Preface

Power electronics and electric drives are two fields of technology, very closely connected. Power electronics devices are the most advanced and effective switches of high power electric circuits. Frequently, they are used as switches for the commutation of windings of electric machines. The system which includes an electric machine, a power converter based on semiconductor switches, and several control devices is known as an electric drive. Today about 60 % of the electric energy produced will be converted and used by electric drives of technological machines.

The flexible control of speed and torque of electric machines is possible due to modern microprocessor control and advanced power electronics devices. Optimal motion control of technological machines is a very urgent problem, the solution of which will lead to higher productivity of machines and essential energy saving.

This textbook is intended for students of universities of applied sciences and remote engineering colleges who study the courses of electronics. It is also useful for students of other specialities, e.g. mechatronics or electric drives and power electronics.

In contrast to the microchips that must be protected against static voltage charges and short-circuit currents, power electronics devices must be protected against the commutation over-voltages and over-temperatures.

The turn-on or turn-off process in power circuits is not only a logic-level operation. The main purpose is the energy conversion. Consequently, power electronics operates in the field of energy conversion and control of energy flow in different technological equipment. Inappropriate operation of energy can cause not only malfunction or failure of equipment, but also a major technological catastrophe. This is a central idea of this textbook.

Electric drives and motion control are the main application areas of power electronics devices, and the electromagnetic compatibility of power circuits is one of the most urgent problems in modern power electronics. A flexible control of energy flow helps us to save energy and the environment and guarantee a sustainable global development.

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INTRODUCTION

1.1. Overview of electromechanical energy conversion

The electric drive is an electro-mechanical system, which includes an electric motor, a mechanical gear, a power electronic converter, different sensors and control devices (e.g., microprocessor controllers) to drive technological, transport or other machines. In some cases, an electric drive can include more than one motor and one power converter.

History. Michael Faraday, an English scientist, founded and formulated the general principle of electro-mechanical energy conversion in 1821. Then in 1831, he established the principle of electro-magnetic induction – the electromotive force in a closed electric circuit is proportional to the velocity of the magnetic flux variation. These discoveries were the first steps in the development of electric drives. On this basis, several types of electric machines and transformers were invented.

An electric drive was first applied in the middle of the 19th century when different types of electric motors were invented. One of the inventors was Moritz Hermann Jacobi, who worked during a short period (1835...1837) at the University of Tartu as professor of architecture. However he was also interested in other sciences. Afterwards he worked for the Academy of Science of Russia in St. Petersburg. His studies in the field of electrical engineering were very successful and Jacobi became known worldwide. Moritz Hermann Jacobi was the first to organize practical application of electric drive in 1839. He installed an electric motor designed by him on a boat and supplied it by electricity from a galvanic accumulator. The boat moved against the water flow at the speed 4.8 km/h. Next year, the electric drive of the boat was modified when M. H. Jacobi invented the current regulator – a rheostat allowing to control the speed of the boat.

Interestingly, the first types of electric machines were direct current machines because accumulators were the current sources. At the end of the 19th century, marked by boost in the development of electrical engineering, main principles and essential equipment for a complete system of electrical power engineering were developed. Thomas Alva Edison, an American inventor, who developed the DC electric generators, distribution net, electric lamps as the consumers of electricity and all needed measuring equipment, was the pioneer of direct current power engineering. Production and consumption of electricity was established as a business.

At the same time, research advanced in different parts of the world. Nikola Tesla, a Serbian engineer and M. Dolivo-Dobrowolski, a Polish-German engineer, developed the first types of alternating current electric motors. Dolivo-Dobrowolski invented the three-phase electric machine and the three-phase electricity distribution system. In 1888, he published the main advantages of the three-phase system. The combination of a three phase synchronous generator and a three-phase asynchronous or induction motor with three-phase distribution lines and transformers proved a very successful technical solution. It revealed the orientation of the development a century ahead. In the competition of direct and alternating current in electrical power systems, a quick launch of a DC system was not successful, because the AC system was more attractive. The main disadvantage of the DC system was the difficulty to transform the DC voltage. The problem was very urgent because of the fast increase in power, which required higher voltages in distribution lines (to minimize the current and losses in lines). Over a hundred years, developments in electrical power engineering were based on the AC transformer. Transformer is still a very effective component of a power system. The
problem of DC voltage conversion still exists, but by help of power electronics and modern control engineering, many good solutions for DC current engineering can be found.

