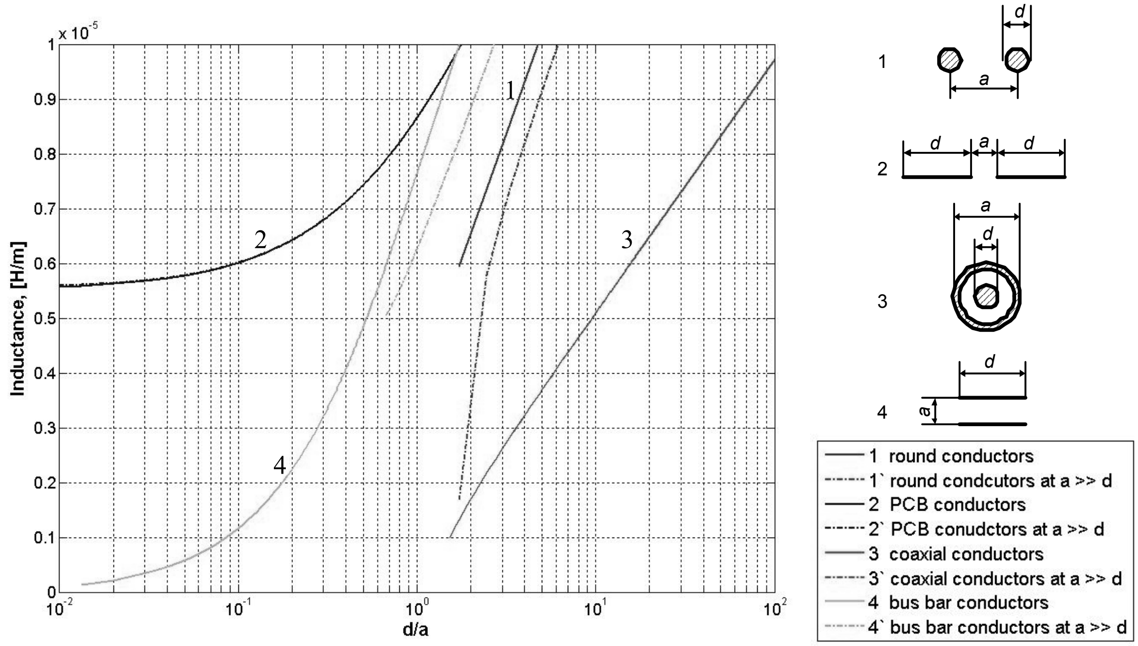


Fig. 2.11. Theoretical inductance characteristics of different conductor shapes

Finally, inductance of two parallel conductors placed on top of each other – like bus bar configuration, (Fig. 2.11. green line) was analysed. In this case the lowest inductance can be achieved 0.14μH/m at d/a = 0,013.

Results of this analytical calculation show that bus bar conductor configuration has the lowest inductance characteristics; hence by implementation of bus bars in converter, the stray inductance is reduced naturally.

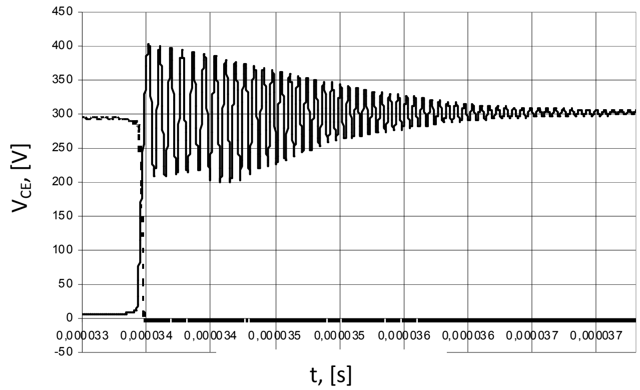
In order to estimate the influence of parasitic inductance in commutation loop of matrix converter a simple PSpice model of one commutation cycle was created and simulated. Magnitudes of parasitic inductances were freely chosen in range from 500nH to 50nH that are probable values for different shapes of conductors.

Simulation assumes commutation for one output phase from one switch to another during which the third switch in another output phase is fully turned-on. During four step commutation sequence current in phase A is transferred to phase C maintaining the same load current direction.

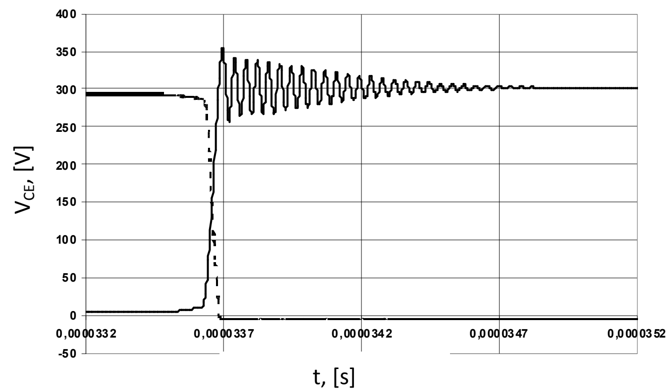
Simulation results presented in Fig. 2.12.a demonstrate overvoltage and voltage ringing at parasitic inductance of 500nH. The value of voltage overshoot reaches 400V, the total value of overvoltage is 100V. The transient time of this commutation is around 2μs. As consequence the power devices are brought under serious voltage stress and can be disrupted if underrated.

Next simulation was done at a 5 time lower parasitic inductance value – 100nH. This time the overvoltage decreased dramatically (Fig. 2.12.b), the voltage overshoot reached 350V that was 50V overvoltage spike and transient duration around 1μs.

Finally simulation of bi-directional switch commutation of MC was done at 50nH (Fig. 2.12.c). From simulation results it is seen that at switch turn-off the voltage overshoot reached 325V – the overvoltage was 25V and transient time decreased to 0.2μs.



a)



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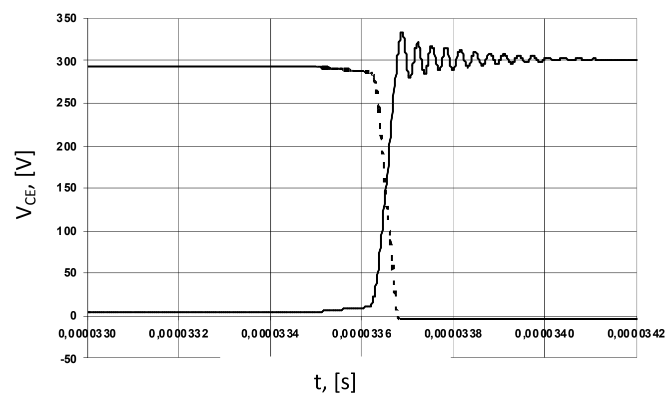


b)

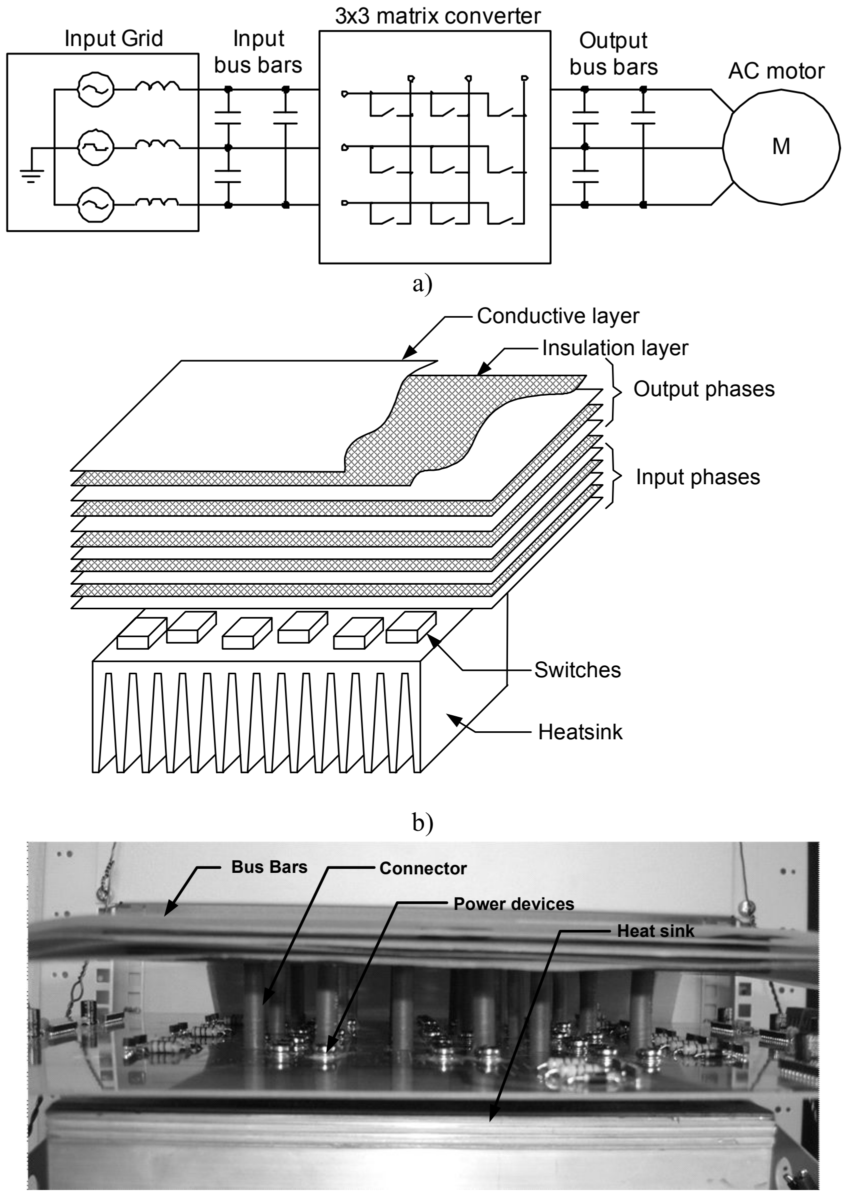
Fig. 2.12. Matrix converter commutation overvoltage a) at 500nH; b) at 100nH; c) at 50nH; solid line – collector-emitter voltage of VT_AX, dashed line – collector-emitter voltage of VT_CX

