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SWITCHING COMPONENTS FOR MEDIUM VOLTAGE DRIVES

Examiners: Professor Pertti Silventoinen

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ABSTRACT

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Switching components for medium voltage drives

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Nowadays power drives are the essential part almost of all technological processes. Improvement of efficiency and reduction of losses require development of semiconductor switches. It has a particular meaning for the constantly growing market of renewable sources, especially for wind turbines, which demand more powerful semiconductor devices for control with growth of power. Also at present semiconductor switches are the key component in energy transmission, optimization of generation and network connection.

The aim of this thesis is to make a survey of contemporary semiconductor components, showing difference in structures, advantages, disadvantages and most suitable applications. There is topical information about voltage, frequency and current limits of different switches. Study tries to compare dimensions and price of different components. Main manufacturers of semiconductor components are presented with the review of devices produced by them, and a conclusion about their availability was made.

IGBT is selected as a main component in this study, because nowadays it is the most attractive component for usage in power drives, especially at the low levels of medium voltage. History of development of IGBT structure, static and dynamic characteristics are considered. Thesis tells about assemblies and connection of components and problems which can appear. One of key questions about semiconductor materials and their future development was considered. For the purpose of comparison strong and weak sides of different switches, calculation of losses of IGBT and its basic competitor – IGCT is presented.

This master's thesis makes an effort to answer the question if there are at present possibilities of accurate selection of switches for electrical drives of different rates of power and looks at future possible ways of development of semiconductor market.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

ABB   Swedish-Swiss-Finnish company in power and automation technologies;

AC   Alternating current;

BJT   Bipolar junction transistor;

CSI   Current-source inverter;

CSTBT   Carrier stored trench bipolar transistor;

DIAC   Diode for alternating current;

DC   Direct current;

DS   Depletion stop;

FACTS   Flexible alternating current system;

FS   Field stop;

FWD   Freewheeling diode;

GaAs   Gallium arsenide;

Ge   Germanium;

GTO   Gate turn-off thyristor;

HV   High voltage;

HVDC   High voltage direct current;

HVIGBT   High voltage insulated gate bipolar transistor;

IEGT   Injection enhanced gate transistor;

IGBT   Isolated gate bipolar transistor;

IGCT   Integrated gate-commutated thyristor;

IPM   Intelligent power module;

IR   International rectifier – manufacturer of semiconductor devices;

JFET   Junction gate field-effect transistor;

JSC   Joint stock company;

LV   Low voltage;

MOS   Metal-oxide-semiconductor;

MOSFET   Metal-oxide-semiconductor field effect transistor;

MV   Medium voltage;

NPC   Neutral-point-clamped;

PIN   Diode with additional i layer between p and n layers;

PV   Photovoltaic;

ROHS   Restriction of hazardous substances directive;

RSOA   Reverse bias safe operating area;

RUR   Russian rouble;

SCR   Silicon controlled rectifier;

Si   Silicon;

SiC   Silicon carbide;

SOA   Safe operating area;

TRIAC   Triode for alternating current;

UPM   Finnish pulp and paper manufacturer;

VSI   Voltage-source inverter;

ZSI   Impedance-source inverter;

Symbols

C_{CE} Collector-emitter capacitance;

C_{GC} Gate-emitter capacitance;

C_{GE} Gate-emitter capacitance;

C_{IES} Gate-emitter input capacitance;

C_{OES} Collector-emitter output capacitance;

C_{RES} Collector-gate reverse transfer capacitance;

E_{ON} Switching losses during the turn-on;

E_{OFF} Switching losses during the turn-off;

E_{RR} Reverse-recovery energy;

f Switching frequency;

I_0 Average forward current;

I_C DC collector current;

I_D Continuous drain current;

I_{DRM} Repetitive peak reverse current;

I_F Continuous forward current;

I_{FAV} Average (rectified) forward current;

I_{FAVM} Maximum average (rectified) forward current;

I_{RRM}	Repetitive peak reverse current;
I_{TAV}	Average forward current;
I_{TAVM}	Maximum average forward current;
I_{TGQM}	Maximum controllable turn-off current;
I_{TQRM}	Repetitive controllable on state current;
Q_R	Gate charge capacity;
r_C	Collector-emitter on-state resistance;
r_D	Diode resistance;
R_{TH}	Transient thermal resistance;
$R_{TH(CH)}$	Thermal resistance of contact between heat sink and case of the device;
$R_{TH(HA)}$	Thermal resistance of heat sink-ambient;
$R_{TH(JC)}$	Thermal resistance of junction-device case;
R_G	Gate resistivity;
t_F	Time in which collector current is reduced from 90% to 10% of maximum value;
T_J	Junction temperature;
V_{BRDSS}	Drain to source breakdown voltage;
V_{CE}	Collector-emitter voltage;
$V_{CE(SAT)}$	Collector-emitter saturation voltage;
V_{CES}	Maximum permissible collector voltage;
V_{DRM}	Repetitive peak off-state voltage;
V_{DS}	Drain to source voltage;
V_{DSM}	Maximum surge peak forward blocking voltage;
V_{DSS}	Drain-source voltage;
V_{GE}	Gate-emitter voltage;
$V_{GS(TH)}$	Gate-source threshold value;
V_R	Reverse voltage;
V_{RRM}	Repetitive peak reverse voltage;
V_{RSM}	Maximum surge peak reverse blocking voltage;
Z_{TH}	Thermal resistance;
€	Euro (European currency).

1. INTRODUCTION

Nowadays power electronics is probably the most developed part of the market of equipment for energy sector and in electrical engineering. The huge advance of power electronics for the last several decades gives the possibility of right choice of semiconductor devices for specific usage, trying to use best characteristics of each switch depending on technical demands and constraints. This question is especially topical in the medium voltage range, where many semiconductor devices can substitute for each other and in order to increase the efficiency and reduce costs the selection of switches should be done as accurate as possible. More in details about voltage rates will be told in section 1.1.

At present there is a goal to substitute hydrocarbon sources of energy by renewable sources as much as possible. In future oil can be replaced by liquid gas and nuclear energetics with additional renewable sources, like wind energy, solar energy, energy of water and usage of biomass. In indeterminate future thermonuclear power can change nuclear power, but nowadays there is not any deserving results in this field. Power switches are key components in process of energy transmission, optimization of generation and network connection. Permanently growing number and power of mounted wind turbines, PV panels and wide usage of power drives causes research of new structures and semiconductor materials. In contemporary wind applications, requirements of quality of electricity have to be implemented, so wind turbines should be connected to the grid without usage of additional power electronics. The main aim of power electronics circuits is to keep output voltage and frequency in specified level, independently of the current state of the wind turbine. As for solar cells, development of semiconductor switches will improve efficiency of the whole solar energy sector. Nowadays main problems in this field appear in solar inverters and lacks concern quite low efficiency, harmonics and electromagnetic interference caused due the usage of long length connecting cables.

The aim of this master's thesis is to make a survey of contemporary semiconductor components which can be used in power drives with emphasis on IGBT. IGBT is chosen as a basis of this study, because at present this device shows the most probable potential of development and usage in electrical drives. History of IGBT structure development, features and main characteristics are presented. This thesis analysis up-to-date semiconductor switches, presents advantages, disadvantages, ap-

plication of different devices and their availability and tries to present the price on some devices. Work contains topical information about main players of semiconductor market and today's voltage and current limits of produced devices.

One of the most interesting questions is to compare devices in different states. This shows applicability of components. Calculation of losses was made with aim to compare an order of losses and understand strong and weak sides of components.

Contemporary semiconductor switches are generally components of DC/AC converters. One of basic questions is a right choice of switches for specific topology of the frequency converters. With this purpose the question of selection of appropriate switches for certain voltage levels is considered.

This study can be quite important in a great number of published surveys devoted to semiconductor components. The main reason is in fact that most of them were made in the last years of previous century and in first years of XXI century. It can be explained by the creation of IGCT approximately in 1996. This device made engineers to compare studiously it with IGBT and with previous types of thyristors. Nowadays plenty of companies produce IGBT and only few of them manufacture IGCT, therefore qualitative surveys and analyses last years were made only by manufacturers who present both IGBT and IGCT. One more advantage of this work is in fact that it contains good results and strong sides of surveys of previous years and also based on up-to-date numbers and information.

Thesis tries to ask the question about potential of development of semiconductor market and development of semiconductor materials, structures and assemblies in particular.

1.1. Concept of medium voltage drives
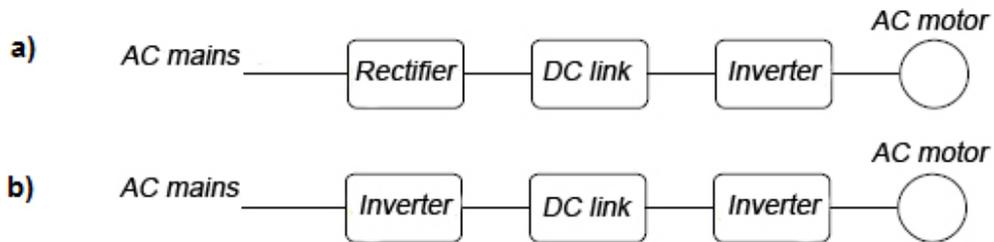
Figure 1 *Simplified working schemes of electrical drive. [29]*

The concept of electrical drive comprises power electronics, electrical motor, controller, measuring equipment and external parameters. Figure 1 depicts simplified general idea of electrical drive. It should be noticed that in some simple applications can be used drive with rectifier- Figure 1a, but it is often necessary to return energy into the ac main or dissipate it in the intermediate circuit of frequency converter. For example this necessity can appear during the electromagnetic braking, while machine starts to act as a generator and rotating speed exceeds the synchronous speed, therefore slip becomes negative and motor reduces the speed. This can be implemented by usage of inverter instead of rectifier, because normally rectifier bridge can not be reversed. [1], [30]

Most of contemporary applications of drives are in the medium voltage range, therefore it is a wide field of usage of medium voltage and high voltage semiconductor components. The definition of medium voltage is depended on industry and application. For AC motors it varies from 1 kV to 15 kV. The European threshold of MV is 1 kV. Existing medium voltage drives have range from 2.3 kV to 7.2 kV. In North America 2.3 kV and 4.16 kV (60 Hz) are referred to the medium voltage range, while prevalent line voltages in Europe and in other parts of the world are 3.3 kV and 6.6 kV (50 Hz). Figure 2 shows average ratings of voltage and power of the concept of MV drives.
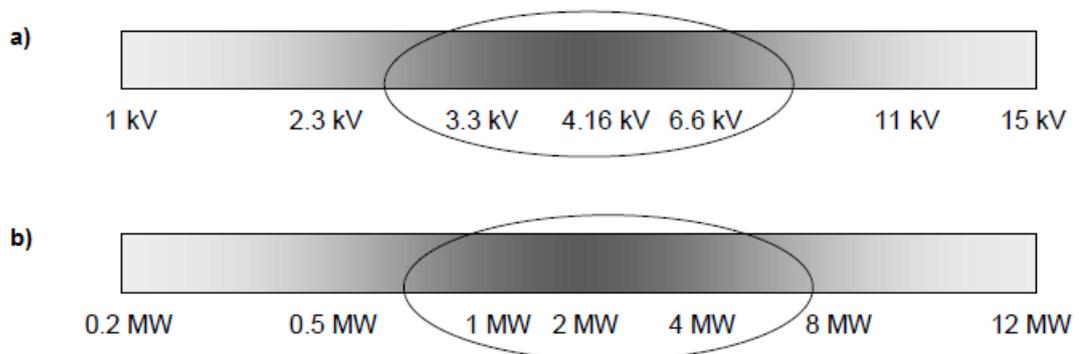
Figure 2 *a) Voltage range, b) Power range of medium voltage drives. [29]*

Further this study will not differentiate medium voltage and high voltage ranges of switching devices, because this border is quite smooth.

1.2. Topologies of DC/AC converters

DC/AC converter is the essential part of electrical drive. Semiconductor components form basis of converters. It is a widely developed field of power electronics. Traditionally there are two types of converters: voltage-source inverters (VSI) and current-source inverters (CSI). Quite recently impedance-source inverter (ZSI) was invented. Simplified schemes of these devices are depicted on the Figure 3.
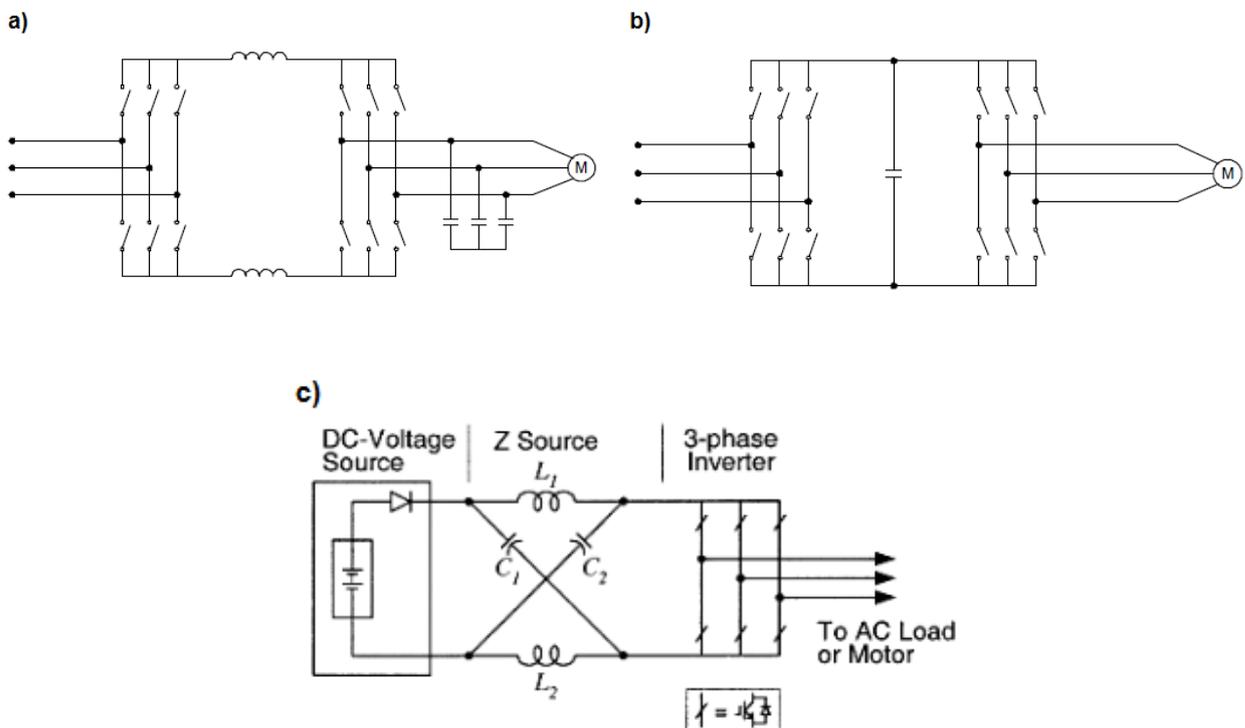
Figure 3 *a) Current-source inverter, b) Voltage-source inverter, c) Impedance-source inverter. [29], [41]*

The main difference between VSI and CSI is that in first device DC link has not impedance in ideal way, but in second device there is impedance approaching to infinity in ideal case. As opposed to VSI and CSI, ZSI uses the shoot through switching state which means that switching components, which connected to the same leg, can be switched-on at the same period. Z-source can be seen on the Figure 3c. Owing to it, the short through state which causes short circuit in traditional schemes is not harmful in this modification of an inverter. [1], [41]

Three types of DC/AC converters described above can be divided on several groups (Figure 4):
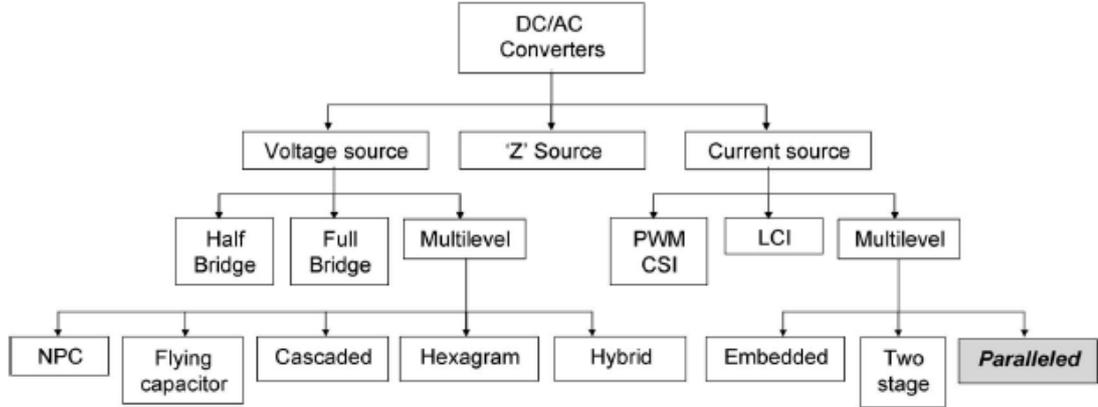
Figure 4 Various levels of DC/AC converters. [40]

Nowadays a plenty of types of converters are used. Main difference is the type of using switches and amount of switching components in the assembly, so there are 2 level VSI, 3 level VSI, different multilevel inverters like NPC, n-level flying capacitor inverters and so on. The main aim of usage such abundance of converters is to avoid appearance of harmonics and raise the output power, while using certain switches. For example 3L-NPC-VSI compared to two-level inverter has double forward blocking voltage for selected device and lower harmonics. For recent years when voltages of IGCT were up to 6 kV, which can be very suitable for this inverter, 3L-NPC-VSI topology could be applied to achieve a line-to-line voltage at the motor V_{LL}=4.16 kV with a single IGCT switch per position. However there are many applications which require output voltage in the range from 6 kV to 6.9 kV. In this case there is a necessity either to connect two IGCT components in series or use switches with increased voltage handling capability. More in details about voltage levels of semiconductor components will be told further.

