Chapter 1
Introduction

This chapter provides introduction to electromechanical energy conversion and rotating power converters. This chapter explains the role of electrical machines in electrical power systems, industry applications, and commercial and residential area and supports the need to study electrical machines and acquire skills in their modeling, supplying, and control. This chapter also discusses notation and system of units used throughout this book, specifies target knowledge and skills to be acquired, and explains prerequisites. This chapter concludes with remarks on further studies.

1.1 Power Converters and Electrical Machines

Electrical machines are power converters, devices that convert energy from one form into another. They convert mechanical work into electrical energy or vice versa. There are also power converters that convert electrical energy of one form into electrical energy of another form. They are called static power converters. Some sample power converters are listed below:

- Power converters that generate mechanical work by using electrical energy are called electrical motors. Electrical motors are electrical machines.
- Power converters that use the electrical energy of direct currents and voltages and convert this energy into electrical energy of AC currents and voltages are called inverters. Inverters belong to static power converters, and they make use of semiconductor power switches.
- Electrical generators convert mechanical work into electrical energy. They belong to electrical machines.
- Power transformers convert (transform) electrical energy from one system of AC voltages into electrical energy of another system of AC voltages, wherein the two AC systems have the same frequency.

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1.1.1 Rotating Power Converters

Electrical machines converting electrical energy to mechanical work are called *electrical motors*. Electrical machines converting mechanical work to electrical energy are called *electrical generators*. Mechanical energy usually appears in the form of a rotational movement; thus, electrical motors and generators are called *rotational power converters* or rotating electrical machines. The process of converting electrical energy to mechanical work is called *electromechanical conversion*. Different from rotational converters, *power transformers* are electrical machines which have no moving parts and convert electrical power of one system of AC voltages and currents into another AC system. The two AC systems have the same frequency, but their voltage levels are different due to transformation. This book deals with the rotating electrical machines, electrical generators and motors, whereas power transformers are dealt with by other textbooks.

Electrical machines comprise current circuits made of insulated conductors and magnetic circuits made of ferromagnetic materials. The machines produce mechanical work due to the action of electromagnetic forces on conductors and ferromagnetics coupled by a magnetic field. Conductors and ferromagnetic elements belong either to the moving part of the machine (*rotor*) or to the stationary part (*stator*). Rotation of the machine moving part contributes to variation of the magnetic field. In turn, an electromotive force is induced in the conductors, which allows generation of electrical energy. Similarly, electrical current in the machine conductors, called *windings*, interacts with the magnetic field and produces the forces that excite the rotor motion. Unlike electrical machines, the power transformers do not involve moving parts. Their operation is based on electromagnetic coupling between the primary and secondary windings encircling the same magnetic circuit.

1.1.2 Static Power Converters

In addition to electrical machines and power transformers, there are power converters whose operation is not based on electromagnetic coupling of current circuits and magnetic circuit. The converters containing semiconductor power switches are known as *static power converters* or *power electronics devices*. One such example is a diode rectifier, containing four power diodes connected into a bridge. Supplied by an AC voltage, diode rectifier outputs a pulsating DC voltage. Therefore, a diode rectifier carries out conversion of AC electrical energy into DC electrical energy. Conversion of DC electrical energy into AC electrical energy is carried out by inverters, static power converters containing semiconductor power switches like power transistors or power thyristors. Static power converters are frequently used in conjunction with electrical machines, but they are not studied within this book.

1.1.3 The Role of Electromechanical Power Conversion

Electromechanical conversion has a key role in production and uses of electrical energy. Electrical generators produce electrical energy, whereas motors are the consumers converting a considerable portion of electrical energy into mechanical work, required by production processes, transportation, lighting, and other industrial, residential, and household applications. Thanks to electromechanical conversion, energy is transported and delivered to remote consumers by means of electrical conductors. Electrical transmission is very reliable, it is not accompanied by emissions of gasses or other harmful substances, and it is carried out with low energy losses.

In electrical power plants, steam and water turbines produce mechanical work which is delivered to electrical generators. Through the processes taking place within a generator, the mechanical work is converted into electrical energy, which is available at generator terminals in the form of AC currents and voltages. High-voltage power lines transmit electrical energy to industrial centers and communities where power cables and lines of the distribution network provide the power supply to various consumers situated in production halls, transportation units, offices, and households. In the course of transmission and distribution, the voltage is transformed several times by using power transformers. Electrical generators, electrical motors, and power transformers are vital components of an *electrical power system*.