From these simulation results it can be concluded that even at first glance insignificant inductance in the commutation loop of matrix converter has negative effect on commutation process, creating dangerous overvoltage and voltage ringing. This can be eliminated if parasitic inductance is reduced by means of proper design of power converter by keeping power leads and connections as short as possible and implementing conductor design that yields lowest possible inductance.

General Features of Bus Bars for 3x3 Matrix Converter

In the MC there is no explicit DC-link, but there are three possible commutation contours related to the same output. For this reason conductor system must consist of three conductors that are placed together in such a way that they create three commutation loops and three equivalent capacitors. Power semiconductor devices must be placed as close to bus bars as possible to eliminate additional stray inductances in connection wires.

In earlier research [74] it has been proposed to apply planar bus bar construction to the input and output of matrix converter (Fig. 2.13.). There are in total six layers of conducting copper plates, one for each input and output phase.

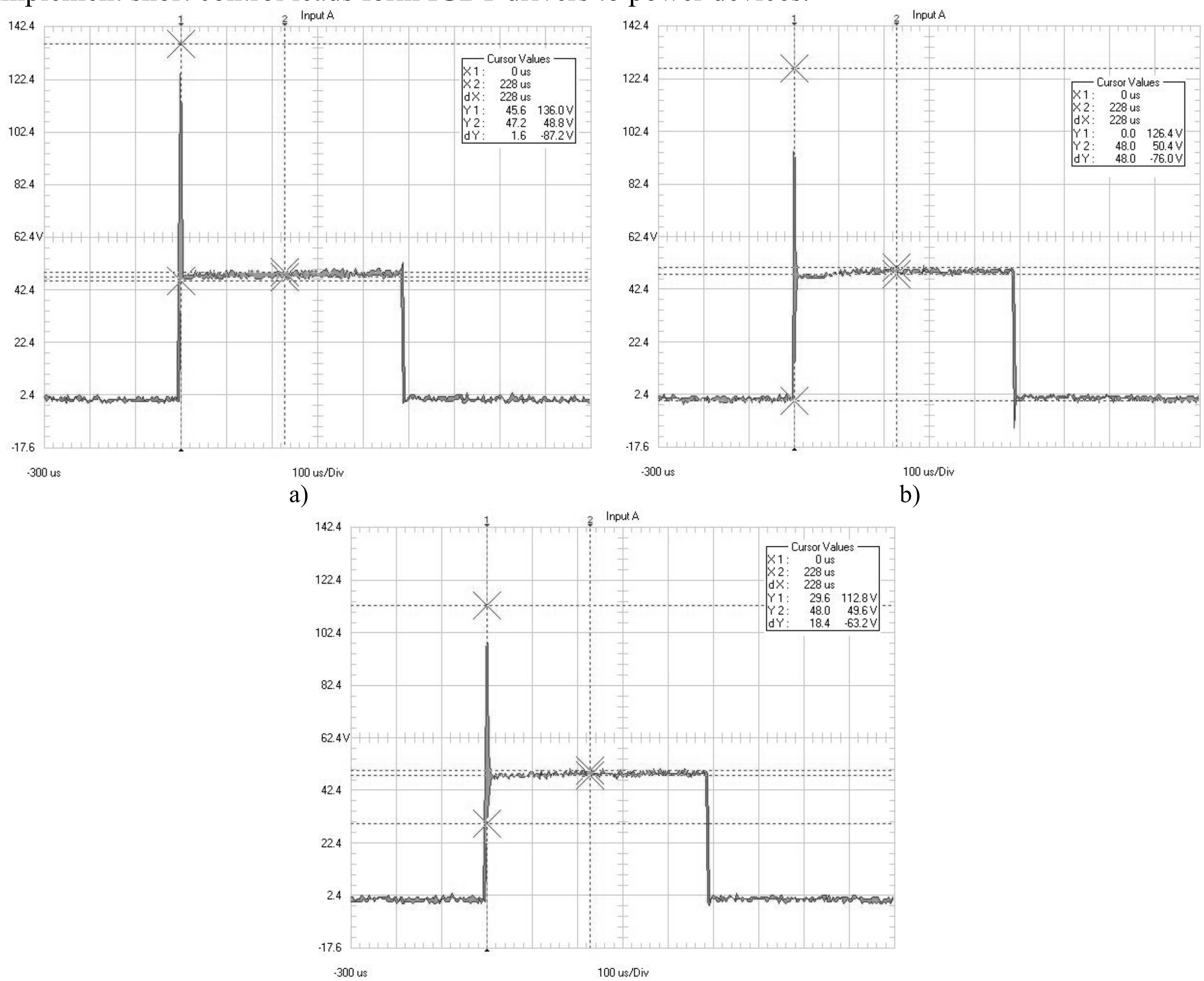


c)

Fig. 2.13. Planar bus bar system for 3x3 matrix a) principal schematic, b) sketch drawingh, c) laboratory prototype

Due to the fact that the converter can be reversed (it can deliver energy from the load back to the grid), bus bars can be placed on the output as well as on input phases.

However in practice this system has several drawbacks some of them are: long connection screws between conductive plates and power devices that increase the total parasitic inductance of the commutation loop. The most significant drawback is unsymmetrical equivalent bus bar capacitance distribution between input or output phases. In this configuration it is difficult to implement short control leads form IGBT drivers to power devices.



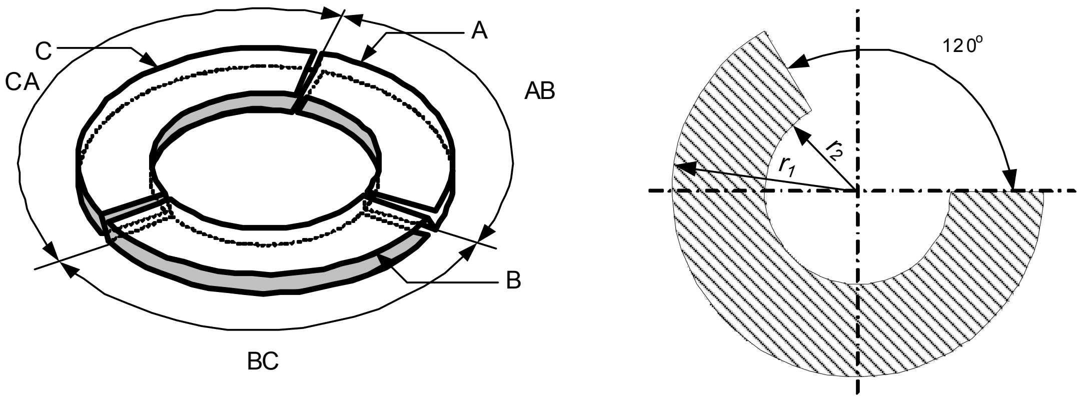
c)

Fig. 2.14. Experimental results of switch commutation: a) without bus bars; with implementation of planar bus bar construction: b) more distant conductors, c) closest conductors

Experiments were done to estimate the influence of bus bar on commutation process in matrix converter (Fig. 2.14.). The effect of bus bar for particular placement of transistors was rather evident – the overvoltage spike ΔV without bus bars was 87V; if there was another copper plate between conducting bus bars the result was ΔV = 67V; if two closest conductors created bus bars, the overvoltage ΔV is 63V – which means the overvoltage can be reduced by 28% without using of any auxiliary overvoltage suppression equipment.

Better results can be achieved if switching devices are placed directly on the bus bar construction, avoiding any circular connection leads. However this bus bar construction does not give any symmetry between phases – this yields unsymmetrical overvoltage reduction.