1.3. Demands to voltage level of applicable switches

Design rules of power converters demand to take into account different influences of supply voltage, so switching components in rectifier have to endure V_{DSM} and V_{RSM}, which can be derived by the equation 1.1. Results of usage this equation are shown in the Table 1.

$$V_{DSM} / V_{RSM} = \sqrt{2} \cdot V_{SUPPLY} \cdot k , \qquad (1.1)$$

where k is safety factor which depends on the quality of supply network. Normally k can be chosen between 2 – 2.5, but for low protected networks it can be higher.

Table 1 *Recommended blocking voltages for chosen devices at nominal line voltages with k≈2.5. [42]*

Nominal line voltage (V_{SUPPLY}), V_{RMS}	Optimum blocking voltage ratings (V_{DSM}, V_{DRM}), V
400	1400
500	1800
690	2400
800	2800
1000	3600
1250	4200
1500	5200
1800	6500

Figure 5 illustrates simple difference between different voltages which influence on the choice of semiconductor components. Misunderstanding of these features can lead to wrong choice of switch and possible failure of equipment.
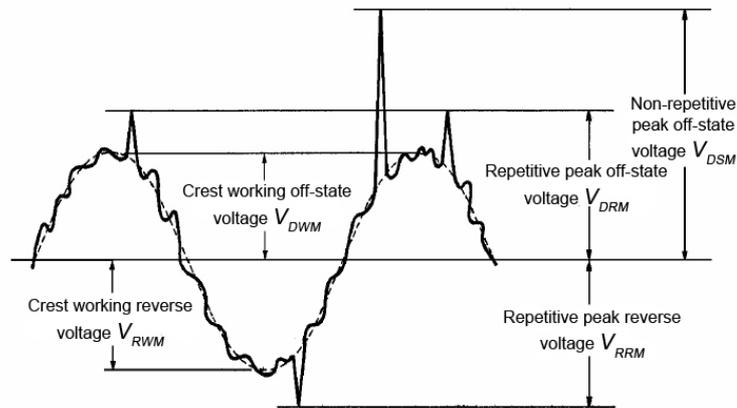
Figure 5 *Definition of different voltages. [42]*

Generally the selection of semiconductor switches for inverters may be based on equation 1.2, but of course these calculations directly depend on the topology of the inverter. In case of inverter line to line voltage fluctuations and voltage spikes during switch-off due stray inductances of the line are taken into account. Approximate results of equation 1.2 are illustrated in the Table 2 and Table 3.

$$V_{\text{CE\_MAX}} = 1.5...2.0 \cdot V_{\text{DC\_NOM}}, \tag{1.2}$$

Table 2 *Required blocking voltage in 3-level VSI. [53]*

Nominal line voltage, V	Nominal DC link voltage, V	Maximum DC link voltage, (25% overvoltage) V	Required semiconductor blocking voltage, V	Number of series connected devices. V_{DRM}=3300-5500 V (number of devices per phase)	Number of series connected devices. V_{DRM}=3300-9500 V (number of devices per phase)
2300	1800	2250	3300	1(4)	1(4)
3300	2460	3100	4500	1(4)	1(4)
4160	3100	3900	5500	1(4)	1(4)
6000	4500	5600	8000	2(8)	1(4)
6600	4900	6200	9000	2(8)	1(4)
6900	5160	6500	9200	2(8)	1(4)
(7200)	5400	6750	9500	2(8)	1(4)

Table 3 *Required blocking voltage in 3-level CSI. [53]*

Nominal line voltage, V	Nominal peak line-to-line voltage, V	Maximum peak line-to-line voltage, V	Required semiconductor blocking voltage, V	Number of series connected devices. V_{DRM}=6500 V (number of devices per phase)	Number of series connected devices. V_{DRM}=3300-9500 V (number of devices per phase)
2300	3394	3734	6500	1(2)	1(2)
3300	4667	5134	9000	2(4)	1(2)
4160	5883	6471	11500	2(4)	2(4)
6000	8485	9334	16500	3(6)	2(4)
6600	9334	10267	18000	3(6)	2(4)
6900	9758	10734	19000	3(6)	2(4)
(7200)	10182	11202	20000	3(6)	2(4)

According to principles described above, the 6.5 kV IGBT module can be chosen for 3.0 kV$_{DC}$ traction applications. Another important field of application is high power industrial drives with 2.3 kV$_{AC}$ lines (or 3.25 kV$_{DC}$). In these applications converter can be connected to lines directly. Drives with 4.16 kV$_{AC}$ (or 5.9 kV$_{DC}$) can be implemented in three level circuit designs, however if to concern 6 kV motors, in recent years they were operated by multilevel drives or LV drives in arrangement with a transformer, which sometimes can't be so suitable as usage of MV drives. Much energy savings can be achieved in drives with more than 6.5 kV motor voltages. Expected cost reduction can be implemented by increasing of the blocking voltage of semiconductor devices to 9.5 kV. Owing to 9.5 kV device it will be possible to make 3-level VSI and CSI without series connection of switches. It will be told more in details about perspectives of development of power semiconductor components in section 9. [42], [44], [53]

As power electronics is developed, the implementation and reliability of DC/AC converters is increased, because the necessity to make converters consisting of large amount of switches is disappear.

1.4. Target industries and applications of medium voltage drives

Power drives nowadays are the essential part of every industrial process and in many everyday and domestic processes. Drives adapt speed of motor to the necessary need and thereby optimizing energy consumption and reducing emission of greenhouse gases. As was told in previous chapter, sometimes low-voltage drives with transformer are used to achieve higher power and LV drives have lower size, but in spite of this MV drives have many advantages over LV drives. Medium-voltage drives operate at much higher supply voltages, therefore at less currents. It reduces losses and length of used cables, which prevent high voltage drop in the cable between drive and motor. Construction of MV cable is more expensive, as a sequence of insulation demands, but amount of copper is less. Other advantages in harmonic mitigation as opposed to LV drives and suitable synchronization with network, because mains are usually MV. [64]

At present medium-voltage drives are used almost in all fields of industry. For example, Finland has strong positions in the field of pulp and paper production. One of the pulp and paper factories which

belongs to UPM is situated in Lappeenranta. Such factories can operate during twenty-four hours, therefore contemporary power drives are demanded to be reliable and robust.

Main applications are presented in the Table 4.

Table 4 Main applications of medium voltage drives. [14], [29]

Petrochemical	Forest Products	Mining and Metals
Pipeline pumps,	Fan pumps,	Slurry pumps,
Gas compressors,	Induced draft fans,	Ventilation fans,
Brine pumps,	Boiler feed water pumps,	De-scaling pumps,
Mixers/ extruders,	Pulpers,	Conveyors,
Electrical submersible pumps,	Refiners,	Baghouse fans,
Induced draft Fans,	Kiln drivers,	Cyclone feed fans,
Boiler feed water pumps.	Line shafts.	
Cement	**Water/ Waste Water**	**Electrical power**
Kiln induced draft fans,	Raw sewage pumps,	Feed water pumps,
Forced draft fans,	Bio-roughing tower pumps,	Induced draft pumps,
Cooler baghouse fans,	Treatment pumps,	Forced draft fans,
Preheat tower fans,	Freshwater pumps,	Baghouse fans,
Raw mill induced draft fans,	Water extraction.	Effluent pumps,
Kiln gas fans,		Compressors,
Cooler exhaust fans,		Wind turbines.
Separator fans,		
Baghouse fans.		
Marine	**Miscellaneous**	
Chemical, product, shuttle tankers,	Test stands,	
Cruise vessels,	Wind tunnels,	
Double-acting tankers,	Agitators,	
Dredgers,	Rubber mixers,	
Drill ships and semi-submersible rigs,	Food and beverage,	
FPSO tankers,	Elevators,	
Icebreakers,	Cranes,	
Offshore support vessels,	Escalators,	
Research and survey vessels,	Household appliances.	
RoRo and RoPax ferries.		

2. MEDIUM VOLTAGE AND HIGH VOLTAGE CONTROLLABLE SWITCHING COMPONENTS

2.1. Thyristor (SCR)

Thyristor is a semiconductor device executed on the basis of a monocrystal of the semiconductor with three or more junctions by transitions and having two steady conditions: turn-off – condition of low conductivity, and turn-on – condition of high conductivity. There are various kinds of thyristors which are subdivided, mainly, on a way of management and on conductivity. Distinction on conductivity means that some thyristors conduct a current in one direction and other in two directions (TRIAC).
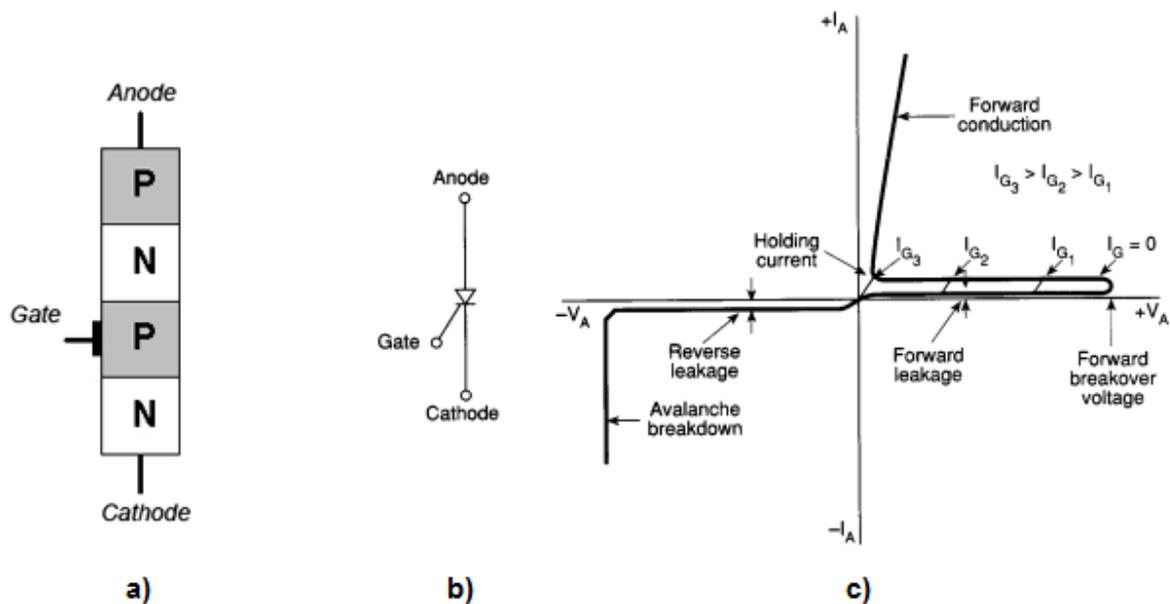
Figure 6 *a) Simplified cross section of a SCR, (b) electrotechnical symbol, (c) I-V characteristics.*
[2], [3], [4]

Thyristor can be switched on, having put a short positive impulse to gate. The forward voltage drop in the turn-on condition is a few volts (as a rule 1-3 V depending on the blocking voltage of the device). It is obviously seen on the I-V characteristics of switch on the Figure 6c.

As soon as the device starts to conduct, it is latched in the turn-on condition, and the current of gate can be removed. Thyristor can't be switched off by the gate, and thyristor works as the diode. Only when the anode current tries to become negative under the influence of a circuit to which it is con-

nected, thyristor is switched off, and the current goes to zero. It allows gate to regain control switch on the device in some controllable time after it has again entered the forward blocking condition.

In reverse bias voltages, only small electric current of leak flows in the thyristor. Forward- and reverse- blocking voltages of the thyristor are usually the same. [1]

2.2. Gate turn-off thyristor (GTO)

GTO is a device oriented to be used in high power applications. Device has four states: turn-on, conducting state, turn-off and latching. GTO can be switched on by a short impulse of a gate current, and being in turn-on condition GTO can remain in the on-state without a gate current. However, unlike the thyristor, GTO can be switched off, putting negative gate-cathode voltage, thereby causing enough big negative current through the gate. This negative gate current amplitude depends on the anode current which should be switched off. Turn-off is provided by bypassing carriers directly to the gate circuit, its turn-off time is short, thus giving it more capability for high frequency operation than thyristors. Simplified structure is shown in the Figure 7a and it illustrates difference with structure of SCR (Figure 6a).
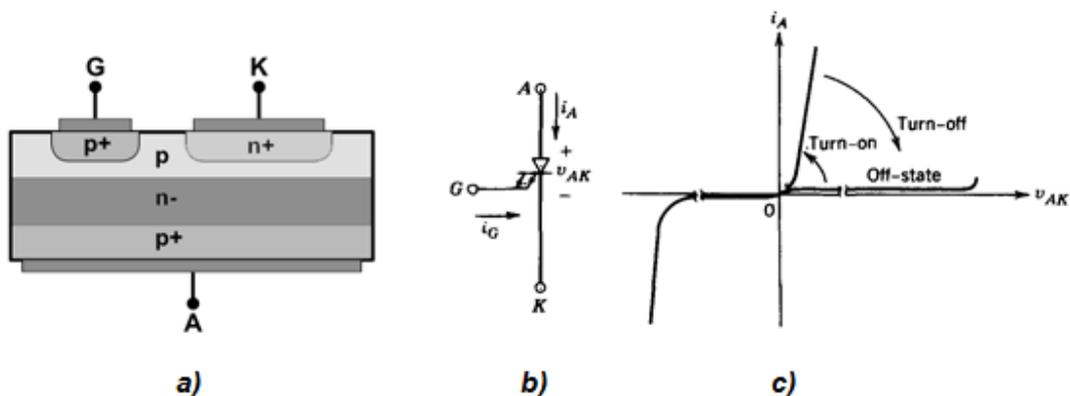
Figure 7 GTO: a) Simplified cross section of a GTO, (b) Electrotechnical symbol, (b) I-V characteristics. [1]

Thus it is not necessary to apply reverse biased anode voltage to achieve turn-off, so expensive commutation circuits, which were used in association with SCR, are not required. Owing to it, turning off is much faster.

Snubber circuits are obligatory for GTO operation. Parallel connected capacitors limit $\dfrac{du}{dt}$ during turn-off and series connected coils limit $\dfrac{di}{dt}$ during turn-on. They increase weight and size and decrease cost efficiency. Sometimes snubbers require additional cooling system. [1], [2], [5]

2.3. Integrated gate-commutated thyristor (IGCT/ GCT)

IGCT has very similar principle as GTO, but fast turn-off is implemented by transformation of thyristor structure into transistor structure while latching, which makes a switch insensitive to $\dfrac{du}{dt}$. Turn-on and turn-off states are achieved by applying a gate signal. Gate driver system of IGCT has very low inductance and general difference in operation with GTO is in turn-off. As against to GTO, IGCT has lower conduction losses and higher overvoltage capability.

IGCT has almost the same structure as GTO. In an IGCT, the gate turn off current is greater than the anode current. This fact follows to stop the ejection of minority current carriers from the lower PN junction, which leads to the faster turn-off. The main differences from the GTO are the lower size of the cell and presence of gate drive in the body of IGCT. The integration of drive circuit into the frame of device causes reduction of resistance and inductance of the connection.

Turn-off times of IGCT are much faster in comparison to GTO's. That allows them to work at higher frequencies – up to several of kHz (more in details in Table 6). But higher losses appear on higher frequencies. Operating frequency for IGCT is limited only by thermal conditions of the device, but typically it is about 500 Hz.