The alternating current energy distribution system won the competition against the DC system in the early 20th century, however many problems still remained. With the automation of industry growing, speed control of electric motors emerged. A three-phase synchronous generator, three-phase AC distribution system and three-phase induction motor composed a very effective remote energy transmitting system. However, speed and torque control of technological machines was a problem, which needed an effective and economical solution. Principally, it was wellknown that the speed of an AC induction motor could be controlled by a supply from a source of variable frequency and voltage. But a frequency controlled AC induction motor drive was very expensive and very complicated to realize. At the same time, the speed and torque control of direct current motors was simply realized by low cost rheostats. The situation that energy generation and transmission was more effective on the basis of three-phase AC system, but most of speed controlled drive applications were realized by DC motors, was typical during a hundred years (from the end of the 19th century to the end of the 20th century). Different problems and unbalance between the fields of energy generation and distribution and effective and flexible consumption were the reasons why scientists around the world made efforts to improve energy converters. The most important problems in this field were:

- energy supply of DC motors from the AC distribution network and development of suitable converters
- speed control of AC motors and development of suitable converters
- decrease in energy losses in the speed control of electric machines and development of high efficiency power converters

A general picture of energy conversion processes is shown in Fig. 1.1. To achieve a flexible operation with an energy flow, different types of converters must be used. Out of the four different conversion processes (shown in the figure), the transformation of AC voltage was the first and most efficient. It was P. Jablotchikov who designed and used the AC power transformer in 1876. In fact, M. Faraday invented the pulse transformer much earlier, in 1831. The transformer helped to solve the problem of AC voltage conversion. For example, the high voltage energy distribution system was involved and transmission of energy over long distances was realized by transformers.

![Figure 1.1. Possibilities of conversion of electrical energy](image-url)
Other processes of energy conversion in Fig 1.1 still attract investigators’ interest. Thousands of different devices, systems and principles were invented, investigated and practically applied during the last century. Some of them were quite complex and expensive because of the indirect conversion method and intermediate converters used. Well-known are the electro-mechanical energy conversion systems with motor-generator aggregates, e.g. Ward-Leonard system for the DC drive. To obtain adjustable DC voltage from the AC network, a system consisting of the induction motor and DC generator is used. The output voltage is controlled by the variation of the excitation current of a DC generator by help of the rheostat in the excitation circuit. The variable voltage and frequency could also be obtained from motor-generator system. In this case, a speed controlled DC motor is used to drive the AC synchronous generator. With the speed variation also the output voltage and frequency must be controlled. This system is suitable to supply an adjustable speed AC induction motor drive, but its drawbacks are high complexity and price.

Electro-mechanical converters were the main type of converters used in drives during the first half of the 20th century. Many types of electrical motors of different design were developed. The main purpose of the manufacturers was to develop a higher efficiency motor. Another purpose was to combine different electrical machines which functioned as energy converters, into one machine unit. An example is the electric machines-amplifiers, which were relatively widely used in the systems of adjustable speed electrical drives.

In the second half of the 20th century, electronics (incl. power electronics) and drive applications developed particularly fast. Electronics developments are covered in detail in section 1.3. In fact, many years before power electronics switches were used in power converters, investigators found that efficient power conversion must be based on switches. The switch, as the energy converter, is described in section 1.2. With reference to the history of energy production, distribution and consumption, today a new period has started. Step by step centralized production of energy will be replaced by distributed production. Lower unit power of renewable energy sources and higher reliability of distributed systems are only some of the reasons of this development. Modern flexibly controlled power converters have opened a new era for a DC electrical power system. New needs, but also new problems have risen.