In order to create symmetrical system bus bars must be placed in such a way that each conductor plate equally overlaps the other two. There are several bus bar constructions such as star, delta and hexagon that are proposed and described in [76] – [80]. However, most suitable for integrated drive application is considered planar disc configuration. Bus bars can be produced of flat conductor rings or even PCB design in case of low power applications can be considered (Fig. 2.15.).



a) b)

Fig. 2.15. Planar disc bus bar configuration a) 3D layout; b) top view of one conductor

In this case each conductor is produced in shape of 240° flat ring sector. Conductors of each phase overlap 120° hence creating one bus bar. Bi-directional switches can be split into three groups as in the case of star and delta configurations, and placed over each bus bar sector.

Since this is a flat ring construction it can be implemented it in front or back of AC machine without losing much space. This configuration is considered as the best solution for integrated drive system.

To make a comparison between bus bar constructions their physical dimensions are compared. In this case circular bus bar configuration is taken as basis for calculations. In other configurations length, that yields the same area and inductance must be calculated. In particular case circular configuration is produced of multilayer board (copper and FR4 insulation material) with physical parameters listed in Table 2.3.

Table 2.3.

Physical parameters of bus bar construction

Parameter	Designation	Units	Value
Outer Radius	r1	mm	65
Inner Radius	r2	mm	9
Overlap angle	α	o	120°
Length (average arc)	l	mm	201.1
Width	c	mm	64
Area	S	m2	$7.04\cdot10^{-4}$
Distance between conductors	d	µm	35
Conductor thickness	b	µm	35
Magnetic permeability	μ_o		$4\cdot\pi\cdot10^{-7}$
FR4 dielectric constant	k		4.7
Permeability of air	e_o		$8.854\cdot10^{-7}$

Such parameters yield inductance of $L_{bb} = 2.3158 \cdot 10^{-9}$ H and equivalent capacitance of $C_{ebb} = 4.1852 \cdot 10^{-10}$ F. In comparison two round conductors with the same length and cross section yield: $L_{rc} = 2.5834 \cdot 10^{-7}$ H and average equivalent capacitance $C_{rc} = 2.7324 \cdot 10^{-12}$ F.

To achieve the same inductance with other bus bar configurations (planar, star or delta) as in the case of planar disc, it is necessary to have same conductor area S. If width c of conductors is considered to be fixed then the length of conductors is also fixed and one side of each bus bar must be 201mm long. However if the width of conductors is changeable, the length can be decreased, but at the cost of much wider conductors. For this reason other bus bar configurations are not considered in integrated drive application since they lack compact design.

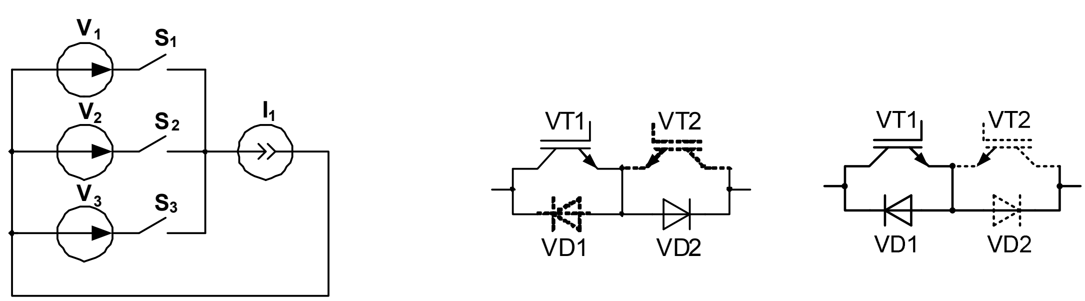
2.5. THERMAL ANALYSIS OF POWER PART

To provide cooling of semiconductor devices assessment of power losses in MC power part must be done. In this thermal analysis only the common emitter bi-directional switch (described in more detail in Chapter II Section 3) is considered since it is most common configuration and is used in this particular case.

Power Losses in Matrix Converter

As in any commutated converter power losses in MC consist of conduction losses and commutation losses. Conduction losses are proportional to forward voltage drop across the semiconductor device and the current flowing through the device. The forward voltage drop is dependent on the current flowing through the device and its junction temperature. Due to this interdependency the calculation of losses, temperature and electric parameters of the switches has to be iterative. In general cases conduction losses per bi-directional switch are composed of conduction losses in IGBT and in corresponding conducting diode.

Commutation losses in IGBT occur due to finite switching time during which device changes its state. Commutation losses are proportional to commutation frequency at which device operates, and these losses are junction temperature dependent that makes iterative loop between electric parameters, losses and junction temperature of the switch more complex.



a) b) c)

Fig. 2. 16. Equivalent schematic of a) one output phase of MC; b) bi-directional switch during static period; c) bi-directional switch during dynamic period

For loss calculation in MC a simplified scheme of three voltage sources – representing input side, and one current source – representing output side can be used (Fig. 2.16.a.). Assumptions regarding switch commutation must be done: each switch is conducting one-third of the period for each output phase, commutation pattern is neglected and commutation is performed at line-to-line peak voltages. Loss calculation is split in to static period of conduction losses (Fig. 2.16.b) and dynamic period of commutation losses (Fig. 2.16.c.).

Total voltage drop across conducting IGBT can be calculated as sum of collector-emitter saturation voltage V_{CES} and collector voltage drop:

$$V_{CE} = V_{CES} + I_C R_C, \qquad (2.2)$$

where i_C is collector current, R_C – collector on-state resistance. The same approximation can be applied for the conducting diode:

$$V_D = V_{f0} + I_f R_D, \qquad (2.3)$$

where V_{f0} is diode zero-current on state voltage (diode forward voltage drop), R_D – diode on-state resistance, and I_f – diode forward current. These parameters can be read from the device datasheet [81].

Conduction losses of MC can be approximated as:

$$P_{loss\ con\ tot} = \sum_{n=1}^{3} \left(\frac{(V_{CESn} \cdot I_{Cav\ n} \cdot d_k) + (V_{fn} \cdot I_{fav\ n} \cdot d_k)}{3} \right) \approx I_C \cdot (V_{CES} + V_f) , \qquad (2.4)$$

where n is number of phases, d – duty cycle for nth period of PWM.

Commutation losses of bi-directional switch consist of turn-on and turn-off energy losses of IGBT and reverse recovery energy losses of anti parallel diode (Fig. 2.15.c) and for all output phases are calculated as sum of products of commutation frequency and total switching energy losses per commutation period:

$$P_{loss\ com\ tot} = \sum_{n=1}^{3} \frac{f_{com} \cdot E_{com\ tot}}{3} . \qquad (2.5)$$

Total power losses in the MC are expressed as the sum of total conduction and total commutation losses:

$$P_{loss\ tot} = P_{loss\ con\ tot} + P_{loss\ com\ tot} . \qquad (2.6)$$

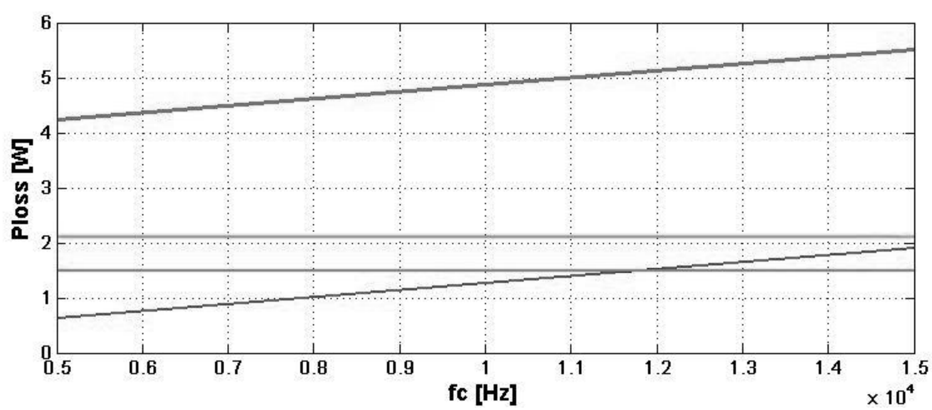


Fig. 2.17. Power losses of Matrix Converter;
From top: total power losses, IGBT conduction losses, diode conduction losses, commutation losses

Total power loss of each component in MC as a function of frequency is shown in Fig. 2.16. This graph is calculated in MATLAB for the particular case of 0.3kW converter using STGB10NC60HD IGBT transistors with integrated ultra-fast-recovery anti-parallel diode.

In [82] a method of reducing the converter losses is proposed. It is achieved by reduction of the number of switch state changes that produce switching losses.

In this study only estimation of power losses in MC is done. For more detailed study of losses in MC switch state function in each time instant must be taken in to account. That is a topic of further research.

Thermal considerations

Safe operation of power semiconductors is limited by maximum allowable power dissipation. Power dissipation is the cause of junction temperature rise that yields chemical and metallurgical changes of semiconductor structure. Too much excessive heat due to losses destroys transistor junction, but over dimensioned cooling system does not allow compact design of the converter. This is why tradeoff between good cooling and compact design must be found.