Available several types of IGCT: asymmetric (IGCT), symmetric or reverse blocking (RB) and reverse conducting (RC). [7], [9]
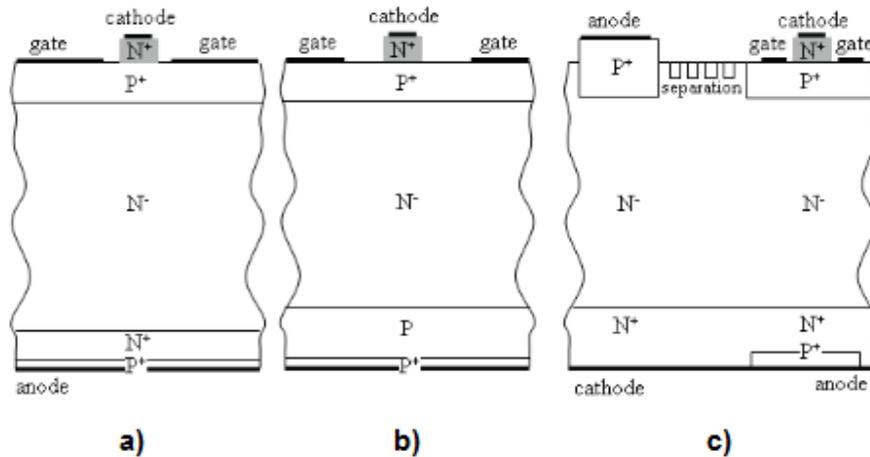
Figure 8 *Typical structures of IGCT. a) IGCT, b) RB-IGCT, c) RC-IGCT. [56]*

Figure 6 illustrates difference in behavior of IGCT depending on the structure of the device.

2.4. Metal-oxide-semiconductor field effect transistor (MOSFET)

MOSFET is a type of JFET with input gate electrically insulated from the main current channel and owing to it MOSFET works as a voltage controlled nonlinear resistor and the current flowing from the drain to source through the main channel. This current is proportional to the input voltage. As a JFET, MOSFET has very high input resistance, because of the isolated input gate. MOSFET is a voltage controlled device. It is fully in the on-state and approaches a closed switch when the gate-source voltage is below the threshold value $V_{GS(TH)}$. MOSFET requires the continuous application of gate-source voltage of appropriate magnitude in order to be in the on-state. The switching times are very short, being in the range of a few tens of nanoseconds to a few hundred nanoseconds depending on the device type. MOSFET can be P-type and N-type.

Structure of MOSFET contains parasitic diode, which can be useful as a clamp diode during a switching over an inductive load. Parasitic diode adds additional recovery losses. Simplified structure of MOSFET is illustrated on the Figure 9a and Figure 9c shows main *I-V* characteristics of the switch. [1], [63]
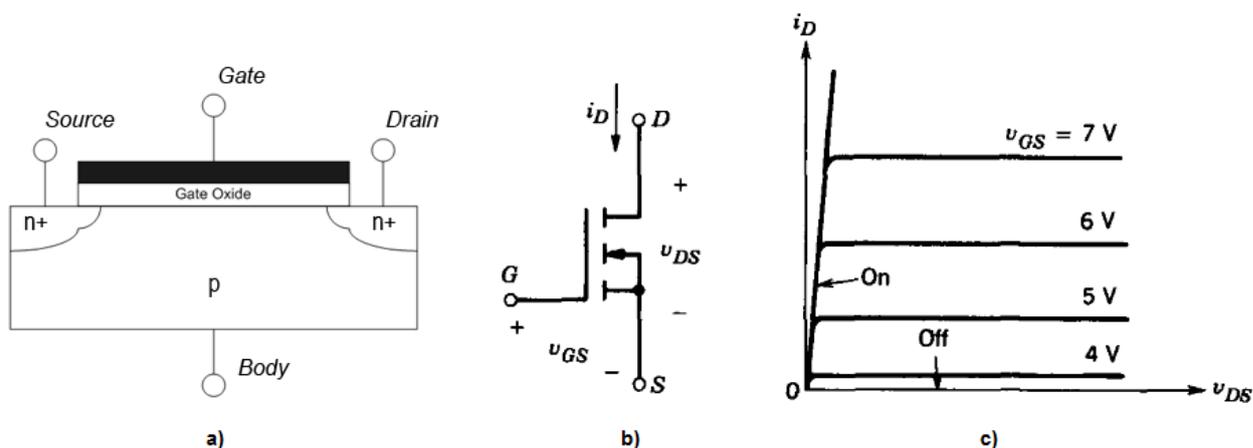
Figure 9 A MOSFET: a) Simplified cross section of a n-type MOSFET (b) Electrotechnical symbol, (c) I-V characteristics. [1], [3]

2.5. Insulated gate bipolar transistor (IGBT)

Insulated gate bipolar transistor consists of bipolar junction transistor which is operated by metal-oxide-semiconductor field effect transistor, which can be seen in the simplified structure of IGBT on the Figure 10a. Also it depicts difference with MOSFET structure (Figure 9a).
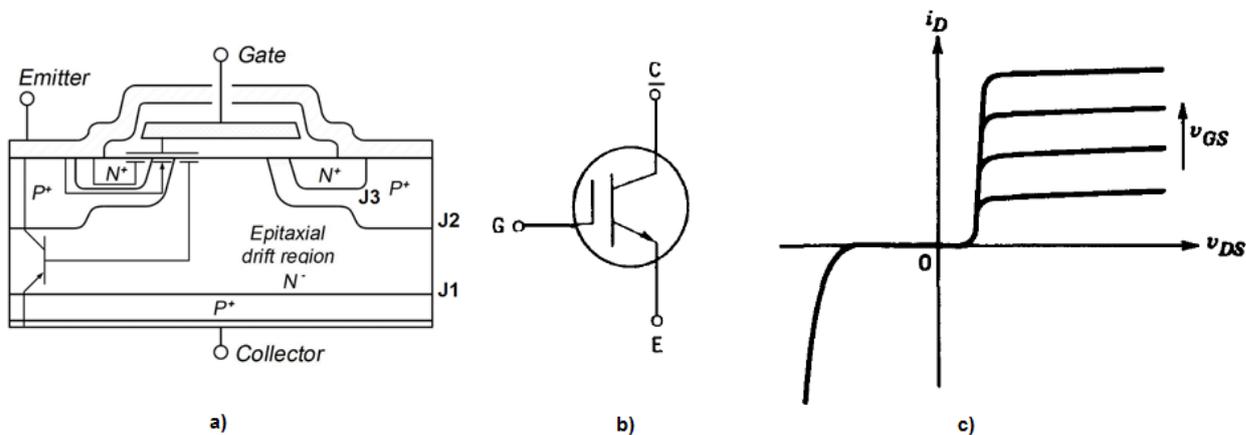
Figure 10 An IGBT: a) Simplified cross section of an IGBT cell, (b) Electrotechnical symbols, (c) I-V characteristics. [1], [3], [4]

The IGBT has some advantages of the MOSFET, BJT and GTO combined. IGBT has high impedance gate which is an advantage of the MOSFET. Owing to it only a small amount of energy requires to switch the device. Similar to GTO, the IGBT can be designed to block negative voltages. IGBT has high conduction current density and low voltage drop in the on-state. It is easy operated,

because of the MOS gate structure, as compared with current controlled switches. IGBT has wider Safe Operating Area than BJT.

As against MOSFET, IGBT has less switching speed, but it has superior switching speed against BJT. The current tail, because of the minority carriers, causes reduction of turn-off speed. Structure of the IGBT contains a parasitic thyristor, so it can be latched.

IGBT and MOSFET occupy a range of average capacities and frequencies, partially replacing each other. Generally, for high-frequency and low-voltage cascades, less than 1000 V most applicable is MOSFET, and the most appropriate switch for voltage rate more than 1000 V is powerful IGBT.

Application of IGBT modules in control systems of traction engines allows (in comparison with thyristor devices) to provide high efficiency, high smoothness of an operation of the machine and possibility of application of regenerative braking almost at any speed. IGBT is applied in devices with voltage rate more than 1000 V, quite high temperature (more than 100 °C) and output power more than 5 kW. The basic applications of IGBT are inverters, pulse regulators of the current and frequency-regulated drives.

In certain cases IGBT and MOSFET – are completely interchangeable. The characteristic of operating signals of both devices – are identical. IGBT and MOSFET demand 12-15 V for switching-on. [1], [36].

Table 5 *Comparison of characteristics of IGBT, MOSFET and BJT. [36]*

Features\ Device	BJT	MOSFET	IGBT
Drive Method	Current	Voltage	Voltage (charge)
Drive Circuit	Complex	Simple	Simple
Input Impedance	Low	High	High
Drive Power	High	Low	Low
Switching Speed	Slow (µs)	Fast (ns)	Middle
Operating Frequency	Low (less than 100kHz)	Fast (less than 1MHz)	Middle
SOA	Narrow	Wide	Wide
Saturation Voltage	Low	High	Low

Table 5 shows comparison of advantages and disadvantages of IGBT, MOSFET and BJT which was made by engineers of Fairchild Semiconductor Corporation.

Traditionally in literature IGBT is described as a voltage controlled device, but in practice it would be incorrect. It is justice to tell that IGBT is controlled by voltage – current combination, namely by a charge. This statement is relied on the gate charge which is proportional to the continuous current rating of the IGBT and required gate current. Process of gate charge is impulsive and at high frequencies high-voltage IGBT requires very high current for gate charge.

Structure and characteristics of IGBT will be discussed more in details further in section 5-6.

2.6. Comparison of power switches

The fully controlled GTO was traditionally used in high power systems, because of its off-state voltage capability and on-state current capability. IGBT was very popular in medium power applications and the lower part of high power, especially when voltage is less than 1.5 kV. With appearance of HVIGBT, IGBT is presented a challenge to predominance of the GTO in high power area. Switching performance of IGBT technology is much better than GTO's, but switching performance of GTO can be significantly improved by driving the gate current to be greater than or equal to the anode current during turn-off. Thus the IGCT appeared. Another important characteristic of the GTO and the IGCT is that they allow only on and off states. These switches are latching devices, while IGBT can always be controlled in the whole range from off to on.

MOSFETs are usually used when there is necessity in very high switching frequency, but these switches are applicable only for relatively low power applications. These devices are not applicable in high power circuits. [12], [13]

Main advantages, disadvantages, voltage and frequency limits of the described above semiconductor switches are presented in the Table 6. Table contains survey of semiconductor components which are presented on the commercial market at present.

Table 6 *Comparison of the semiconductor switches. [5] – [11]*

Type of the device	Advantages	Disadvantages	Voltage rate (V_{DRM}, V_{CES}, V_{DSS}), kV	Switching frequency range, kHz	Range of application
Thyristor	Lowest losses in the turn-on state. The highest overload capacity in comparison to other switches. High reliability.	It is not capable for compulsory latching on an operating electrode.	≤12	traditional-ly f≈0.05, fast thyristors have f<10	DC drives, power suppliers, equipment for welding, melting and heating, static var compensators, HVDC, AC switches.
GTO	Controlled turn-off ability. Relatively high overload capacity. The reliability and cost effectiveness.	High switching, on-state loss, very high loss in the control system. Difficult and expensive turn-off snubbers. High switching losses. Slow switching: 10- 30 µs.	≤6.5	0.1 – 0.5	Adjustable speed drives, static var compensators, HVDC, uninterruptible power supply (UPS), equipment for inductive heating.
IGCT	Controlled turn-off ability. Relatively high overload capacity. Low losses in the turn-on state during the switching. Snubberless turn-off.	IGCT needs additional circuits with inductivity for reduction of $\dfrac{di}{dt}$.	≤6.5	Typical f ≈0.5, upper f< 40 (limited only by thermal conditions of the device).	Power supplies, inverters, converters, HVDC, power drives.

MOSFET	High working fre-quency.	Low power of de-vices.	≤1.5	<1000	Switch Mode Power Supplies (SMPS), uninterruptable pow-er supplies (UPS), inverters and DC mo-tor drives.
IGBT	Controlled turn-off ability. Simple control system with integrated driver.	Current tail during the switch-off, high on-state losses.	≤6.5	≤150	Power drives, unin-terruptible power supply (UPS), static var compensators, HVDC, active filters.

At present in consequence of very rapid development of IGBT it has probably the best characteris-tics for usage in power drives in medium voltage ratings. It concerns to devices of the same power, because in high voltage segment thyristor group is more applicable.

Nowadays only IGCT may be a competitor in medium voltage range. One of the advantages of IGCT over IGBT is fewer amounts of components to achieve rated voltages, than the amount of IG-BTs components. This way old generations of IGBT usually contained great number of chips and connecting wires, while IGCT includes only several parts. Situation has changed with coming of modules and IPM.

Latching behaviour of the IGCT during the on-state means that there is not essential limitation of possible short circuit current. In addition, FWD can not be turned off with high $\frac{di}{dt}$,

which can appear. Therefore DC link contains additional inductivity which limits current spikes and thereby protects FWD. Figure 11 depicts difference in operating of IGCT and IGBT on the example of VSI. On the contrary IGBT in which current of internal transistor structure saturates in the on-state. This allows IGBT to safely switch-off after detection of short circuit. Short circuit turn-off ca-pability of IGBT is an additional advantage to slight MOS control. Parallel connection ability, ow-ing to positive temperature coefficient of $V_{CE(SAT)}$, eases the operation of powerful modules without huge failures. [28], [56]
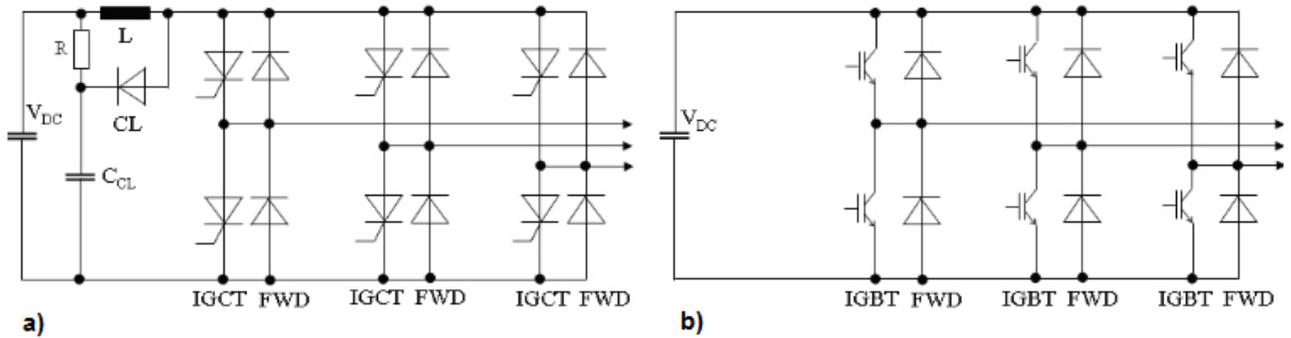
Figure 11 *Comparison of simplified circuits for the operation of a) IGCT, b) IGBT. [54]*

Nowadays all equipment has to be as small as possible and development of components of higher ratings reduces total dimensions of equipment and as result areas occupied by applications. Appendices 1, 2 illustrate sizes of 6.5 kV IGBT and 6.5 kV IGCT. This pictures were taken from datasheets of selected switches and it is obvious from them that IGBT has lower dimensions. This comparison can be correct and for switches of other voltage ranges.

One of the most important factors is price. This factor usually makes the choice of the device. At present it is almost impossible to get price list on high power components in a free access exactly from manufacturers, because of the competition between them. Attempt of analysis of price of different devices was made according to information presented by Russian shop "Chip & Dip" (Saint Petersburg) specializing in electronic components, therefore results are not very accurate. For comparison all prices were led to euro. Average ratio for April 2011 is 1 €=40 RUR. Price is retail for single switch. Results are presented in the Table 7.

Table 7 *Comparison of prices on different semiconductor switches. [54]*

Shop\ Price on the device	Thyristor	GTO	IGCT	MOSFET	IGBT
Chip & Dip (Saint Petersburg, Russia)	U_{RRM}=2000 V, I_{TAV}=230 A, Vishay/ IR Price=184.85 €	—*	—*	N-type MOSFET V_{DS}=1500 V, I_D=2.5 A, Hitachi Price=7.5 €	Single switch with antiparallel diode V_{CES}=6500 V, I_C=200 A, Mitsubishi, Price≈1500 €

* Shop doesn't sell this device

Unfortunately according to Table 7, a detailed conclusion about prices can not be made, but price on the IGBT inverter which contains six switches will be at least $6 \cdot 1500 = 9000$ €.