**Power electronics in the 21st century.** The needs for converters of electric energy are determined by the types of electric generators used in electricity production and by voltage and current used in electricity distribution and consumption. The three phase alternating current generators are very efficient in high power electricity stations, incl. thermal, hydro- and wind power stations. The three-phase AC distribution system is a traditional solution, developed a hundred years ago alone with the AC generators, transformers and motors. Now the power transmitted in the electrical network has tremendously grown. Energy losses in high AC voltage lines are undesirably great. Note that high voltage AC lines won the competition over the DC system, because losses in higher voltage were lower than in lower voltage. Now AC lines suffer from the same problem, but the reason of high losses is the reactive energy, mainly stored in line inductances and capacitors, but oscillating continuously between different line components. Additional losses will appear also in long high voltage cable lines because of capacitive current through cable insulation. Reactive energy is an additional load to the AC network, which generates losses. Possible solutions of this problem could be local compensation of reactive energy, resonant mode power converters or direct current distribution network. All of these solutions will need highly effective power switches and intelligent control devices, which means that electronics is the future of power engineering.
Most of electrical drives today are supplied from the AC network. However, their power converters include a rectifier and drives contain an intermediate DC unit. For example, the frequency converter of an adjustable induction motor drive consists of a rectifier, an intermediate DC link LC filter circuit with a brake chopper and an inverter. Commonly, nearly all AC motor drives are supplied from the AC network but via the intermediate DC link. Consequently, a question arises, why the AC network and many rectifiers are used for the drive supply, while drives need the DC voltage. The DC network with energy storage units based on ultra-capacitors or super-conductive inductances are an example of a future distribution network. The energy storage units with flexibly controlled power electronic converters will regulate the power in the network and will accommodate the consumed and produced capacities. This problem is very important and needs to be solved because the output power of renewable power sources (solar batteries or wind turbines) is random and changing to a great extent. The consumer needs for power are also a random and largely changing function. Distributed production and distribution as well as energy storage problems are very urgent in the 21th century power engineering. During the next ten years, obviously it will be clear does this process will be accompanied by a return to the DC distribution network. Clearly, today power electronics is the key to solving different problems in the field of electrical power engineering.

1.2. Power switch as an energy converter

The switch of power circuits invented along with early uses of electricity was intended to turn on or off or to make interleaved commutations in circuits. Today the power switches have many different functional features, operation modes, voltages and currents. In some cases, the switch operates 2 or 4 times per day, but other switches must commutate circuit thousands of times per second. The features of different power switches are as follows:

- a switch must guarantee safety insulation in a power circuit.
- a switch must be reliable and able to commutate high load currents and stand high pulses of the commutation voltage.
- a switch must be able to dissipate the thermal energy generated by power losses (or by the electric arc in a contact switch) and the energy stored in the circuit components (inductances and capacitors).
- a switch must able to protect circuit components and turn off circuit in any dangerous situation.
- a switch must operate very quickly to be able to regulate the average value of current or voltage.
- a fast operating switch must is able to convert the AC to DC and vice versa.

The main problem of power switching is the conversion of energy stored in circuit components. After the circuit is turned on, the energy will be stored in inductances and capacitors. The energy stored in an inductance can be calculated by the formula $W_L = Li^2/2$. After the circuit turn-off, the stored energy must be dissipated or restored in other components. In the case of inductive load, the energy stored in the inductance will be converted during the turn-off process to the energy of insulation capacity, and high commutation voltage peaks will appear. The energy stored in a capacitor can be calculated from the formula $W_C = Cu^2/2$. In the case of a contact switch, this energy will be dissipated by the electric arc (by the thermal radiation and transmission). The electric arc and the high voltage peaks can be dangerous to the switching device (Fig. 1.2). Hundreds of different
design modes have been developed for contact switches. To guarantee effective switching of circuits, the processes of electric arc have been investigated and chambers distinguishing the arc, based on higher pressure, intensive cooling, the arc moving by blowing or by the effect of the magnetic field, high-speed contacts, special environments, vacuum, etc. have been developed. The electric arc in contact-switches must follow certain rules. It must dissipate a certain amount of energy because the peaks of commutation voltage may not be higher than allowed by circuit insulation properties. On the other hand, the dissipated energy must not destroy the switching device. Very fast switching (without electric arc) of the current carrying circuit (e.g. in the case of vacuum switches), will cause over-voltages which can destroy the insulation of wires or circuit components.

The first switches, in particular those for power circuits, were designed at the end of the 19th century. Contact-based power switches have been developed for over a hundred years. In the middle of the 20th century, non-contact switching apparatus was developed on the basis of saturable ferromagnetic core inductive coils. In 1933, saturable core magnetic amplifiers were used in Germany to control the current of an electric motor. In 1943, as a result of major studies in the field of saturable magnetic circuits, the Swedish company ASEA developed controllable magnetic converters called transducers. In the case of magnetic switching apparatus, the main current can be controlled by a small control current because with positive feedback, the ferromagnetic core can be easily switched from the saturation to the non-saturation state and vice versa. At the same time, reactance will change thousands of times. Transductors were used in low voltage circuits with currents up to a few hundred amperes. The gain of a magnetic amplifier (transductor) is relatively low (less than one hundred). Therefore the cascade connections of transductors must be used. Transductors suffer from slow operation due to high inductivity of the windings on the ferromagnetic core.