The heat generated in semiconductor structure flows to the surrounding matter from junction to case and from surface of case heat is lost by convection or radiation. Another heat path is from junction to copper base, then to heat sink and then to the environment. On the surface of heat sink the heat is dissipated to the surrounding environment by convection or radiation or is further conducted to the liquid cooling system.

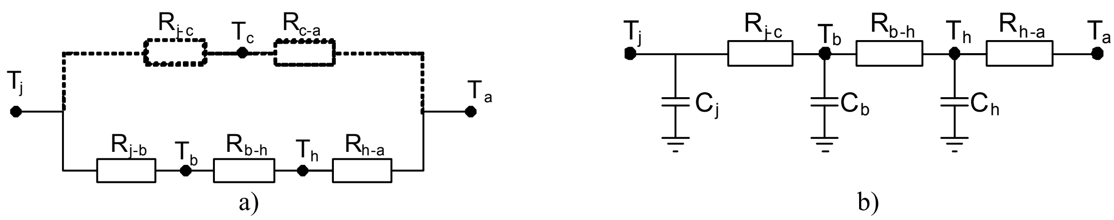


Fig. 2.18. Thermal equivalent circuits for a) steady state heat flow; b) transient operation

Heat conduction path can be described with equivalent circuit of thermal resistances since each material has specific thermal properties. For steady state operation (Fig. 2.18.a) the equivalent circuit contains junction-to-base $R_{j\text{-}b}$, base-to-heat sink $R_{b\text{-}h}$ and heat sink-to-ambient $R_{h\text{-}a}$ thermal resistances in parallel with junction-to-case $R_{j\text{-}c}$ and case-to-ambient $R_{c\text{-}a}$ thermal resistances. In practice since $R_{c\text{-}a}$ is of large value and heat dissipated through this path is negligible – this branch may be ignored. In dynamic heat dissipation, for instance in PWM operation mode, higher peak power dissipation is permitted. Since materials in power transistors have a definite thermal capacity, thus the critical junction temperature will not be reached instantaneously (Fig. 2.18.b). The extension limit is determined by operating frequency and duty cycle of the switch.

To determine cooling conditions of MC, the layout of power devices must be defined. In particular study of integrated drive system and with application of bus bar structure several power circuit layouts are proposed.

Orientation of power converter inside the motor housing is relevant since determines total thermal resistance and hence the cooling capabilities. Two potential power converter placement arrangements are considered: power devices fitted onto motor housing (Fig. 2.18. a) and PCB fitted on the motor housing (Fig. 2.18. b).

Thermal resistance from converter part that is located closer to motor windings to ambient is considered to be much higher than that to cooled side and is not considered here.

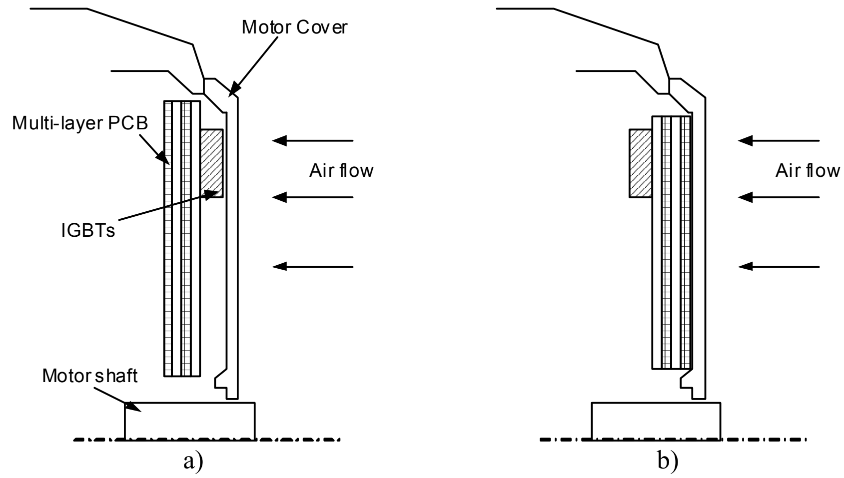


Fig. 2.18. Power board placement on the cooled area of induction motor a) transistor-to-cover, b) bus bar-to-cover

A 6 layer multi-layer PCB (MLPCB) is used for bi-directional switch interconnection and bus bar construction. In MLPCB production copper (Cu) and glass reinforced epoxy FR4 laminate sheets are used. These materials are considered for cooling condition estimation. Material and device thermal properties are listed in Table 2.4.

Thermal resistance of any material is calculated as:

$$R_{th} = a/(G_{th}S), \tag{2.7}$$

where a is thickness, G_{th} – thermal conductivity and S – area of the material. In particular application earlier mentioned materials with physical parameters defined in Chapter II Section 4.2.are used for thermal calculations.

Table 2.4.

Thermal conductivity of materials and devices in planar circular bus bars

Material/Device	Gth,[W/°C·m]	a, [m]	S, [m^2]	R_{th}, [W/°C]
Cooper	380.00	$35\cdot10^{-6}$	0.013	$7.075\cdot10^{-6}$
FR4	0.27	$35\cdot10^{-6}$		0.01
Total bus bar	-	$3.85\cdot10^{-4}$		0.0498
Aluminium	190.00	0.003		$12\cdot10^{-4}$
Silicon paste in tc configuration	0.30	$50\cdot10^{-6}$	0.0014	0.1157
Silicon paste in bc configuration			0.013	0.0128
IGBT/Diode $R_{th\ jb}$	-	-	-	2.08
IGBT/Diode $R_{th\ jc}$	-	-	-	62.50

Total thermal resistance of transistor-to-cover configuration (Fig. 2.18.a) is a sum of all thermal resistances for particular case:

$$R_{th\ tot\ tc} = R_{th\ jc} + R_{th\ cp} + R_{th\ ph} + R_{th\ ha} = 62.50 + 0.1157 + 12\cdot10^{-4} + R_{th\ ha} = 62.6169 + R_{th\ ha}$$

Total thermal resistance of bus bar-to-cover ($R_{th\ tot\ bc)}$ configuration (Fig. 2.18.b) is:

$$R_{th\ tot.bc} = R_{th\ jb} + R_{th\ BB} + R_{th\ Bp} + R_{th\ ph} + R_{th\ ha}$$
$$= 2.08 + 0.0498 + 0.0128 + 12 \cdot 10^{-4} + R_{th\ ha} = 2.1438 + R_{th\ ha} \left[\frac{W}{^oC}\right].$$

$R_{th\ ha}$ is a heat sink to ambient thermal resistance that is dependent on cooling conditions – natural convection or forced cooling. In this particular study forced air cooling is considered. For the particular design of aluminium motor cover thermal resistances are listed in Table 2.5.

Table 2.5.

Heat sink to ambient thermal resistances at different cooling conditions

Cooling Conditions	Rth ha [W/^{o}C]
Natural Convection	5.00
Forced air cooling at 1 m/s	2.60
Forced air cooling at 2 m/s	1.80
Forced air cooling at 5 m/s	1.20

Using these numbers junction temperature can be calculated as:

$$T_j = P_{loss\ tot}\ T_{th\ tot} + T_{amb}, \qquad (2.8)$$

where T_{amb} is ambient temperature varying from 25^{o}C to 50^{o}C.

Maximal junction temperature is determined by the properties of silicon crystal. For particular power devices this temperature is determined to be 150^{o}C. However operation at maximum junction temperature dramatically reduces the lifetime of the device. For this reason safe operation of IGBT in this case is considered to be at 120^{o}C.

It is evident that transistor-to-cover configuration is not acceptable since at nominal load, ambient temperature 25^{o}C and forced air cooling 5 m/s junction temperature reaches 326^{o}C.