3. SEMICONDUCTOR MATERIALS

3.1. Silicon (Si)

Silicon is the second most widely diffused element in the Earth's crust after oxygen. Silicon is a fundamental element in the most of semiconductor devices. Purity of silicon has great influence on its electrical and physical characteristics and consequently on characteristics of the produced semiconductor component. Hyperpure silicon is mostly used for production of single modules of nonlinear semiconductor devices. It is the primary product for the photovoltaic elements.

3.2. Germanium (Ge)

Germanium is applied for production of transistors and diodes. Ge has characteristics which are different from Si, in view of smaller unlocking voltages of PN-junction of Ge – 0.4 V against 0.6 V of Si devices. Besides, back currents of Ge devices on some orders are more than those at Si. Germanium is applicable only in production of low power devices.

3.3. Gallium arsenide (GaAs)

Some electronic properties of GaAs exceed properties of Si. Gallium arsenide possesses higher mobility of electrons which allows devices to work on frequencies to 250 GHz. Semiconductor devices on the basis of GaAs generate less noise, than silicon devices on the same frequency. Because of more high tension of electric field of breakdown in GaAs in comparison with Si, devices from gallium arsenide can work at higher power.

3.4. Silicon Carbide (SiC)

SiC has almost 170 polytypes and each of them has own physical characteristics. The best known are 3C-SiC, 4H-SiC and 6H-SiC. Only last two compounds are commercially available. Nowadays Silicon Carbide is one of the most promising semiconductor materials for manufacturing of power components. It has many favourable characteristics for high temperature, high frequency and high-power applications. In opposite to switches based on GaAs and Si, devices on SiC have following advantages:

- Band gap is several times wider than of GaAs;
- Field strength of electrical breakdown is ten times bigger than of Si ;
- High admissible working temperatures (to 600° C);

- Heat conductivity is three times more over Si and almost ten times more over GaAs;
- High-saturated drift velocity (higher than GaAs);
- Stability at radiation influence;
- Stability of electrical characteristics while temperature is changing;

Silicon Carbide has already been used in production of fast Schottky diodes, PIN diodes, zero recovery rectifiers, field effect transistors, MOSFETs and high-temperature thyristors.

In comparison to Si, SiC is more expensive and quite difficult to be manufactured, so for present Si has much better positions on the semiconductor market.

3.5. Gallium nitride (GaN)

GaN has even better physical parameters than SiC, specifically the excellent transport properties and low sensitivity ionizing radiation, which makes this material suitable for using in PV panels. It has the biggest success in optoelectronics, owing to its wide band gap which is 3.39 eV. In comparison to GaAs, GaN can work at higher temperatures and at much higher voltages. GaN is used for manufacturing of MOSFETS.

Table 8 Comparison of general properties of semiconductor materials. [39], [58], [59]

Characteristics\ Material	Si	Ge	GaAs	3C-SiC	4H-SiC	6H-SiC	GaN	Diamond
Band gap, eV	1.12	0.67	1.42	2.2	3.26	3	3.39	5.5
Breakdown field, MV / cm	0.6	0.1	0.6	2	3	3.2	3.3	6
Thermal conductivity, W/mK	150	60.2	50	500	490	490	130	2000
Electron drift $V_{SAT} \cdot 10^7$, cm / s	1	3.1	8	2.5	2	2	2.5	2
Electron mobility, cm^2 / Vs at 300K	≤1400	≤3900	≤8500	≤800	≤900	≤400	≤1000	≤2200

According to Table 8 it is obviously that traditional Silicon concedes in several properties, so all presented types of SiC have better results in all qualities. GaN has almost the same results, but it has

less thermal conductivity, than Si. From the other point of view production of Si is organized for many years and for today it is cheaper than produce other semiconductor elements. Production of SiC on the contrary is more difficult and expensive and in recent years it had not enough current capability because of defect levels. SiC based devices had not sufficient operating experience to ensure its reliability. But in spite of these SiC is very proper for usage in high-voltage application owing to its wide band gap and high breakdown voltage.

Diamond is presented in the Table 8. This material has outstanding qualities, but it is very expensive and extremely hard, so it accepts new shapes very difficult. Diamond is used in thin layers for special purposes, for example in combination with SiC. This compound is promising from the side of its great conductivity. [38], [58], [59]

4. MANUFACTURERS

4.1. ABB

ABB is global company which appeared in 1986 by the consolidation of Swedish ASEA (established in 1883 in Stockholm, Sweden) and Swiss BBC (established in 1891 in Baden, Switzerland). ASEA acquired Finnish Stromberg in 1987. Stromberg was established in 1889 in Helsinki, Finland. Headquarters of ABB is in Zurich, Switzerland. The semiconductors division of ABB is situated in Switzerland and it produces the whole range of semiconductor components:

Table 9 Survey of semiconductor devices produced by ABB. [14]

Type of the device	Voltage range (V_{DRM} / V_{RRM} / V_{CES}), V	Current range (I_C / I_{TGQM} / I_{TAVM} / I_{TAVM} / I_{FAVM} / I_{AV}), A
Thyristors	1200 – 8000	350 – 5080
GTO Thyristors	2500 – 4500, 3000 – 4500	800 – 4000
IGCTs	4500 –6500	520 – 4000, 1290 – 1700, 110 – 1010
IGBT and Diode dies	1200 – 6500	25 – 150
IGBT and Diode modules	1700 – 6500	150 – 3600

4.2. Infineon Technologies (Eupec)

Infineon Technologies has a global presence. Its headquarter is in Germany.

Table 10 Survey of semiconductor devices produced by Infineon Technologies. [15]

Type of the device	Voltage range (V_{DRM} / V_{RRM} / V_{CES} / V_{DS}), V	Current range (I_C / I_{TSM} / I_{FSM} / I_D), A
Diodes and modules	400 – 4400, 400 – 9000	710 – 110000
Thyristors and modules	200 – 10000	1050 – 100000
MOSFETs	30 – 900	-250 – 180
IGBT modules	600 – 6500	6 – 1200

4.3. Semikron

Semikron is global company with headquarters Nuremberg, Germany. It was established in Germany in 1951. Semikron presents following types of switches:

Table 11 Survey of semiconductor devices produced by Semikron. [16]

Type of the device	Voltage range $(V_{DRM} / V_{RRM} / V_{CES} / V_{DS})$, V	Current range $(I_C / I_{FAV} / I_{FSM} / I_D)$, A
Thyristor/ Diode modules	400 – 2000, 400 – 2000	15 – 1100
MOSFET modules	55 – 1700	10 – 400
IGBT modules	55 – 1700	10 – 400

4.4. International Rectifier

International rectifier (IR) was founded in 1947 in Los Angeles, USA. The main aim was production of Selenium rectifiers. Nowadays IR manufactures:

Table 12 Survey of semiconductor devices produced by International Rectifier. [17]

Type of the device	Voltage range (V_{BRDSS} / V_{CES}), V	Current range I_C at 100°C, A
MOSFET	12 – 300	3.5 – 303
IGBTs and modules	250 – 1200	3.9 – 130

4.5. Dynex Semiconductor

Dynex Semiconductor was established in 1956 and based in Lincoln, England. Company produces following components:

Table 13 Survey of semiconductor devices produced by International Dynex. [18]

Type of the device	Voltage range (V_{DRM} / V_{RRM}), V	Current range $(I_C$ at 80-85°C / I_{TAV} / I_{FAV} at 65-75°C), A
Diode modules	600 – 6000	295 – 10205
Thyristors	3300 – 4500, 16 – 20	493 – 760
GTO thyristors	1300 – 6500, 16 – 6500	250
IGBT modules	1200 – 6500,	200 – 2400

4.6. Mitsubishi Electric

Mitsubishi Electric was founded in 1921. The company appeared after Mitsubishi Shipbuilding Co. (now Mitsubishi Heavy Industries, Ltd.) extended activity of a factory in Kobe, Japan which made electrical motors for ocean vessels. New company was called Mitsubishi Electric Corporation. The head office is situated in Tokyo, Japan.

Table 14 *Survey of semiconductor devices produced by Mitsubishi Electric. [19]*

Type of the device	Voltage range $(V_{DRM} / V_{RRM} / V_{CES} / V_{DSS})$, V	Current range $(I_C / I_D / I_{TAV} / I_{TQRM} / I_F)$, A
Diode modules	300 – 6500 (max)	6.6 – 1200 (max)
Thyristor modules	300 – 1600 (min), 300 – 1600 (min)	10 – 200 (min)
GTO Thyristors	2500 – 6000	1000 – 6000 (min)
GCT Thyristors	6500 (max), 6500 (max)	400 – 1500 (max)
Power MOSFET modules	75 – 150	100 – 300
IGBT modules	600 – 1700	50 – 1000

4.7. Hitachi

Hitachi was founded in 1910 in a small Japanese town of the same name. Now headquarters of Hitachi is in Tokyo, Japan. Production of Hitachi is presented in the table below.

Table 15 *Survey of semiconductor devices produced by Hitachi. [20]*

Type of the device	Voltage range (V_{RRM} / V_{CES}), V	Current range (I_C / I_{FAV}), A
Power Diodes	100 – 14000	0.035 – 3
IGBTs	1200 – 6500	100 – 3600

4.8. Toshiba

Toshiba was established in 1875 Japan. Today it is a global network with headquarters in Tokyo, Japan. Company presents following devices:

Table 16 *Survey of semiconductor devices produced by Toshiba. [21]*

Type of the device	*Voltage range* $(V_{DSS} / V_{DS} / V_{CES}$ *at 25°C* $/ V_{RRM})$, V	*Current range* $(I_D / I_C / I_0)$, A
Diodes	100 – 1000	0.2 – 100
MOSFETs	-60 – 150, 600 – 650	-120 – 50
IGBTs	400 – 1500	5 – 60

4.9. Fuji Electric Systems

Company was founded in 1923 in Japan. Headquarter of company is in Tokyo, Japan. Fuji produces following range of semiconductor switches:

Table 17 *Survey of semiconductor devices produced by Fuji Electric Systems. [22]*

Type of the device	*Voltage range* $(V_{RRM} / V_{CES} / V_{DSS})$, V	*Current range* $(I_0 / I_D / I_C)$, A
Diodes	20 – 800	0.5 – 30
Power MOSFETS	-60 – 900	-25 – 100
IGBTs and modules	600 – 1700	2.5 – 3600

4.10 IXYS

IXYS started its activity in 1983 in a Silicon Valley, USA. Nowadays it manufactures:

Table 18 *Survey of semiconductor devices produced by IXYS. [23]*

Type of the device	*Voltage range* $(V_{CES} / V_{DSS} / V_{RRM} / V_{DRM})$, V	*Current range* $(I_C / I_D / I_{FAV} / I_{TAV}$ *at 55°C)*, A
Diodes	200 – 6000	130 – 3770
Thyristors	600 – 4500, 200 – 4000	16 – 6974
Power MOSFETs and modules	-600 – 4000	-140 – 340
Power IGBT and modules	600 – 4500	160 – 2400

4.11. Powerex

Powerex was established in 1986. Company was a result of consolidation of the Power Semiconductor Divisions of General Electric Company (GE) and Westinghouse Electric Corporation. At present

GE and Mitsubishi Electric share equal ownership of Powerex. Headquarters of company is in Youngwood, Pennsylvania. List of production is in the Table 19.

Table 19 Survey of semiconductor devices produced by Toshiba. [24]

Type of the device	Voltage range (V_{CES} / V_{DSS} / V_{RRM} / V_{DRM}), V	Current range (I_C / I_D / I_{TAV} at 80°C), A
Diode and Thyristor modules	600 – 6500	20 – 2000
Discrete rectifiers	200 – 6500, 200 – 6500	51 – 2500
Discrete Thyristors	200 – 6500, 200 – 6500	40 – 5000
MOSFET modules	75 – 1200	100 – 600
IGBTs	250 – 6500	10 – 1500

4.12. Fairchild Semiconductor

Fairchild semiconductor was founded in 1957 in Santa Clara Valley (also known as Silicon Valley), in Northern California, USA. Nowadays company has headquarters in San Jose, USA.

Table 20 Survey of semiconductor devices produced by Fairchild Semiconductor. [32]

Type of the device	Voltage range (V_{CES} / V_{DS} / V_{RRM} / V_{DRM}), V	Current range (I_C / I_D / I_{FAV}), A
Diodes and rectifiers	50 – 1000	0.5 – 35
MOSFETs	12 – 1000	-50 – 277
IGBTs	300 – 1500	2.7 – 180

4.13. JSC «Electrovipryamitel»

This factory was established in 1941 in Saransk, Russia. The headquarters of company is in the same city. Nowadays it is probably the most powerful Russian factory of semiconductor devices.

Table 21 Survey of semiconductor devices produced by JSC «Electrovipryamitel». [25]

Type of the device	Voltage range (V_{CES} / V_{RRM} / V_{DRM}), V	Current range (I_C / I_{RRM} / I_{DRM}), A
Diodes and modules	100 – 6000	3 – 150
Thyristors and modules	100 – 6000,	3 – 1000
IGBT modules	600 – 6500	600

4.14. JSC «Proton–Electrotex»

Proton-Electrotex was founded in 1996 in Orel city, Russia. It is young and promising company, which presents next devices:

Table 22 Survey of semiconductor devices produced by JSC «Proton–Electrotex». [26]

Type of the device	Voltage range (V_{CES} / V_{RRM} / V_{DRM}), V	Current range I_{AV}, A
Diodes and Diode modules	400 – 4400	68 – 7100
Thyristors and Thyristor modules	100 – 6500	160 – 3600

4.15. Resultant comparison of manufacturers

Comparison of range of produced switches, which is based on tables in section 4, can be made. Tables 9-22 give an understanding of availability of different components and their voltage and current ranges. Table 23 gives possibility to estimate the amount of companies producing every kind of switches.

The most interesting voltage range for this study is 6.5 kV and upper, but for the commercial market 6.5 kV is a limit for fully controlled switches nowadays. At present in the medium voltage drives only IGBT and IGCT can be applicable and will provide this voltage. Information about manufacturers who produce these devices with the highest current data also is shown in the Table 23.

Table 23 Comparison of production lines of the main players on the semiconductor market.

Manufacturer\devices	Diode	Thyristor	GTO	IGCT	MOSFET	IGBT
ABB	+	+	+	Asymmetric: V_{DRM}=6500V, I_{TGQM}=3800A. Reverse cond.: V_{DRM}=5500V, I_{TGQM}=1800A.		V_{CES}=6.5kV, I_C=750A.
Infineon Technologies (Eupec)	+	+			+	V_{CES}=6.5kV, I_C=750A.
Semikron	+	+			+	+
International Rectifier					+	+
Dynex Semiconductor	+	+	+			V_{CES}=6.5kV, I_C=400A.
Mitsubishi Electric	+	+	+	V_{DRM}=6500V, I_{TQRM}=1500A.	+	+
Hitachi	+					V_{CES}=6.5kV, I_C=750A.
Toshiba	+				+	+
Fuji Electric Systems	+				+	+
IXYS	+	+			+	V_{CES}=6.5kV, I_C=600A.
Powerex	+	+			+	+
JSC «Electrovipryamitel»	+	+				V_{CES}=6500V, I_C=600A.
JSC «Proton–Electrotex»	+	+				
Fairchild Semiconductor	+				+	+

If to analyze the thyristor group (thyristor, GTO, IGCT), it is obviously that thyristor is the most available device, but GTO and IGCT are not very available, because only three companies produce first device and only two produce the second one.

While analyzing availability of IGBT, it becomes evident that it hasn't any competitors and consumers have great possibility of choice between different manufacturers. This follows that nowadays

all main players of the semiconductor market produce IGBT. It shows that IGBT is the most available device for the MV drives. IGCT is maybe the best component for the upper rates of voltage in medium voltage and for high-voltage drives, at least till time at which there isn't IGBT of the same voltage ratings.

5. IGBT STRUCTURE TECHNOLOGIES

First generation of IGBT was produced in the end of 1980's of the last century. The first generation switches were quite slow in switching and inclined to failure. Second and third generations appeared in the early 1990's and were much improved. Development of devices goes in the direction of the increase working voltages and currents, efficiency and reduction of static and dynamic losses. Also in process of improvement of characteristics of IGBT, the thickness of crystal is decreased. Nowa-days PT IGBT, Non-PT IGBT and DS Trench IGBT generations are manufactured.