1.1.4 Principles of Operation

Electromechanical energy conversion can be accomplished by applying various principles of physics. Operation of electrical machines is usually based on the magnetic field which couples current-carrying circuits and moving parts of the machine. The conductors and ferromagnetic parts in the coupling magnetic field are subjected to electromagnetic forces. Conductors form contours and circuits carrying electrical currents. Flux linkage in a contour (called *flux*) can change due to changes in electrical current or due to motion. Flux change induces electromotive force in contours. The basic laws of physics determining electromechanical energy conversion in electrical machines with magnetic coupling field are:

- Faraday law of electromagnetic induction, which defines the relationship between a changing magnetic flux and induced electromotive force
- Ampère law, which describes magnetic field of conductors carrying electrical current
- Lorentz law, which determines the force acting on moving charges in magnetic and electrical fields
- Kirchhoff laws, which give relations between voltages and currents in current circuits and also between fluxes and magnetomotive forces in magnetic circuits

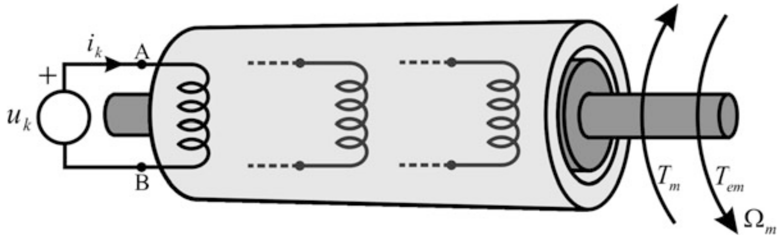

Fig. 1.1 Rotating electrical machine has cylindrical rotor, accessible via shaft. Stator has the form of a hollow cylinder, coaxial with the rotor

1.1.5 Magnetic and Current Circuits

The process of electromechanical energy conversion in electrical machines is based on interaction between the magnetic coupling field and conductors carrying electrical currents. Magnetic flux is channeled through magnetic circuits made of ferromagnetic materials. Electrical currents are directed through current conductors. Magnetic circuits are formed by stacking iron sheets separated by thin insulation layers, while current circuits are made of insulated copper conductors. The three most important types of electrical machines, DC current machines, asynchronous machines, and synchronous machines are of different constructions, and they use different ways of establishing magnetic fields and currents. Rotating electrical machines have a nonmoving part, *stator*, and a moving part, *rotor*, which can rotate around machine axis. The magnetic and current circuits could be mounted on both stator and rotor. In addition to the magnetic and current circuits, electrical machines also have other parts, like housing, shaft, bearings, and terminals of current circuits.

1.1.6 Rotating Electrical Machines

Mechanical work of electrical machines can be related to rotation or translation. Majority of electrical machines is made of rotating electromechanical converters producing rotational movement and having cylindrical rotors, like the one shown in Fig. 1.1. Electrical machines creating linear movement are called *linear motors*. Linear motors are rather rare.

Current circuits of a machine are called *windings*. They can be connected to external electrical sources or to electrical energy consumers. The ends of the winding are accessible as electrical terminals. In Fig. 1.1, terminals of *k*th winding are denoted by letters A and B. The electrical terminals permit *electrical access* to the machine. Since electrical machines perform electromechanical conversion, they have both electrical and mechanical accesses. Via electrical terminals, the machine can receive electrical energy from external sources or supply electrical energy to consumers in the circuits which are external to the machine. When an electrical machine has N windings, the power at electrical access of the machine is given by (1.1):

$$p_e = \sum_{k=1}^{N} u_k i_k. \tag{1.1}$$

Rotor is positioned inside a hollow cylindrical stator. Along rotor axis is a steel shaft, accessible at machine ends. Angular frequency of revolution of the rotor is also called *the rotor speed*, and it is denoted by Ω_m. At one end of the shaft, shown on the right of Fig. 1.1, the electrical machine can deliver or receive mechanical work. The shaft makes *mechanical terminal* of the machine. It transmits *rotational torque* or simply *torque* of the machine to external sources or consumers of mechanical work. The torque T_{em} in Fig. 1.1 is created by the interaction of the magnetic field and electrical current. Therefore, it is also called *electromagnetic torque*. In cases when the torque contributes to motion and acts toward the speed increase, it is called *driving torque*.

An electrical motor converts electrical energy to mechanical work. The later is delivered via shaft to a machine operating as a mechanical load, also called *work machine*. The motor acts on the work machine through the torque T_{em}, while the work machine opposes the rotation by the load torque T_m. In the case when the driving and load torques are equal, angular frequency of the rotation Ω_m does not change. Power delivered to a work machine by the electrical motor is determined by the product of the torque and speed:

$$p_m = \Omega_m T_m. \tag{1.2}$$

An electrical generator converts mechanical work to electrical energy. It receives the mechanical work from a water or steam turbine; thus, power p_m has a negative value. Rotational torque of the turbine T_m tends to set the rotor into motion, whereas the torque T_{em}, generated by the electrical machine, opposes this movement. By adopting reference directions shown in the right-hand side of Fig. 1.1, both T_{em} and T_m have negative values. Variable p_e, given by relation (1.1), defines the electrical power taken by the machine from external electrical circuits, i.e., the power taken from a supply network. Since electrical generator converts mechanical work to electrical energy and delivers it to a supply network, the generator power p_e has a negative value. The sign of these variables has to do with reference directions. Changing the reference directions for torques and currents in Fig. 1.1 would result in positive generator torques and positive generator power.