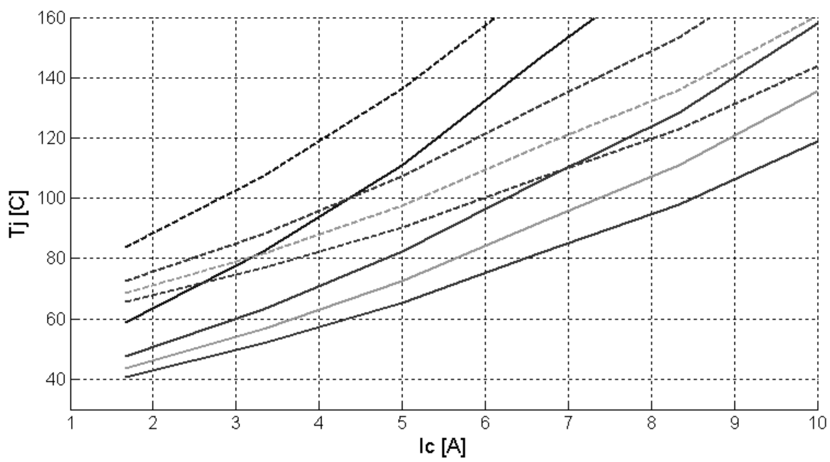
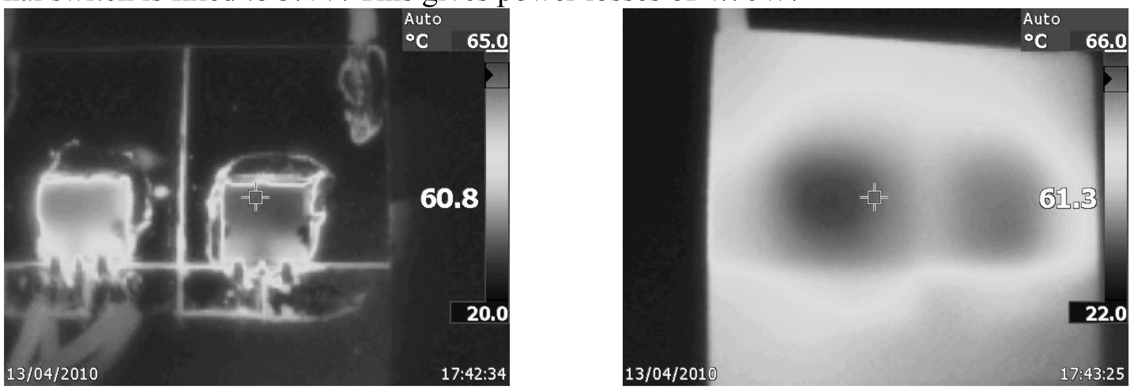


Fig. 2.19. Junction temperature as function of collector current at different cooling conditions;
From top: natural convection, forced cooling at 1m/s, forced cooling at 2m/s, forced cooling at 5m/s;
Solid line at ambient temperature 25^{o}C, dashed line at ambient temperature 50^{o}C

Junction temperature as function of collector current at different cooling conditions with bus bar-to-cover configuration can be plotted (Fig. 2.19.). Such configuration ensures proper semiconductor cooling even at 4A operation, natural convection and ambient temperature 50^{o}C. Nominal motor current is 1.24A this is 3 times less than permissible collector current. Despite good cooling characteristics of power semiconductors in bus bars-to-cover configuration, forced air cooling must be introduced in order to provide sufficient cooling of the whole drive system. Since in this case temperature of motor windings and rotor is not taken in to account, total cooling conditions may be deteriorated. In fixed speed induction motors cooling of the machine is performed by a ventilator that is fixed on the shaft of the machine. However in variable speed drives it is important to ensure motor cooling at low RPM.

Experiments are carried out in current conduction mode at 1.4A when one IGBT is commutated at 13kHz frequency and 50% duty cycle. In this case the voltage drop across the bi-directional switch is fixed to 3.4V. This gives power losses of 4.76W.



a) b)

Fig. 2.21. Temperature of a) bi-directional switch at 1.4 A at commutation frequency 13 kHz; b) back side of PCB

Case temperature of experimental bi-directional switch is captured and is presented in Fig. 2.21. As expected, conduction and commutation losses of intrinsic diode are lower than in IGBT hence it has lower case temperature. In MC the conduction in bi-directional switch is determined by output current polarity which means that in one modulation cycle both transistors conduct the same amount of time.

Power loss and case temperature estimation of one bi-directional switch of matrix converter has been done. Both numerical calculation and experiments approve that in particular case temperature of power switches of MC in nominal operation mode does not exceed permissible limit even with natural convection cooling.

2.6. OTHER DRIVE ELEMENTS

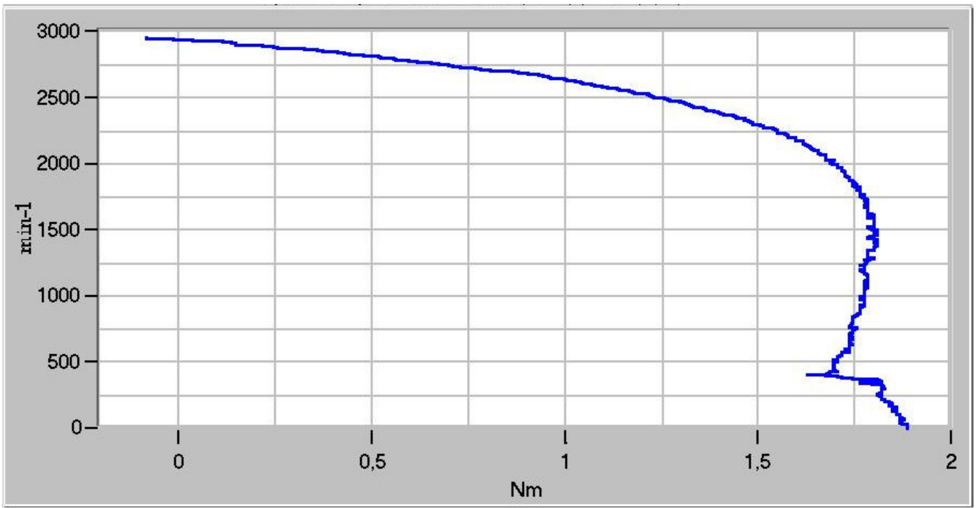
In order for the whole drive system to operate. additional circuits such as input filter, low voltage power supplies, voltage, current and shaft speed measurement are required. Auxiliary power supplies for power IGBT gate drive and low voltage power supply. Input filters ensure higher harmonic filtering and conducted EMI proper attenuation. Protection circuits are required for MC safe operation during fault conditions on the input or output of the matrix converter. Finally to perform Space Vector modulation and ensure save MC switch commutation electrical measurement circuits are required.

Description and parameter calculation of these circuits for particular application is done in doctoral thesis in chapter II section 6.

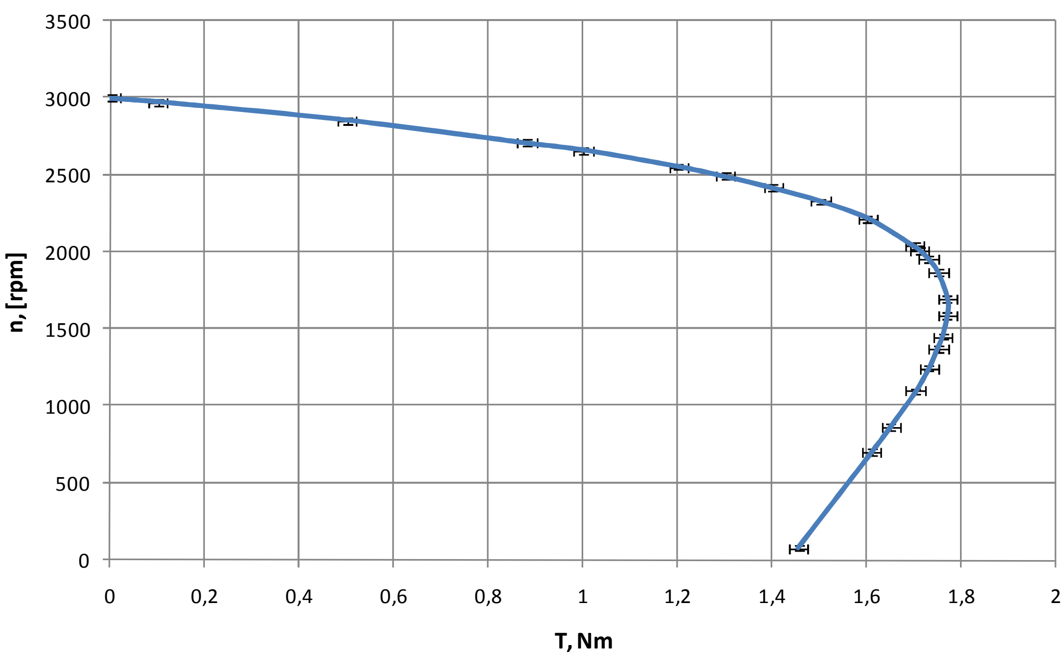
2.7. INDUCTION MOTOR AND PARAMETER EXTRANCTION

In doctoral thesis chapter II section 7 induction motor parameter extraction is described and experiments are performed. For particular test bench development a Siemens 3 phase squirrel cage motor was chosen (catalogue number: 1 LA5063-2AA10). Tests are performed according to [95] – [97] on HPStest bench in laboratory of electrical drives in the Institute of Industrial Electronics and

Electrical Engineering. Result verification by means simulation in Matlab Simulink is done (Fig. 2.22.).



a)



b)

Fig. 2.22. Induction motor mechanical characteristic a) experimental; b) simulated in MatLab Simulink

Simulation and experimental results are comparable and parameter extraction has been performed with satisfactory precision. Nominal operation point at shaft speed 2720 rpm and load torque 0.88 Nm has 0.6% error boundary in both simulation and experimental results.

2.8. CONTORL SYSTEM

In doctoral thesis Chapter II Section 8 several most common control of strategies are described.