Today there are 600V, 1200V, 1700V, 2500V, 3300V, 6500 IGBTs on the market and developers permanently try to increase these ratings.
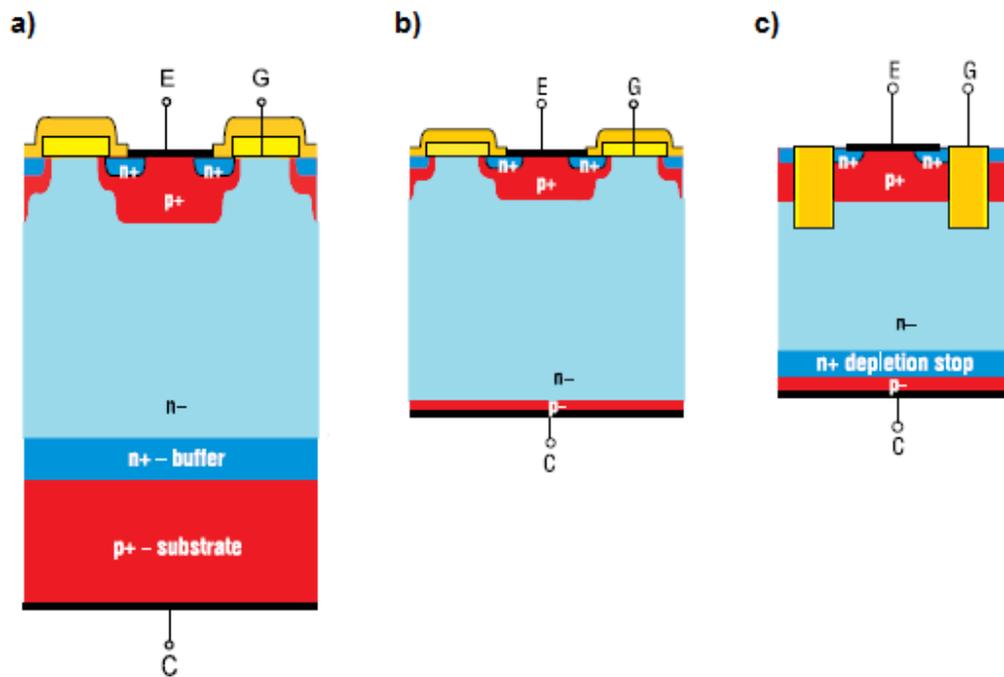
Figure 12 *a) Punch-through IGBT structure, b) Non-punch-through IGBT structure, c) Trench IGBT struc-
ture. [17]*

5.1. Punch-through (PT-IGBT)

Punch-through IGBT is used quite thick chips made from epitaxial wafers with additional
buffer N+ layer, which plays role of field stop layer. Extra layer has two general functions: avoids failure by punch-through action because the depletion region expansion at applied high voltage is restricted by this layer and reduces the tail current during turn-off and shortens the fall time of the IGBT, because the holes are injected by the P+ collector partially recombine in this layer. The small

tail current is a typical characteristic of NPT-IGBTs. The thickness of crystal of PT-IGBTs is more than 300 μm. PT-IGBT structure is presented on the Figure 12a.

5.2. Non-punch-through (NPT-IGBT)

Non-punch-through IGBT has P-N-P-N structure, which is very similar to structure of power MOSFET except of P+ injecting layer. For the N-type IGBT, which is presented in the Figure 10a, N+ layer on the top is emitter and P- on the bottom is collector. Transistor can be P-type. In this case the structure of the device is reversed. NPT-types have thinner chips, which are lower cost, because they haven't extra N+ layer. The thickness of IGBT crystal is about 87 μm. NPT-IGBT structure is depicted on the Figure 11b.

NPTs are medium speed switches, so they have a good balance between switching and conduction losses.

NPT-IGBTs have the same forward and reverse breakdown voltages, therefore they are proper for AC applications. PT-IGBTs have less reverse breakdown voltage than forward breakdown voltage, so they are more suitable in DC circuits, where there isn't necessity to conduct in reverse direction.

The comparison table of PT- and NPT- types of transistors was made by Abdus Sattar from IXYS Corporation. This research is presented in the Table 24.

Table 24 Comparison of PT- and NPT-IGBT. [31]

Characteristic\ Type of IGBT	PT	NPT
Switching loss	**Low** Short tail current. Significant increase in E_{OFF} with T	**Medium** Long, low amplitude tail current. Moderate increase in E_{OFF} with T
Conduction loss	**Low** Flat to slight decrease with T	**Medium** Increases with T
Paralleling	**Difficult** Must sort on $V_{CE(ON)}$	**Easy** Optional sorting. Recommend share heat
Short-circuit rated	**Limited** High gain	**Yes**

PT-IGBT and NPT-IGBT have planar cell design for the gate-emitter structure.

5.3. Soft-punch-through/ Light-punch-through IGBT (SPT/LPT-IGBT)

Soft-punch-through concept is based on the usage of low doped N-buffer layer on the anode side of the IGBT. SPT-type took best qualities from each of PT and NPT. In comparison to existing NPT technology, SPT has 20% lower on-state losses, 20% lower switching losses and it hasn't increase of thermal resistance. Relative comparison of new modification with traditional NPT was made by ABB and presented on the Figure 11.
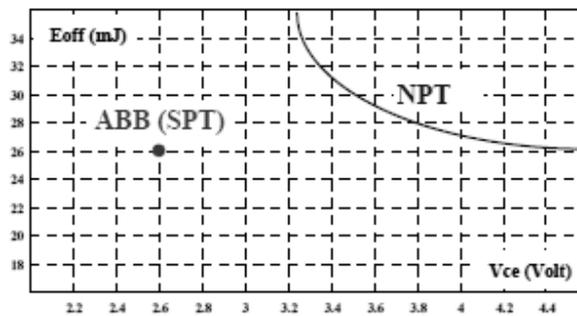
Figure 13 Comparison of SPT and NPT. [33]

Soft-punch-through IGBT was designed for using in the LoPak modules. Owing to its resistive characteristics, SPT is well suited to parallel connection. [33], [34]

5.4. Depletion stop/ Field stop trench IGBT

The next generation of IGBT has trench design of gate-emitter structure. It contains vertical gate and depletion layer, which is also known as a field stop layer. The thickness of crystal becomes about 70 µm. Structure is shown on the Figure 12c.

Trench cell design has very low $V_{CE(ON)}$, because it increases channel density and reduces the resistance of JFET, which was typical for the planar structure. Trench IGBTs have lower conduction losses and switching losses. It is particularly valuable in the low frequency applications, where low conduction losses are most important.
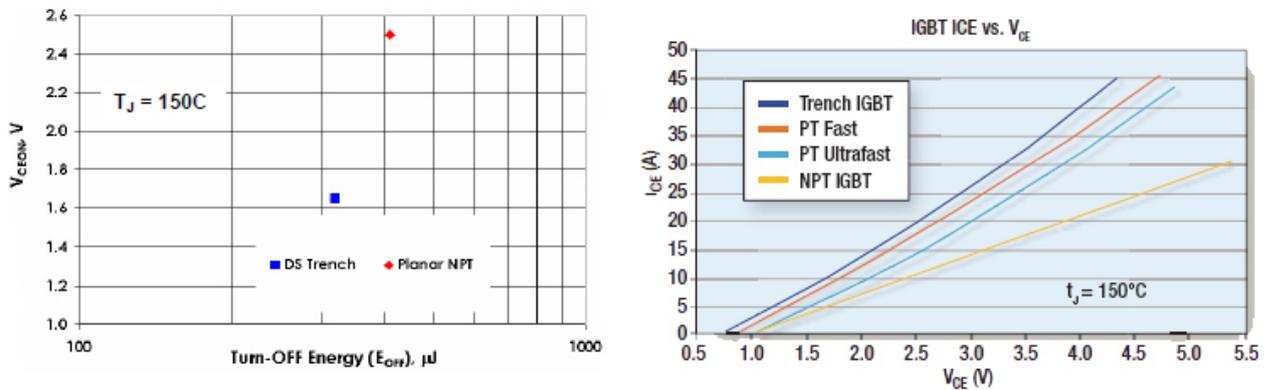
Figure 14 Benefits of trench structure over planar structure. [35], [36]

With help of Figure 12 it is evident how the structure of IGBT and thickness of crystal was changed during the development of IGBT.

5.5. Injection enhanced gate transistor (IEGT)

This device unites advantages of traditional IGBTs: low power for operation and large safe operational area. MOS gate structure in IEGT works as an emitter with high electron injection and it stores high amount of carriers in the N-type high resistance base layer at the emitter side. IEGT has similar on-state characteristics with a thyristor. This switch has high current capability which demands high short circuit ability. Like a thyristor it has same distribution of current density and low forward voltage drop. These differs IEGT from conventional IGBT. IEGT also can have planar structure. Example of trench structure IEGT is depicted on the Figure 15a. [51]

5.6. Carrier stored trench bipolar transistor (CSTBT)

CSTBT is quite new invention of Mitsubishi Electric. Device has advantages of the conventional trench structure IGBT. In addition to traditional structure CSTBT has extra N-type layer in the emitter side for the carrier storing. The concentration of the N layer, which is known as conservation of charge layer, is higher than the N-layer, thus N layer can control the shift of holes to the P base. The function of charge conservation significantly improves characteristics of the on-state in comparison with traditional trench IGBT. CSTBT structure is depicted on the Figure 15b and can be compared with IEGT structure (Figure 15a) and classical trench IGBT structure (Figure 12c). [50]

a)

b)
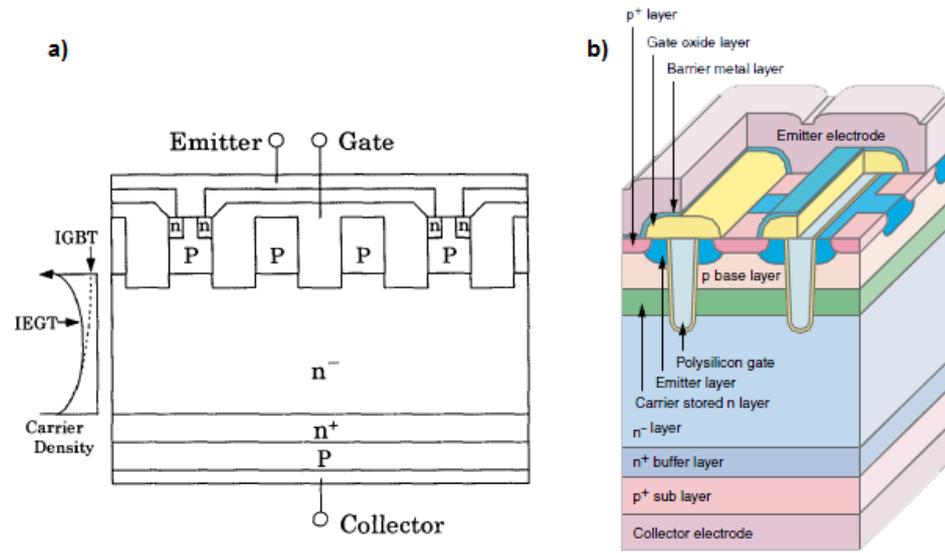
Figure 15 *a) Current density and IEGT structure, b) CSTBT structure. [50], [51]*

6. CHARACTERISTICS OF IGBT

Examples of characteristics were taken from the datasheet of FZ750R65KE3T IGBT with V_{CES}=6.5 kV/ I_{C_NOM}=750 A, produced by Infineon Technologies.

6.1. Static characteristics

In the on-state V_{CE} depends on I_C, V_{GE} and T_J. V_{CE} presents voltage drop while IGBT is conducting. It shows dissipation losses, therefore collector-emitter voltage should be as low as possible. V_{CE} increases in direct proportion to I_C and inversely proportional to V_{GE}. If value of I_C is small, while T_J increases, so V_{CE} decreases and vice versa, if I_C is large and T_J increases, so V_{CE} increases. [37]
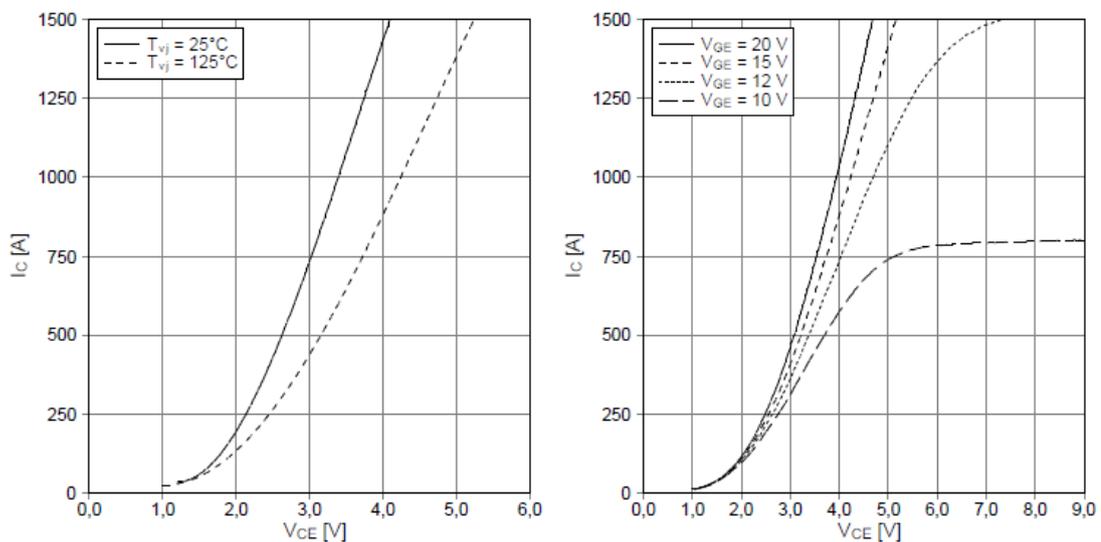
Figure 16 $I_C - V_{CE(SAT)} - V_{GE}$ *characteristics of FZ750R65KE3T. [45]*

6.2. Switching characteristics

First of all switching losses appear because of slow elimination of holes in the drift layer after the V_{GE} became lower than the threshold voltage, which turns off the switch. The holes recombine or are swept out by the voltage deviation. This process causes current tail. For example in PT-IGBTs additional buffer layer quickly absorbs remaining holes.

At higher I_C or T_J, the switching time increases causing higher losses. When IGBT is used in different assemblies like inverter, switching time can exceed dead time of the adjacent IGBT which lead to short circuit. If t_9-t_{10} or t_F (Figure 18b) is too short, the transient current will rapidly change ($\dfrac{di}{dt}$)

and because of the circuit inductance, voltage spike will occur ($L\frac{di}{dt}$). The gate resistance also influences on losses with direct proportion.

Switching losses E_{ON} and E_{OFF} occurs permanently during the switching, so they should be minimized as much as possible. [36], [37]
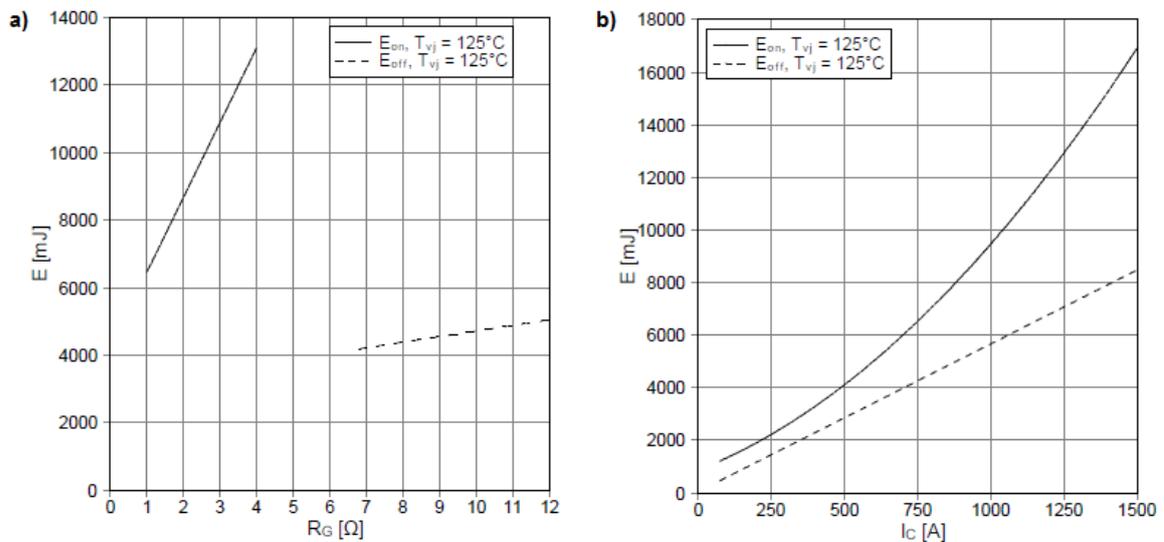
Figure 17 Switching losses of IGBT: a) E_{ON}, E_{OFF} – R_G curves, b) E_{ON}, E_{OFF} – I_C characteristics of FZ750R65KE3T. [45]