For this reason, electric drives with transductors in a supply circuit suit for the machines that do not need a fast control response. Occasionally, transductors were successfully used up to the 1970s.

Synchronous switches were developed for switching of AC circuits, because throughout any period, circuit current is instantaneously equal to zero. If the switch operates at that moment (when current is equal to zero), the energy converted by a switch can be lowered to a minimum. In the case of contact-switches, this principle is extremely difficult to realize because of very slow operation of mechanical contacts. The principle of synchronous switching has been very successfully used in power electronic converters because electronic devices are capable of very quick turn on or off.
1.3. Historical development of power electronics

On June 1, in 1921 F. W. Meyer, a German electrician, first formulated the main principles and development trends of power electronics [1]. This date could be considered as the birthday of power electronics. During prehistory of modern power electronics, first operation principles of power components were developed and the first experiments of their application were carried out. Theories that form the basis of power electronics are known since the end of the 19th century. In 1882 J. Jasmin (1818−1886), a French research physicist, found that the mercury electric arc has a capability of conducting current only in one direction, and instead of mechanical switches, this effect was proposed to be used for rectifying alternating current. In 1892 L. Arons (1860−1919), a German physician, invented the first mercury arc vacuum valve. P. Cooper Hewitt (1861−1921), an American electrician, developed the first mercury arc valve, with practical applications in 1901. A year later he patented the mercury arc rectifier. J. A. Fleming (1849−1945) invented the first vacuum diode in 1906. In the same year, G. W. Pickard (1877−1950), an American electrician, invented the silicon valve. In 1907 L. de Forest invented the vacuum triode. All these devices, characteristic of with very low power switching capability, were unable to switch power circuits. However later, on the basis of the same principles, many types of power switches were developed.

In the first half of the 20th century, power converters of electric drives and other power equipment were mainly based on gas-discharge valves, thyratrons, mercury arc rectifiers and ignitrons. A thyatron is a lamp valve with three electrodes, such as a triode. The third electrode – gate electrode, can control current from anode to cathode. Higher control voltage on the gate electrode will activate electron movement. If the control voltage exceeds the threshold level, the electric arc discharge will appear between the anode and the cathode. Thyratrons were mainly used in rectifiers and pulse generators. In the next stage of development, instead of thyratrons, ignitrons (also known as mercury arc valves) were taken into use. Note that in 1914 Dr. Irving Langmuir (USA) recommended to control the mercury arc in a closed bulb of a diode valve by the third grid electrode. He showed that that an electrode could be used to ignite the arc in a valve during each period of AC voltage. In 1922 French scientists used the principle of phase angle variation to control the moment of ignition and the output voltage of an ignitron rectifier. The US Westinghouse Company started serial production of ignitrons in 1933. The maximum current values of ignitrons are hundreds of amperes with the breakdown voltage of tens of kilovolts. For thermal energy dissipation, the ignitrons have an air or water-cooling system. Ignitrons were widely used in power converters and traction drives of electric transport. From 1959 to 1985, ignitrons were produced in the Tallinn Plant of Electric Equipment (Estonia).

A new era of power electronics began at the end of the 1940s. In 1948 the transistor was invented. In 1952 the General Electric manufactured the first germanium-power diode. A year later Texas Instruments produced the first silicon transistor. The thyristor, a silicon controlled rectifier (SCR), was invented in 1956 by a US researchers team lead by John Moll. Based on these inventions, several generations of power devices have been developed. The period of 1956−1975 can be considered as the era of thyristors (SCR) or the era of the first generation power devices. Thyristors were called controlled rectifiers because they were mainly applied in rectifiers. The use of thyristors in inverters is relatively complicated because the current carrying thyristor cannot be turned off by a control signal. A thyristor turns off after the main current drops under the threshold level close to zero. Therefore the forced commutation circuit with additional energy carrying components (capacitors) must be used. As a result, thyristor inverters were very complicated and unreliable. The automatic control system of
drives includes a thyristor converter, transistor amplifiers (later integrated circuits), analogue type regulators, different current and speed sensors, and optrons for galvanic separation of signals. The principle of error driven feedback control was used.

During the period of second-generation power devices (1975−1990), the power MOSFETs (metal-oxide-semiconductor field-effect transistor, 1980), bipolar npn and pnp transistors and power bipolar junction transistors (BJT), the power gate turn-off (GTO) thyristors were developed. The automatic control system of drives is composed of microprocessors; application specified integral circuits (ASIC), and power integral circuits (PIC). Often the advanced control methods (e.g., the model based control) were used instead of the feedback control.