The whole control system can be divided into two major parts – the control system of induction machine that deals with the space vector modulation to ensure proper operation of the motor, and the matrix converter control part that provides the correct commutation of the switches and switch state calculation in order to ensure the correct output vector for motor control.

Description of control algorithms of matrix converter includes: analytical description of matrix converter, modulation strategy – optimum output voltage, scalar, indirect, direct and space vector modulation description. For induction motor scalar and vector control principles are described.

2.9. EXPERIMENTS WITH INDUCTION MOTOR AND MATRIX CONVERTER

Experiments with matrix converter drive system have been carried out in the Laboratory of Electrical Drives of Institute of Industrial Electronics and Electrical Engineering. Experimental setup consists of HPS laboratory test-bench for loading experimental motor and torque measurements; matrix converter; matrix converter control unit; and measurement equipment: Fluke Scope and Fluke Mains Analyser (Fig.2.23.).

Matrix converter input and output voltage and current waveforms at 50Hz output are presented in Fig. 2.24. loaded with induction motor that operates at nominal load torque.

Unfiltered output voltage and current waveforms are presented in Fig. 2.25. to show MC high frequency PWM.

Three phase voltages at different output frequencies are presented in Fig. 2.26.

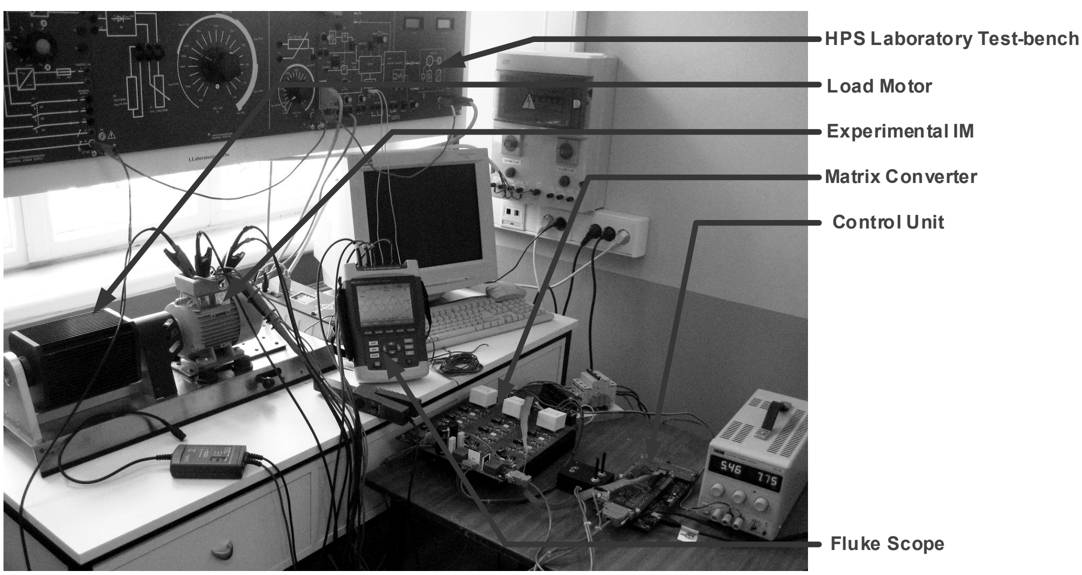
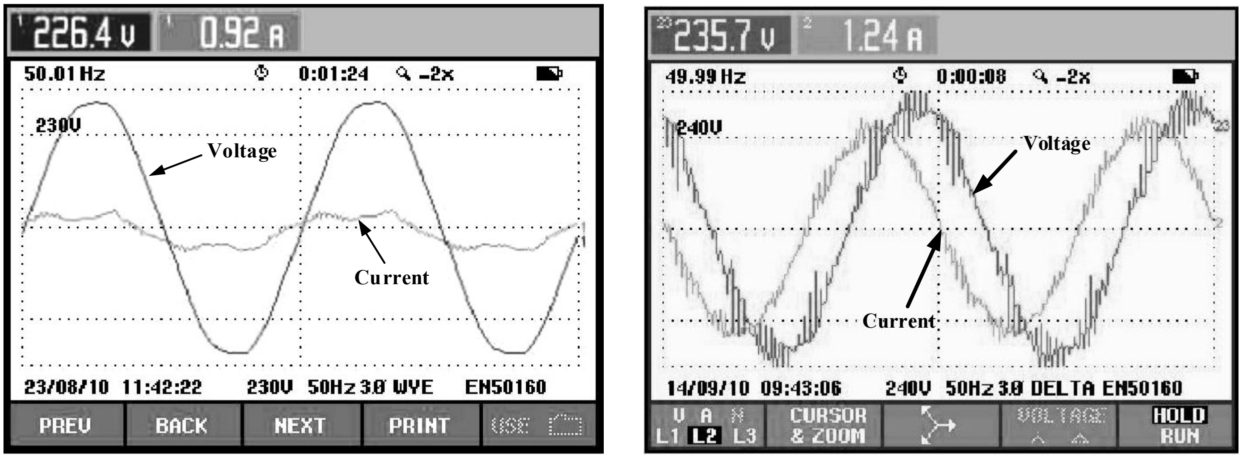
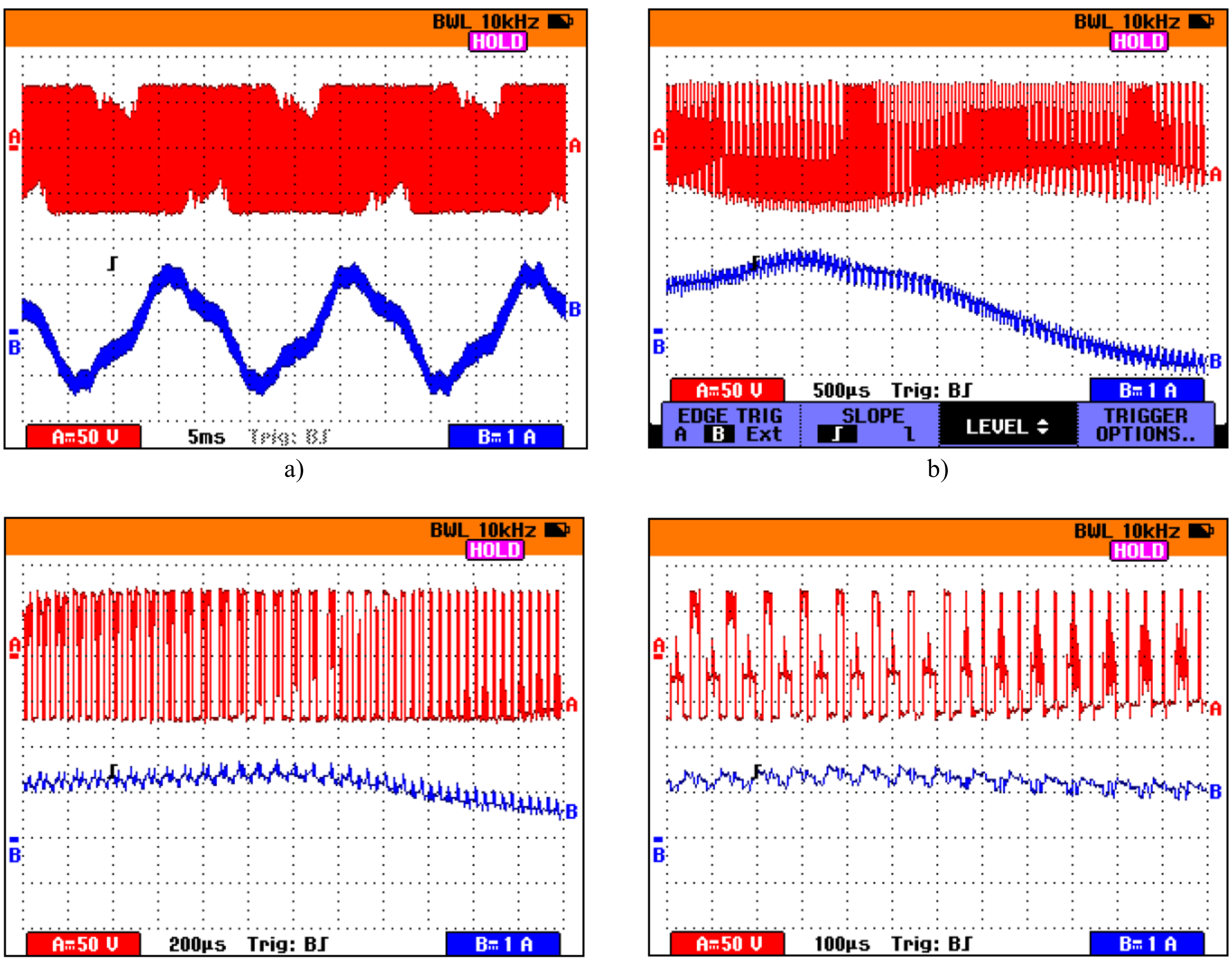