6.3. Gate resistance

Process of gate charge is controlled by gate resistance. If the resistance is smaller, so loss and switching times will be smaller, but in this case noises can appear. If IGBT is used with FWD in module, smaller values of R_G follows to switching on higher $\frac{di}{dt}$, therefore diode has to recover on higher $\frac{du}{dt}$ which cause overvoltage transients. R_G influences on RBSOA and SCSOA (more in details about SOAs in chapter 6.5). The rated value is usually given in datasheets by manufacturers and example of dependence of dissipated energy form gate impedance is illustrated on the Figure 17a. [38]

Turn-on characteristics are determined by MOSFET part of structure and they are influenced by the gate drive impedance. Turn-off characteristics are determined by the minority carriers recombina-

tion, which is indirectly influenced by MOSFET turn-off. Increasing of gate drive resistance continues the Miller effect and causes delay in the current fall, which also is named as current tail. Current tail can be seen on the Figure 18b on the time interval t_{10}-t_{11}. Turn-on losses appear in switches independently on the speed of switching, whereas turn-off losses depend on the speed of IGBT. This way fast IGBT will be less affected by the qualities of gate drive impedance, than ultrafast IGBT. Thus ultrafast IGBT should have lower gate drive impedance than fast IGBT.
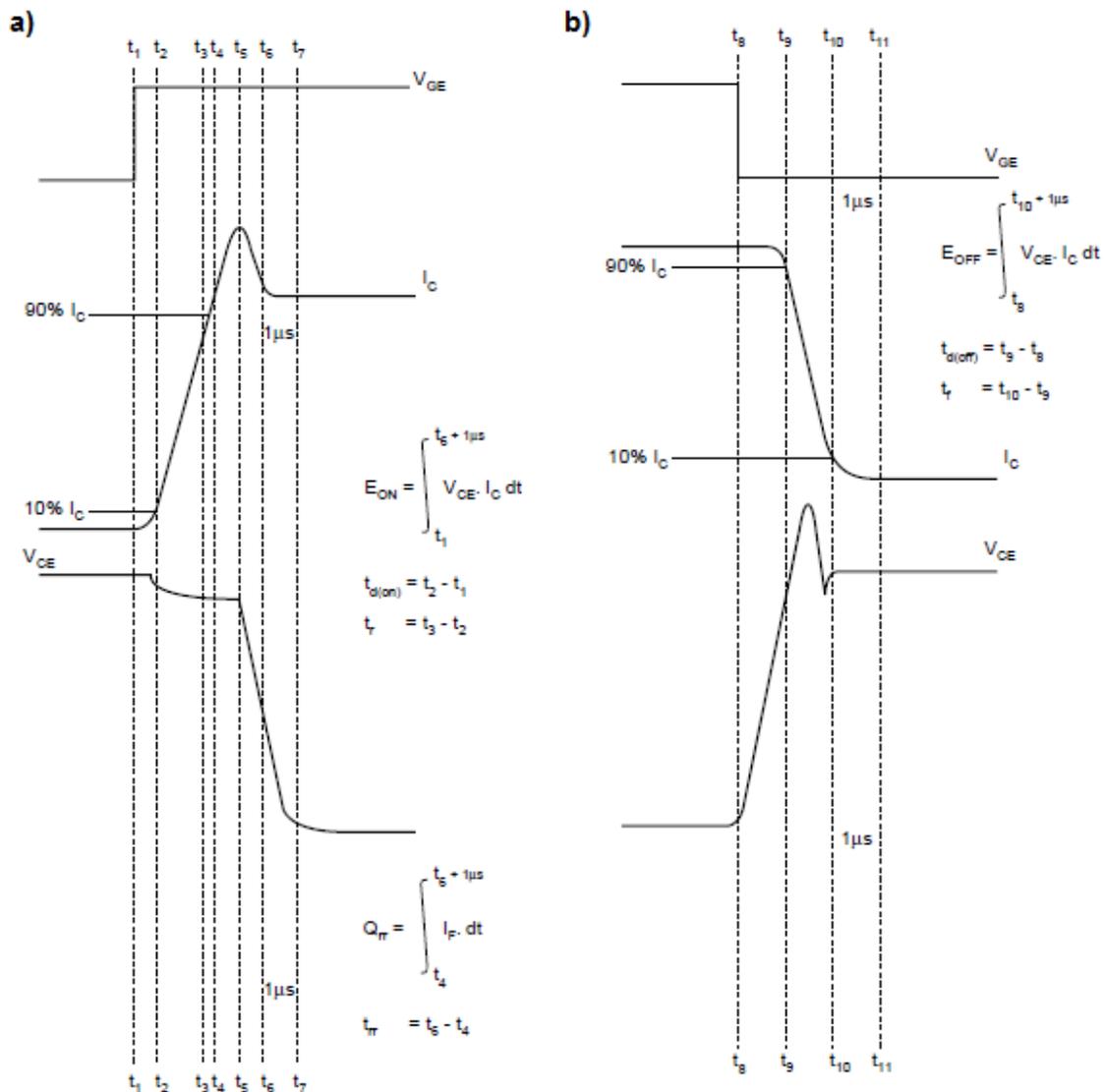
Figure 18 Typical switching characteristics of IGBT. a) Turn-on, b) Turn-off. [38]

It should be mentioned that in different sources gate resistance is named as gate impedance. From the point of view of classical physics it is wrong substitution, but in case of

semiconductor devices both of these definitions suppose resistance or active power dissipation.

6.4. Capacitance characteristics

The knowledge of capacity of the gate charge gives estimation of charge which required for operating the IGBT and power supply capacity of the drive circuit can be determined. Capacitances of IGBT are usually measured under special conditions. Some manufacturers specify typical values: V_{GE}=0 V, f=1 MHz and V_{CE}= 30 V. IGBT has several following parasitic capacitances:

$$C_{IES}=C_{GE}+C_{GC} \ (C_{CE} \text{ is shorted}), \tag{7.1}$$

$$C_{RES}=C_{GC}, \tag{7.2}$$

$$C_{OES}=C_{CE}+C_{GC}, \tag{7.3}$$

Characteristics described above should be taken into account while designing the drive circuit.
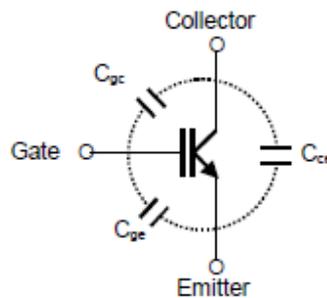
Figure 19 Equivalent circuit showing parasitic capacitances. [36]

During the charging of gate charge, V_{GE} and V_{CE} are fluctuating. [36], [37]

6.5. Safe operating areas (FBSOA, RBSOA, SCSOA)

Following SOAs show limits of safety operation of the device in different operation modes. This information is usually provided in datasheets.

Forward Bias Safe Operating Area *(FBSOA)* in IGBT shows the maximum voltage which device can withstand without failure, when the I_C is saturated.
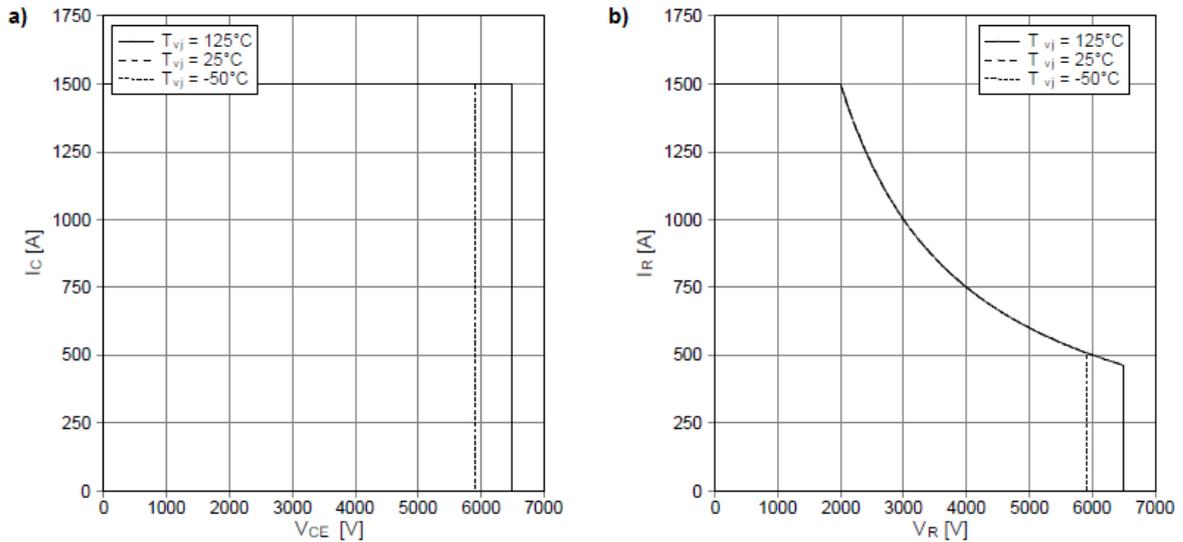
Figure 20 a) RBSOA of IGBT, b) SOA of FWD of FZ750R65KE3T. [45]

Reverse Bias Safe Operating Area (RBSOA) is area of safe operation of the IGBT, during the switch off. RBSOA gives maximum values of voltage and currents which the component is capable to switch. The maximum I_C is usually 200% of rated current at 85 % of V_{CES}, with T_J=125°C. As opposed to FBSOA in RBSOA a snubber circuit is important for safe switching off.

Short Circuit Safe Operating Area *(SCSOA)* determines borders of safe operation during the fault. Example of SOAs is depicted on the Figure 20 on the previous page. [36], [37], [38]

6.6. Internal diode (FWD) characteristics

Free wheel diode connected in anti-parallel with IGBT. It allows module to conduct in reverse direction. This made when inductive load is used. FWD prevents voltage spike in case of change or reduction of voltage over the inductive element.

Characteristics of diode depend on I_C and T_J. Diode current ratings I_F are usually about $\frac{2}{3}$ of nominal IGBTs ratings. Blocking voltage and junction temperature are the same to IGBT. Figure 21 presents example of main characteristics of FWD. [37], [38]
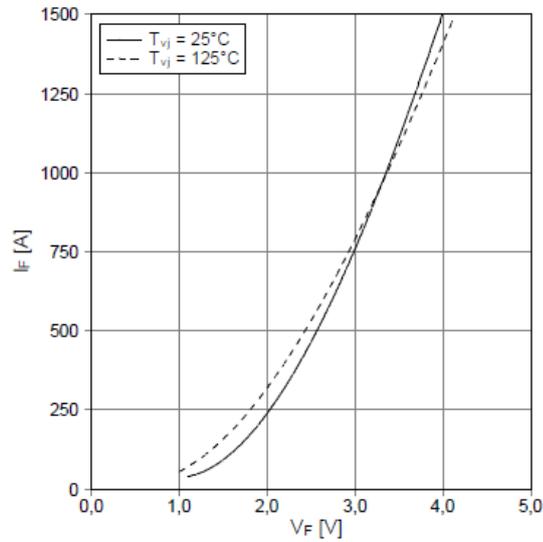
Figure 21 I_F – V_F *characteristics of the FWD of FZ750R65KE3T. [45]*

6.7. Transient thermal resistance characteristics

During the work IGBT module dissipates energy in form of heat. This makes worse characteristics and reduces the lifetime of the equipment. Transient thermal characteristics are used to calculate the temperature rise of the module and the heat sink should be chosen relying on these results. Example of dependence of thermal impedance from time for selected IGBT is illustrated on the Figure 22.
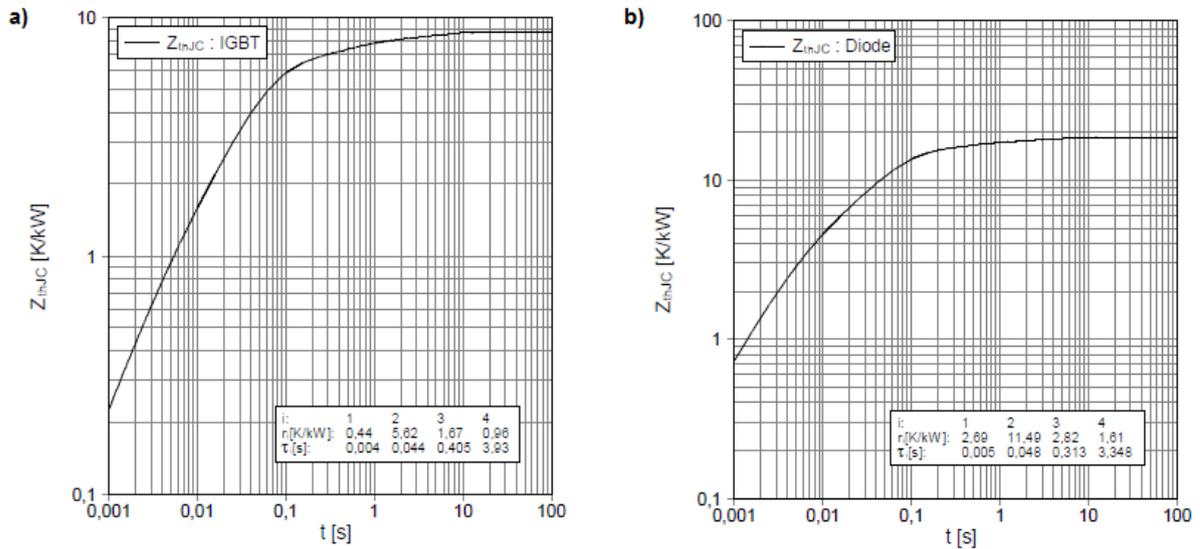
Figure 22 Thermal impedance – time characteristics of a) IGBT b) FWD of FZ750R65KE3T. [37]

Thermal characteristics include Z_{TH} and R_{TH}. Z_{TH} shows the change of temperature of the device in time. R_{TH} shows the conduction properties of the switch and it can be divided on several parts (equation 7.4). [36], [38]

$$Z_{TH}=Z_{TH(JC)}+Z_{TH(HA)}+Z_{TH(CH)}, \tag{7.4}$$

7. CONNECTION OF IGBT

7.1. Series connection of IGBT

Permanent grow of voltage ratings leads to necessity connect either one powerful switch or several in series connection. Series connection hasn't lost its urgency even with development of 6.5 kV power devices. Series connection strongly depends on device characteristics and mismatching of the drive circuit. Turn-off of series connected devices has difficulty appearing because of following factors:

- Unequal device switching characteristics;
- Unequal device leakage current;
- Unequal stray inductance in the series circuit;
- Unequal gate drive delay;

One of important moments in series operation is to match static and dynamic balancing of voltages. The problem of static voltage balancing can be easily solved by adding a resistor in parallel connection with each switch. There are two available dynamic voltage balancing technics: load side balancing and gate side balancing. The load side balancing demands a snubber circuit and a clamp circuit. This scheme is not applicable in high voltage application, because these circuits cause high losses which directly proportional to switching frequency. On the contrary active gate control may be more preferable. [60]

7.2. Parallel connection of IGBT

Modern high power applications and industrial drives require switches which can handle high voltages and currents. The solution is parallel connection of components. A difference of output characteristics of parallel connected IGBT can cause a voltage and current imbalance. This is shown on the Figure 23b.
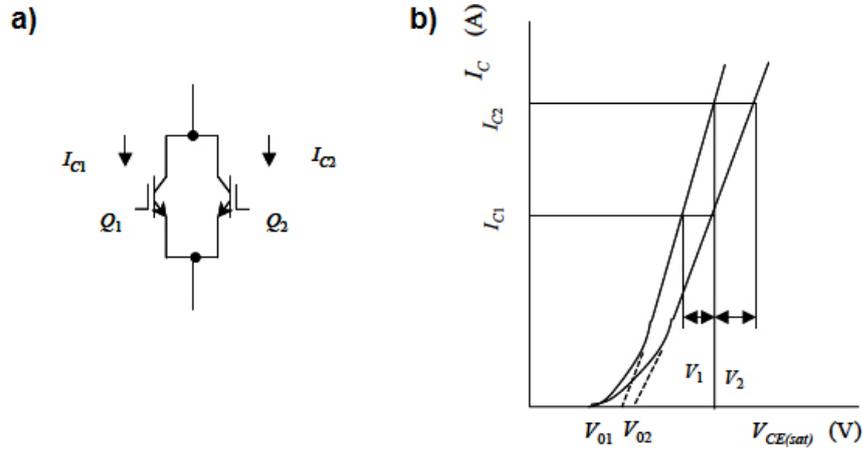
Figure 23 a) Parallel connection of IGBT, b) $I_C - V_{CE(SAT)}$. *[37]*

The output characteristics of IGBT are expressed in equations 8.1 – 8.4.