Introduction of the third generation of power devices began at the end of the 20th century. The insulated gate bipolar transistor (IGBT) was established as the most common power switch in electrical drives. In some applications, MCT or MOS controlled thyristors, or MOS controlled GTOs are used. A new trend in power electronics is the use of intelligent power devices (IPD) or intelligent power modules (IPM). The automatic control systems of drives are often based on principles of sensor-less model based control, expert systems, fuzzy logic, or neural networks.

**Conclusion.** Energy conversion in the 21st century will be based on power electronics and depends on the achievements in the field of power electronics. Power electronics devices will be mainly used in rectifiers, inverters, frequency converters, static compensators of reactive power, and different power supply sources. The phase-controlled converters, such as thyristor rectifiers, will lose their position in electrical drives because of low quality of energy and low power factor. The pulse width modulation (PWM) will dominate in different types of converters with varying power capacity. Advancement of direct frequency converters (cycloconverters and matrix converters) is slower than that of double PWM converters. The latter include the interconnected PWM controlled rectifier and inverter, with similar power circuits, allowing energy flux in both directions. Voltage-fed inverters (VFI) have some advantages over current-fed inverters (CFI). In some applications, an optimal solution could be achieved by help of a resonant pole converter.

Power modules with integrated power MOSFETs, IGBTs or GTOs are in high demand, and power components will be increasingly integrated with control and snubber circuits. The quality of switching processes and commutation losses depends on the features of an anti-parallel fast switching diode. With a wide use of intelligent power modules, the topology of power converter circuits proves more essential. The design of electrical drives, power converters and their components will be increasingly based on system and circuit modelling. Software packages (e.g. PSpice etc.) with several component libraries make this work easy and enhance the quality of design. An optimal design of power converters and drives is possible only by help of modern computer-aided design methods.

The history of power electronics and modern developments in this field shows that an ideal power switch is a dream which will never be achieved in reality. According to the energy conservation law, any switching, current or voltage variation involves dissipation of losses and will be executed during a finite time interval.
1.4. Developments in the field of electric drives

In the analysis of developments in electric drives, we can focus on trends related to electric machines, power converters and control devices as well as to the control principles separately. The technology of electrical machines is quite conservative, so no substantial changes during the next years are expected. In industrial applications, the most important type of electric motors is still the AC induction motor. Reductions in the production of conventional DC motors are typical. DC motors with electronic collectors will be widely used instead of traditional DC motors. The permanent magnet alternating current machines (PMAC) are more extensively used than motors with excitation windings, however, PMAC machines have very good technical and economic parameters. Synchronous motors with excitation winding suit best for high power applications, when use of permanent magnets is excessively expensive. Switched reluctance motors can also be used to drive small power mechanisms. In traditional textbooks, reluctance machines are described as low efficiency machines (approx. 50 %), but their modern application in vector controlled drives is more effective and their efficiency is in the same order as that of induction motors. Because most of the electric motors are fed from power converters and have a complex control system and approximately the same output characteristics, it is difficult to classify drives and motors according to traditional principles. Vector controlled AC motors can be used as DC motors to achieve the same technical properties. In many cases, dimensions of power converters are so small that they could be mounted on a motor’s frame. The integration of a motor and a converter allows a common cooling system to be used and the wiring between the motor and the converter to be minimized.

The efficiency and reliability of electrical machines and drives will increase, resulting from advanced design software packages, computer-aided design (CAD) methods and high quality materials. The weight of machines per unit power will decrease. The most common method for the design of different machines and devices is the finite element method (FEM). It is used to calculate electric and magnetic fields as well as thermal fields or mechanical stresses. In view of future energy costs rising, a higher efficiency and reliability must be preferred to a lower initial cost of a machine.

In most of industrial applications, AC induction motor drives with frequency converters are used. The simple principle scalar control (the voltage and frequency are varied proportionally) is used to control the speed of pumps, fans and compressors. The most complicated principle of vector control is used to control the drives of machine tools, robots, transport machines etc. In servo drives, the permanent magnet synchronous motor (PMSM) is the optimal solution.

Many methods of modern information technology will be also used in drives. Remote control via information networks (incl. Internet), on-line parameter identification, machine diagnostics, and human-machine interface functions will be added to the modern drives. Artificial intelligence and neural networks will be part of modern drive control systems.