Fig. 2.23. Experimental setup of Induction Motor Drive with Matrix Converter



a) b)

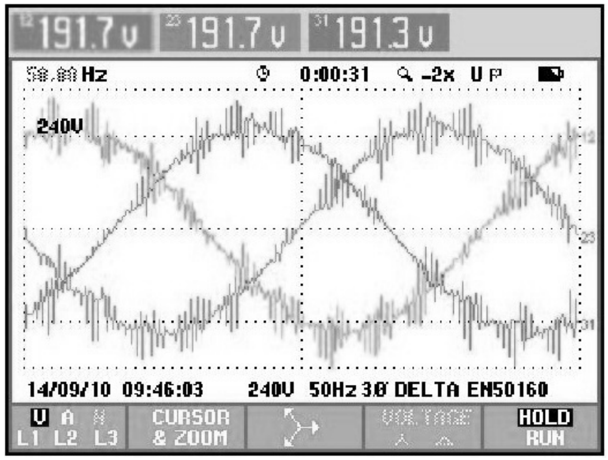
Fig. 2.24. Matrix Converter a) input, b) output voltage and current waveforms (colour removed to improve visibility)



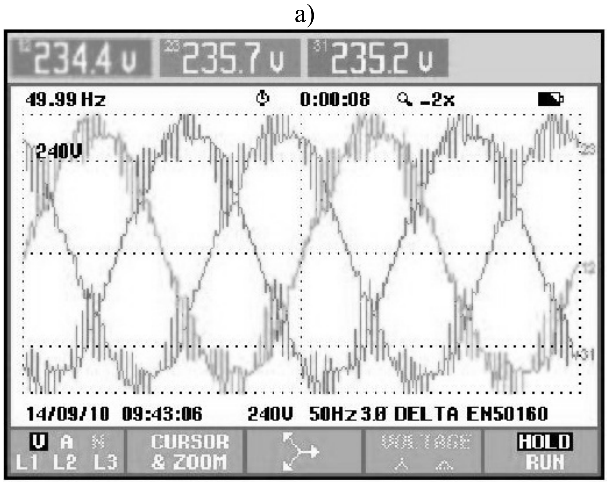
a) b) c) d)

Fig. 2.25. MC unfiltered output voltage (top) and current (bottom) waveform a) 5ms, b) 500µs, c) 200µs and d) 100µs time frame;

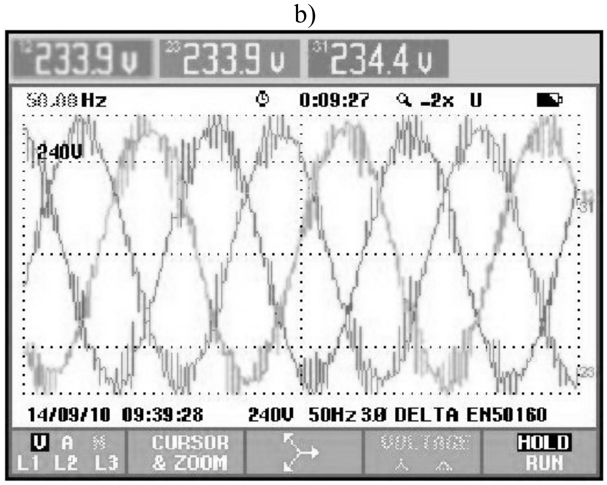
Differential voltage probes are used with ratio 1:20



a)

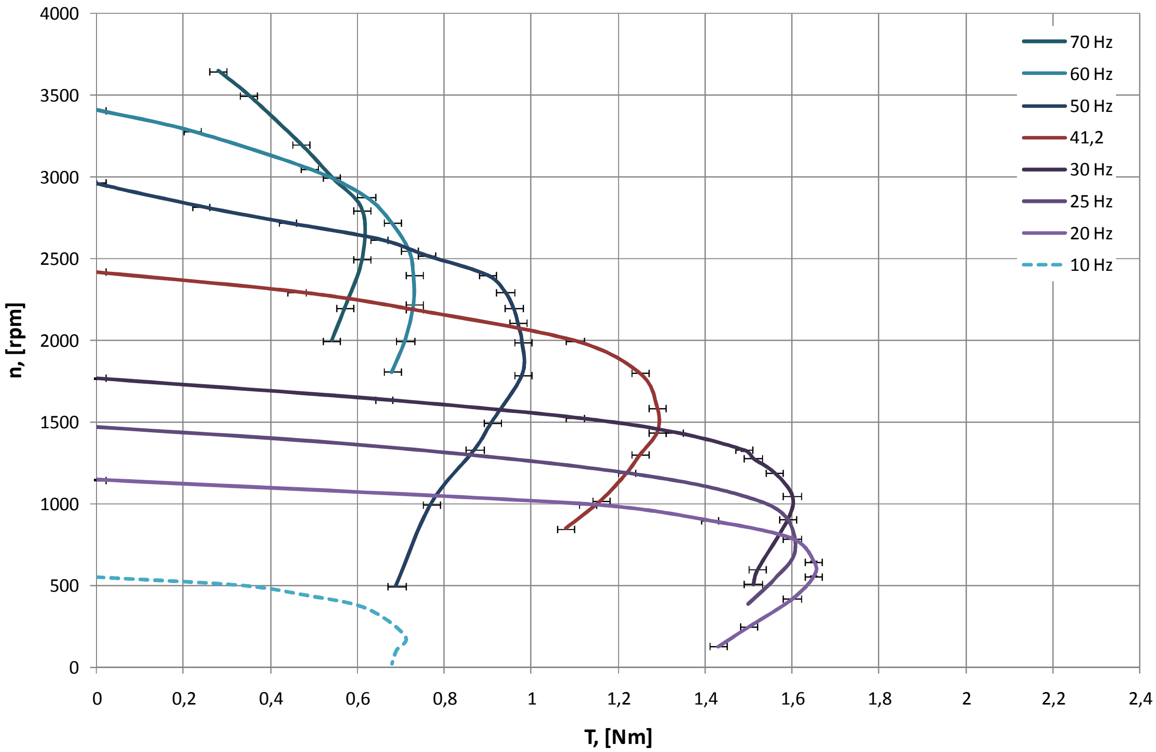


b)

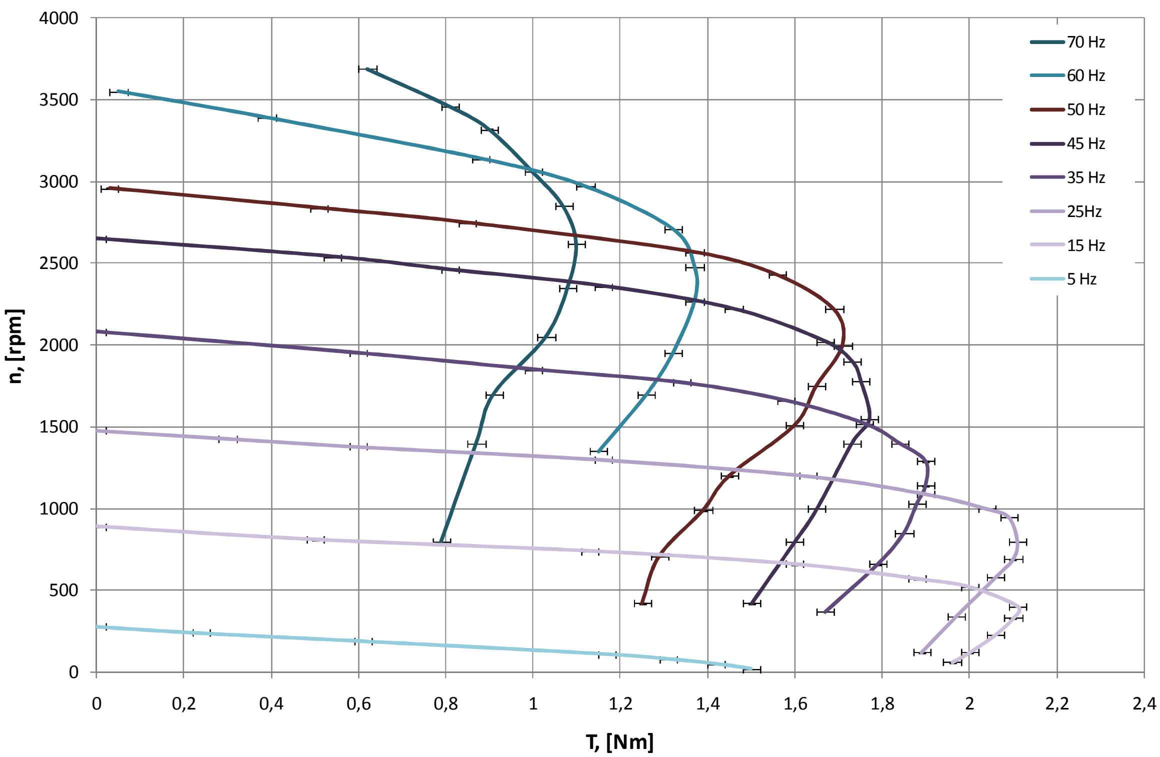


c)

Fig. 2.26. Line-to-line three-phase output voltage waveforms of matrix converter a) 25Hz, b) 50Hz, c) 70Hz



a)



b)

Fig. 2.27. Experimental results of IM drive with MC for winding a) “Y” configuration and b) “Δ” configuration

Experiments with standard Siemens 1 LA5063-2AA10 induction motor and matrix converter were carried out on HPS test bench in laboratory of electrical drives in the Institute of Industrial Electronics and Electrical Engineering.