$$V_{CE\_Q1} = V_{01} + r_1 \cdot I_{C1}, \qquad (8.1)$$

$$r_1 = V_1 / (I_{C1} - I_{C2}), \qquad (8.2)$$

$$V_{CE\_Q2} = V_{02} + r_2 \cdot I_{C2}, \qquad (8.3)$$

$$r_2 = V_2 / (I_{C1} - I_{C2}), \qquad (8.4)$$

It is evident that total current in parallel connection of switches is a sum of currents through the devices:

$$I_{C\_TOTAL} = I_{C1} + I_{C2}, \qquad (8.5)$$

Consequently, collector currents of each IGBT can be derived as following:

$$I_{C1} = (V_{02} - V_{01} + r_2 \cdot I_{C\_TOTAL}) / (r_1 + r_2), \qquad (8.6)$$

$$I_{C2} = (V_{01} - V_{02} + r_1 \cdot I_{C\_TOTAL}) / (r_1 + r_2), \qquad (8.7)$$

$V_{CE(SAT)}$ is the principal factor which influences on the appearance of imbalance, so it is very important to select devices with similar value of $V_{CE(SAT)}$. [37]

It is impossible to exactly avoid imbalance only by choosing right semiconductor switches, so there are several voltage/current balancing technics which are shown on the Figure 24. This thesis doesn't tell in details about these technics, their advantages and disadvantages, but only shows existing variety of them and points out the appearance of problems while using parallel connection.
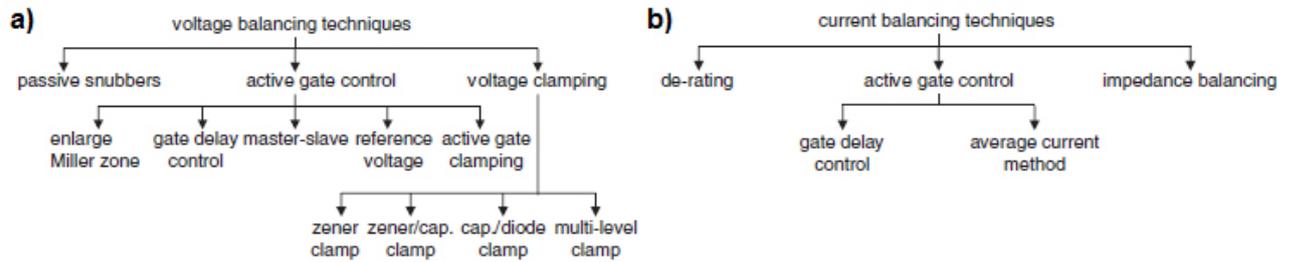
Figure 24 a) Voltage balancing technics, b) Current balancing technics. [43]

Special packages for parallel connected IGBT modules are used. Different manufacturers have different technologies, but all of them use similar principles. Further in section 9 it will be told more in details about principles of assembly of modern semiconductor devices.

7.3. Hybrid IGBT-IGCT switch

At present there is a range of semiconductor devices with finite amount of advantages and disadvantages. It can be bright idea to unite several switches in the same assembly with aim to use their strong sides.

Performance of power application can be improved by usage of IGBT and IGCT connected in parallel. Characteristics of switches have to correspond to each other. Advantage of IGCT is in low turn-on and on-state losses, while IGBT has high overcurrent capability and low turn-off losses. Construction contains IGBT associated with FWD and asymmetrical IGCT.
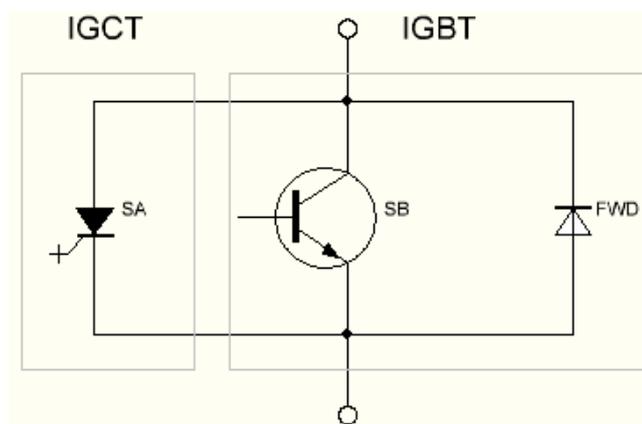
Figure 25 Scheme of considered hybrid switch. [61]

This idea was implemented in PSPICE software by scientists of Tallinn University of Technology. They selected 4.5 kV press-pack switches: 5SHY35L4512 (ABB) and T0900EA45A (Westcode, IXYS). [61] Devices have similar turn-on behavior, while at turn-off IGCT is much slower, which causes higher losses. Switches conduct full input current, as opposed to parallel connection of same switches. In the other point of view total power dissipation is decreased in comparison with single switches, which allow increasing of switching frequency and reduction of cooling requirements. In case of failure of one of switches, second is able to operate individually.

Following parameters were chosen for the simulation: the input voltage was equal 2800 V, the maximum load current – 750 A and the switching frequency was 750 Hz. Some results of combined work of two devices are presented on the Figure 26.
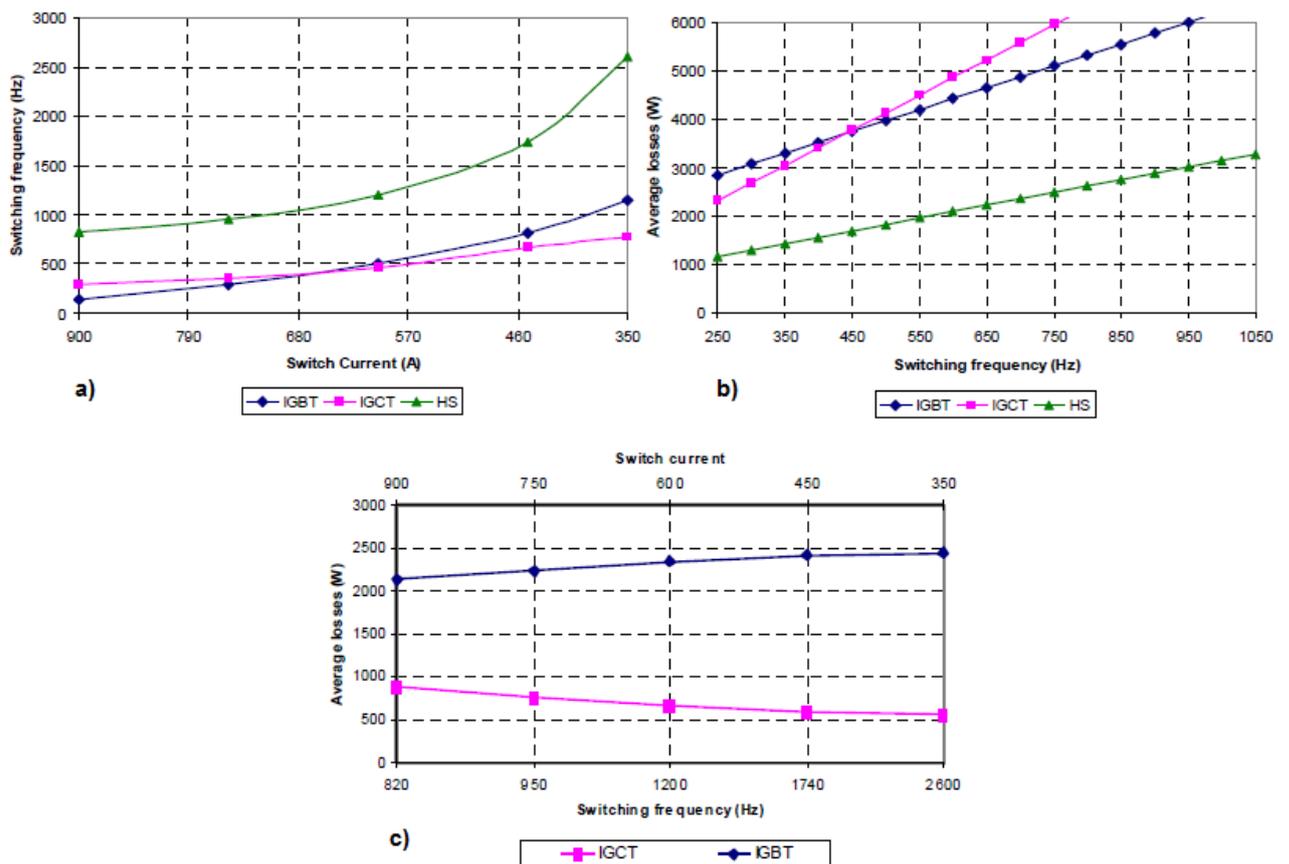
Figure 26 a) Switching frequency – current, b) Switch power dissipation – switching frequency, c) Breakdown of power losses. [61]

In spite of advantages of hybrid switch it also has disadvantages in comparison with parallel connection of same switches:

- Price;
- Decreased maximum current capability;

Presented hybrid switch can be useful in applications where higher frequencies and reduced cooling systems are required. [61]

8. LOSS CALCULATION

As was told in the section 2.6, nowadays the most attractive semiconductor components for medium-voltage drives are IGBT and IGCT, so it is necessary to compare losses of these two devices.

Methodology used for calculation of IGBT losses was taken from the application note of Infineon Technologies. IGCT is calculated with usage of methodology of ABB. Switching frequency for both calculations is average.

8.1. IGBT loss calculation

IGBT module FZ750R65KE3T produced by Infineon Technologies was selected for the losses analysis. This device is suit for MV converters and traction drives. V_{CES}=6500 V, I_{C_NOM}=750 A. Assume that T_j=125 °C, V_{GE}=15 V, f_{SW}=500 Hz.

Curves presented on the Figure 27 are taken from the datasheet of chosen device and give a possibility to get r_C, r_D, U_{CE0} and U_{D0}.
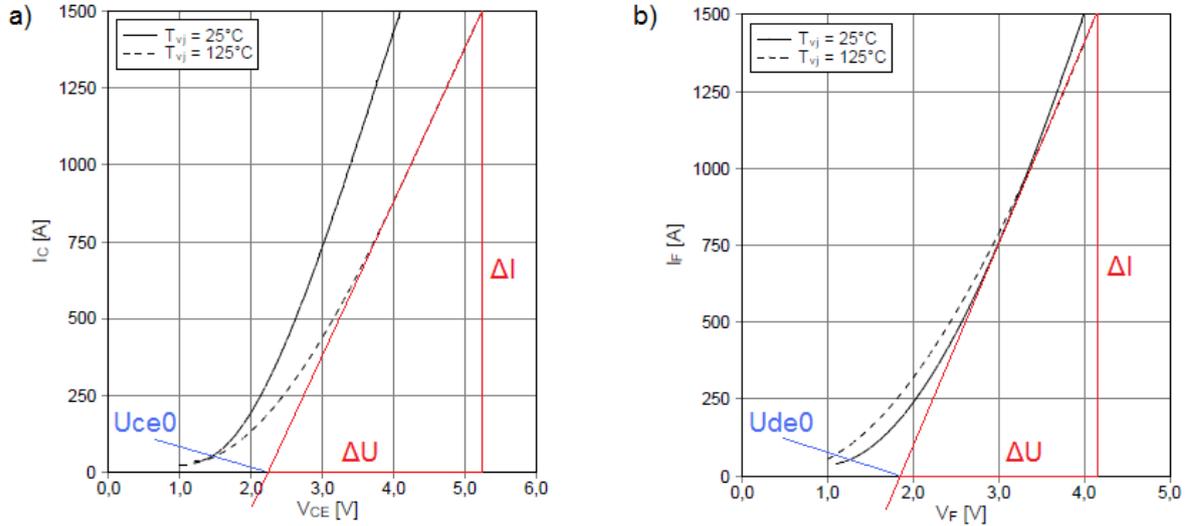
Figure 27 *Determination of a) r_C of IGBT, b) r_D of the diode. [47]*

Received from Figure 27 values of voltages ΔU and currents ΔI are put into equations 9.1, 9.2:

$$r_C = \frac{\Delta U_{CE}}{\Delta I_C} = \frac{3}{1500} = 2 \cdot 10^{-3}\, \text{Ohm}, \qquad (9.1)$$

$$r_D = \frac{\Delta U_F}{\Delta I_F} = \frac{2.4}{1500} = 1.6 \cdot 10^{-3}\, \text{Ohm}, \qquad (9.2)$$

Conducting losses of IGBT and diode are calculated as follows in 9.3 and 9.4 respectively:

$$P_{\text{CT}} = \frac{1}{T_{\text{SW}}} \cdot \int_0^{T_{\text{SW}}} (u_{\text{CE0}} \cdot i_{\text{C}}(t) + r_{\text{C}}(t) \cdot i_{\text{C}}^2(t))dt = 2.2 \cdot 200 + 2 \cdot 10^{-3} \cdot 750^2 \approx 1570 \, \text{W}, \qquad (9.3)$$

$$P_{\text{CD}} = \frac{1}{T_{\text{SW}}} \cdot \int_0^{T_{\text{SW}}} (u_{\text{D0}} \cdot i_{\text{D}}(t) + r_{\text{D}} \cdot i_{\text{D}}^2(t))dt = 1.8 \cdot 250 + 1.6 \cdot 10^{-3} \cdot 750^2 = 1350 \, \text{W}, \qquad (9.4)$$

Switching losses are found by using of turn-on state and turn-off state losses in the 9.5 equation. These values are taken from the datasheet.

$$P_{\text{SWT}} = (E_{\text{ON}} + E_{\text{OFF}}) \cdot f = (4200 \cdot 10^{-3} + 3600 \cdot 10^{-3}) \cdot 500 = 3900 \, \text{W}, \quad (9.5)$$

Turn-on energy of the diode mostly consists of reverse-recovery energy, which is taken from datasheet: E_{REC}=1400 mJ, and power can be calculated as follows in 9.6:

$$P_{\text{SWD}} = E_{\text{REC}} \cdot f = 1400 \cdot 10^{-3} \cdot 500 = 700 \, \text{W}, \qquad (9.6)$$

Power losses of the IGBT and the diode can be determined as a sum of conductive losses and switching losses:

$$P_{\text{TOT}} = P_{\text{CT}} + P_{\text{SWT}} + P_{\text{CD}} + P_{\text{SWD}} \approx 7500 \, \text{W}, \qquad (9.7)$$

Result analysis will be made in the section 8.3. [45], [47]

8.2. IGCT loss calculation

Reverse conducting GCU08BA-130 GCT produced by Mitsubishi Electric, was selected for losses analysis. The main reason of the choice of this model of GCT is its ability for reverse conducting and correspondence of voltage and current to IGBT selected in the previous section. Almost all values for calculation are taken from the datasheet. Main values are $V_{\text{RRM}}/V_{\text{DRM}}$=6500V, I_{TQRM}=800A. For calculation of power in the on-state it is necessary to find $P_{\text{AV(M)}}$, I_{TAVM} and $I_{\text{T(RMS)}}$. These was made in equations 9.8-9.10.

$$P_{\text{AVM}} = \frac{T_{\text{vjmax}} - T_C}{R_{\text{th(jc)}}} = \frac{125°C - 80°C}{0.025k/W} = 1800 \, \text{W}, \qquad (9.8)$$

Values of I_{TAVM} and $I_{\text{T(RMS)}}$ can be taken from the datasheet.

$$I_{\text{TAVM}} = 2 \frac{\sqrt{V_{(\text{T0})}^2 + r_{\text{T}} \cdot \pi^2 \cdot P_{\text{AVM}}} - V_{(\text{T0})}}{r_{\text{T}} \cdot \pi^2} = 330 \, \text{A},$$

$$(9.9)$$

$$I_{\text{T(RMS)}} = I_{\text{TAVM}} \cdot \frac{\pi}{2} = 330 \cdot \frac{\pi}{2} = 520 \text{ A}, \tag{9.10}$$

On-state power is calculated in the 9.11. This methodology of losses calculation was taken in the ABB tutorial, but Mitsubishi Electric does not give r_T and V_{T0} which are necessary for calculation, so assume that $r_T = 0.56 \cdot 10^{-3} \, \Omega$ (value was taken in the datasheet of 5SHY 42L6500 assymetric IGCT, produced by ABB with V_{DRM}=6500 V/ I_{TGQM}=3800A) and assume that $V_{(T0)} = V_{\text{GT}} = 1.5 \text{ V}$ (value of V_{GT} is the nearest to $V_{(T0)}$ which can be used. Officially this substitution probably is not correct.)

$$P_{\text{ON\_STATE}} = V_{\text{T0}} \cdot I_{\text{TAV}} + r_T \cdot I_{\text{T(RMS)}}^2 = 1.5V \cdot 330A + 0.56 \cdot 10^{-3} \Omega \cdot 520^2 A \approx 650 \text{ W}, \tag{9.11}$$

Further power during the switching is found:

$$P_{\text{TURN\_ON\_IGCT}} = E_{\text{ON}} \cdot f = 0.6J \cdot 500Hz = 300 \text{ W}, \tag{9.12}$$

$$P_{\text{TURN\_OFF\_IGCT}} = E_{\text{OFF}} \cdot f = 2.3J \cdot 500Hz = 1150 \text{ W}, \tag{9.13}$$

$$P_{\text{TURN\_OFF\_DIODE}} = E_{\text{RR}} \cdot f = 4.4J \cdot 500Hz = 2200 \text{ W}, \tag{9.14}$$

The total sum of losses is presented in the equation 9.15:

$$P_{TOT} = P_{\text{ON\_STATE}} + P_{\text{TURN\_ON}} + P_{\text{TURN\_OFF}} + P_{\text{TURN\_OFF\_DIODE}} \approx 4300 \text{ W}, \tag{9.15}$$

Result analysis will be made in the section below. [48], [49], [66]

8.3. Loss calculation analysis

Received values and calculations are not verified and couldn't be used for accurate choice of equipment. Obtained results shows order of losses.