Open loop scalar control V/f=const was used to control shaft speed. First experiment was carried out at IM “Y” winding configuration (Fig. 2.27.).

The output line-to-line voltage of MC was approximately 0.866VIN = 346V. This had influence on pullout torque (explained in more detail in Appendix C), as it is seen form experimental results (Fig. 2.27.a) the pull-out torque of the machine was reduced. Such configuration allowed motor operation at nominal torque (0.88Nm) with frequencies below 42Hz or shaft speed below 2100rpm. Higher operating frequencies yielded operation close to pullout torque region. To be able to implement this configuration either stator windings had to be changed or motor had to be operated at lower load torque.

Solution to this was the change of motor winging from “Y” to “Δ” configuration. In such a way the nominal winding voltage is 230V. This allowed IM operating at nominal speed and torque (Fig. 2.27.b).

Conclusions

Investigation of matrix converter comparisons with other frequency converters can be concluded that matrix converter is compact and effective solution for integrated induction motor drives. Practical implementation of power IGBT commutation overvoltage reduction methods by means of active gate drivers and bus bar conductor system are demonstrated. Both techniques display effectiveness in overvoltage reduction.

It is also experimentally demonstrated that even with voltage transfer ratio 0.866 matrix converter can be used in standard induction motor speed control without decreasing nominal load torque and rotational speed operating point if stator winding is changed and higher stator current is achieved.

3. ECONOMIC EFFICIENCY

One of the main criteria that is taken in to account when any product is developed is its final costs that determine its ability to compete on the market. The economic analysis requires definition of material costs, production energy consumption, maintenance and investment costs. Because it is not possible to estimate precise production expenses at this point, only approximate hardware costs. Production and installation expenses will be discussed to have a general idea of the economic potential of MC Integrated drive.

Different part expenses of Matrix Converter and Back-to-Back converter are compared in Fig. 3.1.

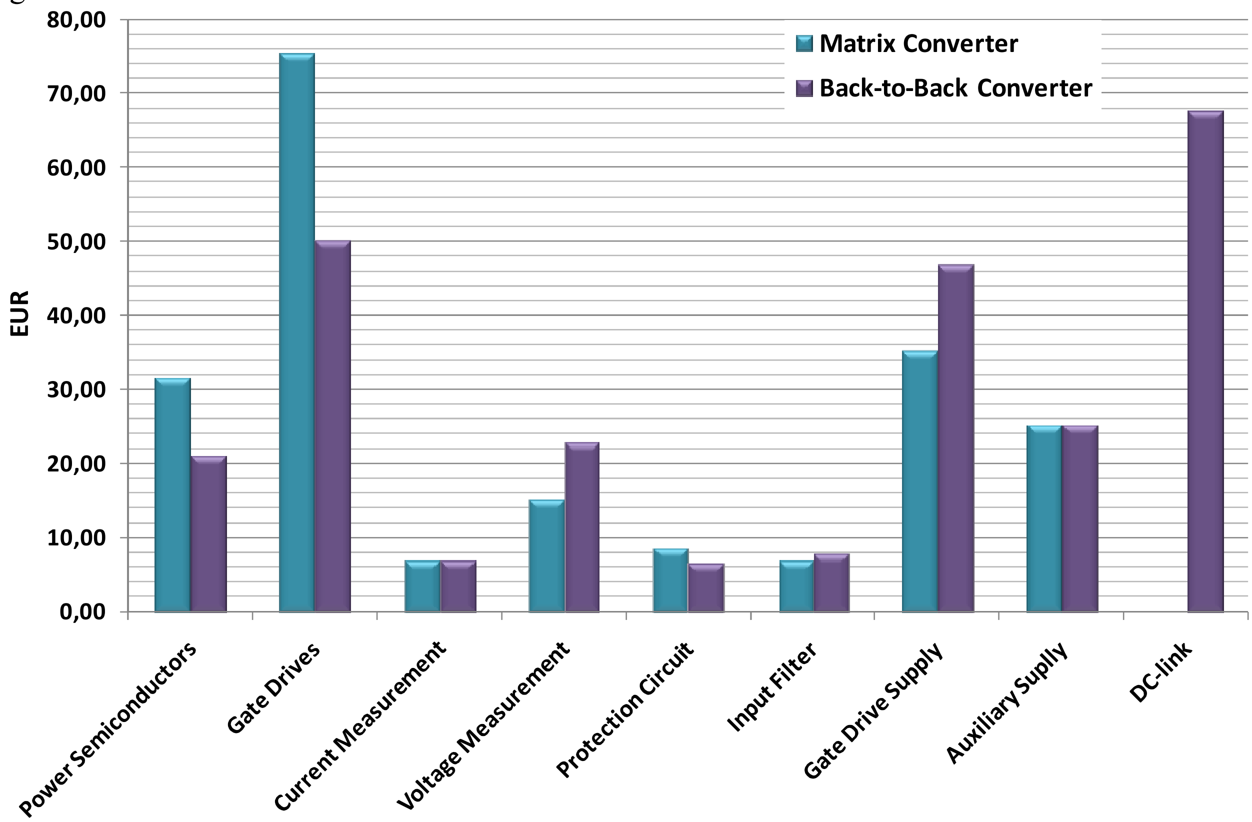


Fig. 3.1. Matrix Converter and Back-to-Back Converter laboratory prototype expense comparison

Matrix converter integrated drive solution is a promising alternative to the existing electrical drives. Although, its potential price is in the range of conventional VSI drives, installation costs of the drive are significantly lower – around 36%. This could be the most important issue of using this kind of drive system in high-cost-labour countries. For instance average installation costs in Sweden are approximately three times higher than in Latvia.

CONCLUSIONS

In this doctoral thesis a study regarding integrated adjustable AC drives with matrix converter has been done. During the study electric power consumption and energy saving potential has been done. The study demonstrates that the most promising trend in energy saving is modernisation of electric drives and implementation of adjustable speed systems.

Different power converter topology comparison to matrix converter has shown that despite inherent drawbacks, matrix converter topology has shown similar reliability factor as back-to-back converter and has potential in integrated drives due to compact – "all silicone" structure.

Power IGBT commutation has been investigated in terms of matrix converter bi-directional switch implementation. Due to the lack of ready-made bi-directional switch on the market, discrete devices have been considered. Pre-selected power IGBT gate drive circuits have been simulated and experimentally tested. As the result of this study most promising gate drive circuit for power applications is considered to be double-fed half-bridge since it is capable to deliver and draw most energy to and from power IGBT. The same study involves simulation and experiments of overvoltage suppression with active gate control. Assuming hard commutation conditions (large parasitic induction in commutation loop and no freewheeling path), active gate control allows reduction of dangerous overvoltage spikes across switching devices. Active gate current control allows overvoltage spike reduction by 85% compared to passive commutation.

A study of conductor shape influence on inductance has been done. Numerical evaluation of different conductor shape and placement influence on inductance has shown that flat conductors placed on top of each other (as bus bar construction) yield the lowest inductance. Bus bar implementation in power converter applications leads to parasitic inductance reduction and hence commutation overvoltage reduction. In the particular case experiments show overvoltage reduction potential by 28% at active-inductive load without current freewheeling path.

Overvoltage reduction by means of bus bar implementation for matrix converter bi-directional switch interconnection has been further developed for particular application in integrated drives.

Particular bi-directional switch power losses are calculated and cooling conditions have been estimated. Thermal calculation results approve feasibility of proposed construction and its overload operation capability under forced air cooling conditions.

Peripheral circuits – auxiliary and gate driver power supplies, voltage and current measurement and protection circuits have been developed for particular integrated drive application.

Economic evaluation of matrix converter prototype expenses has been done in order to compare it to equivalent VSI prototype. Based on prototype costs production expenses have been calculated. Not only resulting prices have been compared to existing integrated and conventional drive solutions, but also drive installation expenses are compared. From this study it has been concluded that matrix converter integrated drive has a high potential competitiveness to existing drive solutions on the world market.

Overall results of this study are affirmative for further product development of integrated induction motor drive with matrix power converter.

Future work will comprise the following activities: obtaining a patent regarding active IGBT gate drive circuits, development of fully digital integrated active gate driver with overvoltage and short circuit current protection, research of AC drives with integrated matrix converter and more sophisticated vector control system.

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