Both of switches have advantages and disadvantages. Losses calculation of single switch helps to confirm strong and weak sides of devices in different states. Switching frequency used in calculation was quite low and it is obvious that switching losses directly depend on frequency.

In the on-state IGCT obviously has more favourable characteristics than IGBT. It is caused by the high impedance of IGBT in the on-state. During turn-on IGBT dissipates more energy than IGCT, whereas during turn-off IGBT has lower losses as opposed to IGCT.

Table 25 *Comparison of results of calculation of losses of IGBT and IGCT in different states at f=500 Hz.*

State/ Device	IGBT	IGCT
On-state (conduction losses), W	1570+1350 (IGBT+diode)	650
Turn-on (switching losses), W	2100	300
Turn-off (switching losses), W	1800+700 (IGBT+diode)	1150+2200 (IGCT+diode)
Total losses, W	7500	4300

Total losses of IGBT are bigger than IGCT losses. It should be noticed that IGBT module contain three single switches and each with antiparallel diode, while IGCT contains only one switch. In case of the simplest inverter, which consists of 6 switches, it will be necessary to use only two IGBT modules and six IGCT ones, therefore total losses of IGBT based inverter would be less.

At present IGBT and IGCT have very similar losses in the same power ratings, so sometimes it can be very difficult to choose more appropriate switching component for some applications. In case of low voltages of MV segment, IGBT probably will remain the most attractive semiconductor switch, because as was told in chapter 4.15 it is the most available component.

From the point of view of ideal switch, IGCT can be named ideal in conduction state owing to its low losses and high overload ability, whereas IGBT is ideal in turn-off state. It is evident that this opinion is very optimistic, but it shows main idea.

9. FUTURE OF POWER SEMICONDUCTORS

9.1. Assemblies of IGBT

At present new demands to ease of usage and reduction of influence on the environment employ new technologies of performance power semiconductor modules. It leads to reduction of size and power losses and increasing of reliability in the motor controllers. Today manufacturers make an emphasis on production devices with environmentally friendly behaviour. Contemporary switches should be compliant with ROHS directive, which came into force in European Union in 2003. According to this directive all produced components have to tend to reduction of amount of used hazardous substances.

There is a tendency to assemble several arrangements in the same case. It allows reducing size and weight of the equipment. In addition to modules companies develop hybrid devices which unite advantages of several other devices. At present hybrid integrations can be divided on following groups: module, IPM, intellectual subsystem and intellectual electronic power system. This is depicted on the Figure 28.
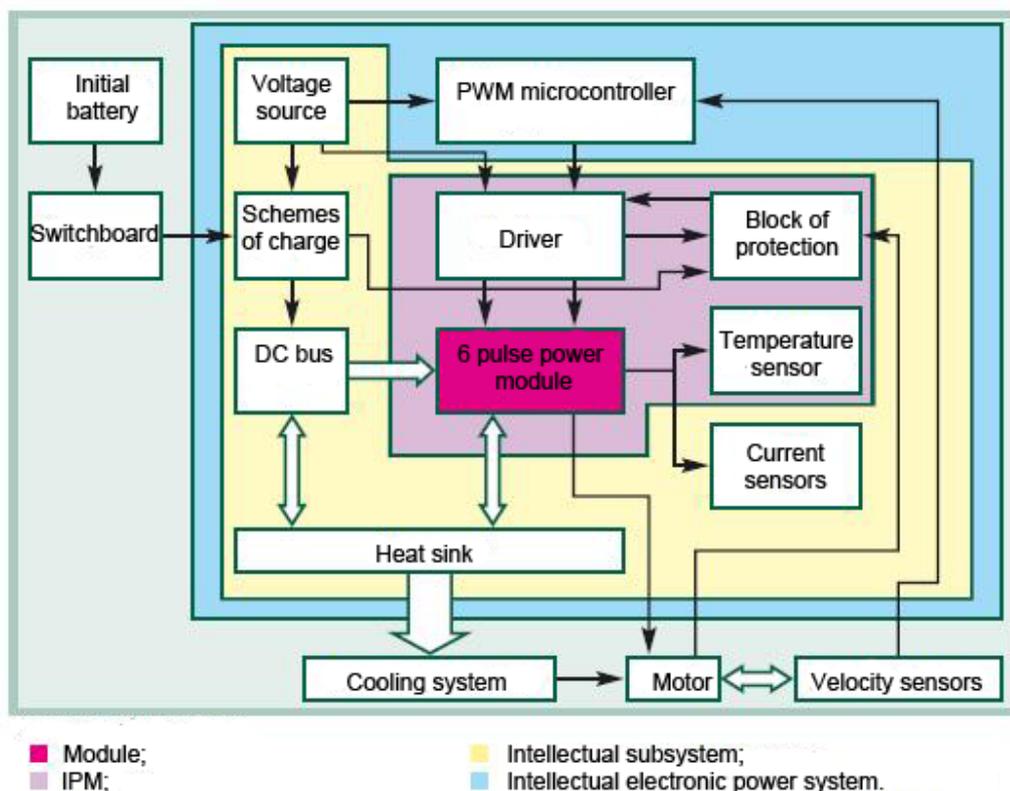

Figure 28 Levels of hybrid system integrations. [52]

Table 26 presents different power modules which tend to minimization and size effectiveness.

Table 26 *Levels of system integration. [52]*

Number of level of system integration	Examples of power modules	Assembly
1	Econopack (Infineon), LoPak 3, 4, 5 (ABB), SKiM 4, 5 (Semikron)	IGBT modules, diode rectifiers with system for breaking
2	IPM produced by Mitsubishi, Fuji, Hitachi	3 phase bridge inverter, schemes of operation and blocks of protection
3	SKiiP (Semikron)	Power modules with built-in driver, voltage sensors and overvoltage protection on the DC bus which are mounted on the liquid cooling system.

Reduction of size and desire to gather as much components as possible in one case lead to improvement of reliability, reduction of losses and finally reduction of price. The main reason of reduction of losses is absence of large number of long connecting wires and additional components.

9.2. Perspectives of development of the semiconductor industry

Power ratings of semiconductor devices will constantly increase. Mostly it will be realized by thinning and changing the crystal structure. Second main change concerns to the material of crystal in devices.

In November 2009 semiconductor division of ABB presented 10 kV IGCT. This element will be focused on speed-controlled drives for MV motors, rail network interconnections in frequency and energy management systems, also this device can be used in HVDC and FACTS applications. General investigation was emphasized on increasing the robustness against cosmic ray radiation. While blocking voltage of IGCT was increased from 6.5 kV to 10 kV, its switching properties became significantly worse and therefore SOA was reduced. It demanded to develop new structure. One of the difficult tasks was to create freewheeling diode corresponding new IGCT. Standard high-voltage diodes often oscillate at high voltages. It leads to huge over-voltages and high-frequency current os-

cillations during the turn-off and reverse recovery. This required making changes in the diode structure, so diodes acquired soft switching characteristics. Creation of 10 kV device makes possibility for operation of 12 MW drives with 7.2 kV input voltage. Nowadays 10 kV IGCT is not presented on the semiconductor market. Its presentation is planned on the 2011. [14]

Future of semiconductors will be uninterruptedly related with development of new materials. Materials with wider band gap than Si, like SiC and GaN, will be used in a few years. 10 kV SiC MOSFET with I_D=10 A was created quite recently. In comparison with standard 6.5 kV IGBT it presents approximately only $\frac{1}{200}$ th of total switching energy of the IGBT. In spite of quite low power this device can be successfully used in PV panels. SiC MOSFET is a good reason for expecting the development of high power SiC IGBT with voltage more than 10 kV. 12 kV IGBT based on 4H-SiC has already been created. [55], [56], [57]

Manufacturers permanently try to increase reliability of semiconductor components, but sometimes reliability depends on external factors. Influence of cosmic rays on high current and voltage devices was revealed in early 1990's. This kind of radiation can disturb normal operating state of series of devices. All kind of semiconductor components can be exposed to suffer under the cosmic rays and risk of failure is higher as the altitude above the sea level is higher. Today contemporary high power components are designed in conditions while failure rate due to the action of cosmic rays is reduced to an admissible level. In future probably this failure rate will be reduced while semiconductor technology will be more developed.

CONCLUSIONS

From the second half of the last century, when first semiconductor devices were created, industry is constantly developed. At present power electronics is used almost in all technological processes and home appliances. Mostly power switches are utilized in DC/AC converters. Dimensions, efficiency and reliability of converter depend on the amount of switches, therefore creation of devices of higher voltage and current ratings allows to reduce usage of series or parallel connection. Main problem of series and parallel connection is a discrepancy of characteristics of components, which causes voltage and current imbalance. DC/AC converters are fundamental elements of power drives. Electrical drives are widely used almost in all fields of industry and it is very important to improve operation characteristics of drives in order to improve efficiency of the whole manufacture.

Today there are several semiconductor switches, which have advantages, disadvantages and can be chosen properly in respect to their characteristics. Classical SCRs are successfully applicable in high-voltage and high-power applications, like HVDC and different FACTS equipment. Thyristors nowadays are the most powerful devices. GTO owing to its ability for controlled operation can be used in adjustable drives and also in energy networks, like thyristors. MOSFET is the fastest switch, but it is not suitable for MV range. Even if to take into account the creation of 10 kV SiC MOSFET with I_D=10 A, its power is about 100 kW, which is much less than average power ratings of MV range. For usage in power drives IGBT and IGCT are the most applicable switches. They have quite equal losses, but IGCT is better in the on-state and IGBT is better during the turn-off. This was proved by the calculation of losses. Calculation in this thesis doesn't show exact losses of switches and can't be used for selection of devices, but it shows an order of losses and gives understanding of strong and weak sides of components.

One the most decisive factors which can mark out the switch towards other is the price. Unfortunately this information is much hidden, because of the hard competition between manufacturers. Thus thesis could not make a comprehensive analysis of price of different devices. But it answered the question about availability. It becomes evident that IGBT is produced by all main producers of semiconductor components, whereas IGCT is manufactured only by two of them.

IGBT was selected as a basic component in this study. Development of structure of IGBT was considered. It is obvious that dimensions of crystal are reduced, but voltage and current ratings are increased from the development of the first IGBT. Thus manufacturers after years of development created trench structure, which has more favourable characteristics over planar structure. Today further development mostly depends on the usage of new materials with wide band gap, like SiC and GaN. Creation of IGBT with voltage ratings more than 10 kV is a step in this direction. In recent years 12 kV IGBT has already been created and it is a very promising switch.

Nowadays manufacturers tend to minimize and optimize power modules. This way they try to unite several components into one case and receive intellectual subsystems and intellectual electronic power systems. This reduces dimensions and weight of equipment and consequently less length of required bonding wires. Thus losses can be reduced and efficiency can be increased. One of the most topical questions for every field of industry is the influence of equipment on the environment. Some producers follow ROHS directive and usually mention this fact in datasheets.

The main conclusion which can be made is that for nowadays IGBT is the most attractive semiconductor switch for lower voltage rates in MV drives. It has several disadvantages which give to IGBT unprofitable appearance. This switch has the highest losses in the on-state over other switches which are caused by collector-emitter voltage, which should be low as possible. V_{CE} increases in direct proportion to I_C and inversely proportional to V_{GE}. V_{CE} and I_C depend on the temperature of junction. Switching losses are caused by slow elimination of holes in the drift layer after V_{GE} became lower than the threshold voltage, which turns off the switch. This forms current tail which is inherent to IGBT. Gate resistance of IGBT is also influences on the energy dissipation and it is directly proportional to appearing losses. R_G influences on RBSOA, SCSOA and modes of FWD conduction. FWD in IGBT can be a powerful source of losses, therefore diodes for high-voltage switches in voltage ratings more than 6.5 kV were improved. FBSOA, RBSOA and SCSOA limit safe operation of device. But in spite of described above disadvantages IGBT has better switch-off characteristics than all switches of the thyristor group.

For higher voltage levels of MV rate IGCT is the only suitable switch. It has much lower conduction losses than IGBT and high overload ability, but it is worse during the switching off and needs addi-

tional inductance in the circuit which limits current spikes and protects FWD. During the turn-on IGBT and IGCT have quite similar characteristics.

Today developers of MV drives have good and suitable solutions for constant growth of efficiency and reduction of losses in their equipment in all power and voltage ratings. Nowadays there are wide possibilities of accurate selection of semiconductor components for all needs. In future these possibilities will be only expanded.

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APPENDICES

Appendix 1. *Dimensions of FZ750R65KE3T IGBT module, produced by Infineon Technologies (V_{CES}=6500 V, I_C=750 A). [45]*
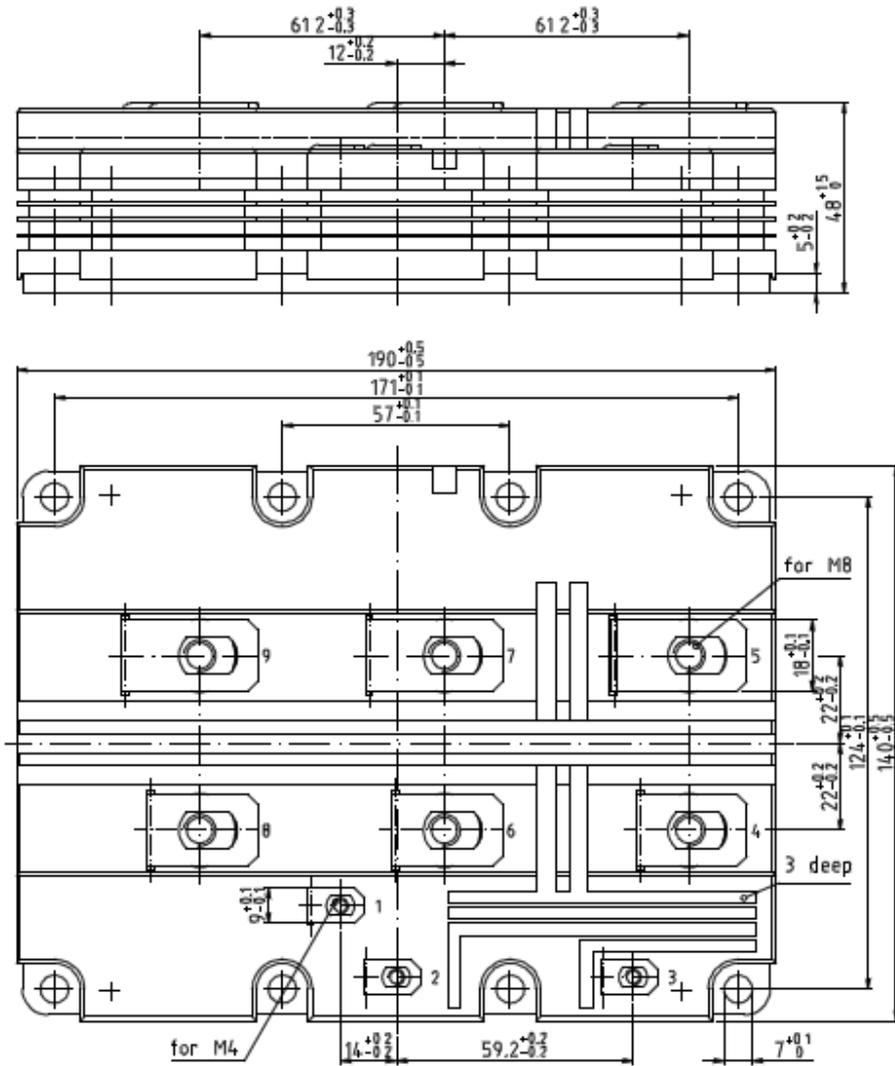
Appendix 2. *Dimensions of GCU08BA-130 IGCT, produced by Mitsubishi Electric (V_{DRM}=6500 V, I_{TQRM}=800 A). [66]*