1.1.7 Reversible Machines

Electrical machines are mainly reversible. A reversible electrical machine may operate either as a generator converting mechanical work to electrical energy or as a motor converting electrical energy to mechanical work. Transition from the

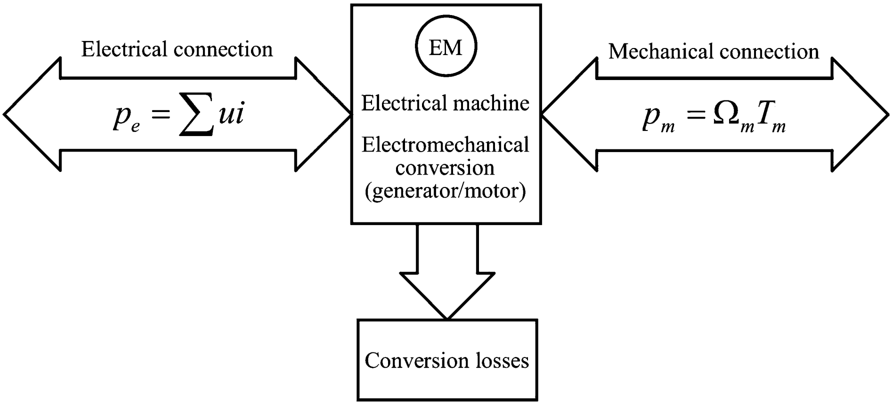

Fig. 1.2 Block diagram of a reversible electromechanical converter

generator to motor operating mode is accompanied by changes in the electrical and mechanical variables such as voltage, current, torque, and speed. The operating mode can be changed without modifications in the machine construction, with no changes in the current circuits, and without variations in the shaft coupling between the electrical machine and the work machine. An example of a reversible electrical machine is asynchronous motor. At angular rotor speeds lower than the *synchronous speed*, an asynchronous machine operates in the motor mode. If the speed is increased above the synchronous speed, the electromagnetic torque is opposed to motion while asynchronous machine converts mechanical work to electrical energy, thus operating in the generator mode.

Reversible energy conversion is shown in Fig. 1.2. Direction from left to right is taken as the reference direction for the power and energy flow. Power p_e at the electrical and p_m at the mechanical terminal of the machine have positive values in the motor mode, whereas in the generator mode these values are negative. Energy conversion is accompanied by energy losses in the current circuits, magnetic circuits, and also mechanical energy losses as a consequence of various forms of rotational friction. Due to losses, the power values at the electrical and mechanical terminals are not equal. In the motor mode, the obtained mechanical power p_m is somewhat lower than the invested electrical power p_e due to conversion losses. In the generator mode, the obtained electrical power $(-p_e)$ is somewhat lower than the invested mechanical power $(-p_m)$ because of the losses.

1.2 Significance and Typical Applications

Electrical energy is produced by operation of electrical generators. The produced energy is transmitted and distributed to energy consumers, mainly consisting of electrical motors which create controlled movement in work machines, whether household appliances, industry automation machines, robots, electrical vehicles, or machines in transportation systems.

The role of electrical machines in the processes and phases of production, transmission, distribution, and application of electrical energy is shown in Fig. 1.3. A brief description is given for each individual phase:

(a) Electrical energy can be obtained by using the potential energy of water accumulated in lakes; by using energy of coal, natural gas, or other fossil fuels; by using wind and tidal energy; by using nuclear fission, heat of underground waters, and energy of the sun; and by other means. These resources are the *primary energy sources*.
(b) In electrical power plants, the primary energy is at first converted to mechanical work. By burning fossil fuels, or using thermal springs, or in a nuclear reactor, generated heat is used to evaporate water and produce *overheated steam*. The steam acts on the blades of a steam turbine which rotates at speed Ω_m, creating rotational torque T_m. In hydroelectrical power plants, flow of water is directed to the blades of a hydroturbine. A turbine is also called *primer mover*.
(c) The obtained mechanical power $P_m = \Omega_m T_m$ is delivered to electrical generator, the electrical machine which converts mechanical work to electrical energy.
(d) Synchronous machines from 0.5 to 1,000 MW are predominantly used as generators in electrical power plants. Stator of the generator has three stationary *phase windings*. The rotor accommodates an *excitation winding* which determines the rotor flux. This flux does not move with respect to the rotor. Since the rotor revolves, the magnetic field of the rotor rotates with respect to the stator windings. Therefore, the rotor motion causes variation of the flux in the stator phase windings. Due to variation of the flux, an electromotive force is induced in the stator phase windings. Consequently, an AC voltage $u(t)$ is obtained at the stator winding terminals. When these terminals are connected to an external electrical circuit, AC currents $i(t)$ are established in the stator phase windings. The machine is connected to a transmission network which takes the role of an electrical consumer. The AC currents in the phase windings are dependent on the electrical load connected to the generator via transmission network. Electrical power obtained at machine terminals is $p_e = \sum ui$. The interaction of phase currents in the stator windings and magnetic field within the generator produces electromagnetic forces acting on the rotor which results in an electromagnetic torque T_{em}. This electromagnetic torque is a measure of mechanical interaction between the stator and the rotor. The electromagnetic torque acts on both the rotor and the stator. The stator is fixed and cannot move. The rotor speed depends on the torque T_m, acting toward the speed increase, and the generator torque T_{em}, acting toward the speed decrease. In an electrical machine operating as a generator, the torque T_m is obtained by operation of the steam or a hydroturbine. This torque tends to start and accelerate the rotor. The electromagnetic torque T_{em} opposes the rotor movement. Mechanical power input is higher than the obtained electrical power due to power losses in the electrical machine. In addition to the losses within the generator itself,

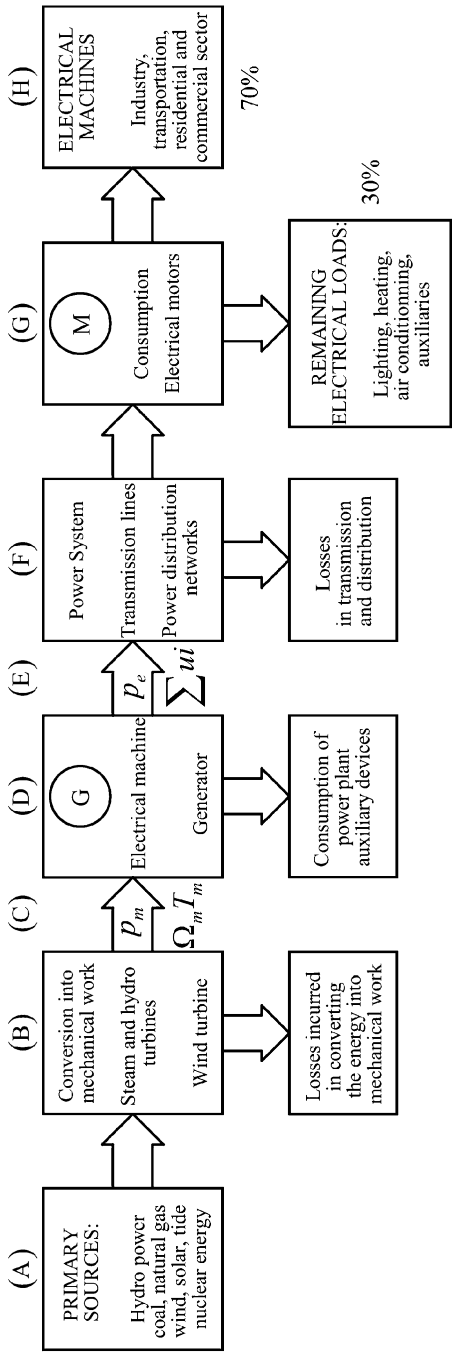

Fig. 1.3 The role of electrical machines in the production, distribution, and consumption of electrical energy

a part of the produced electrical energy is spent on covering consumption of the power plant itself. Contemporary electrical power plants are equipped with three-phase synchronous generators.[1]

(e) The electrical power obtained at generator terminals is determined by the voltages and currents. The system of AC voltages at the stator terminals has the rms[2] value from 6 to 25 kV, and frequency 50 Hz (60 Hz in some countries). A generator is connected to a *block transformer*, receiving the stator voltages on the primary side and providing the secondary side voltages compatible to the voltage level of the transmission power line.[3] At present, these voltages range up to 750 kV, and introduction of voltages of 1,000 kV is being considered.

(f) High-voltage power lines transmit electrical energy from power plants to the cities, communities, industrial zones, and transportation nodes, wherever the consumers of electrical energy are grouped. Distribution of electrical energy is carried out by the lower voltage power lines. Factories and residential blocks are usually supplied by 10–20 kV power lines or cables. Power transformers 10 kV/0.4 kV reduce the line voltages to 400 V and phase voltage to 231 V, supplied to the majority of consumers. Transmission and distribution of electrical energy are accompanied by losses in power lines and also in the transmission and distribution power transformers.

(g) Industrial consumers are using electrical motors for operating lathes, presses, rolling mills, milling machines, industrial robots, manipulators, conveyers,

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[1] At the end of nineteenth century, the production, transmission, distribution, and application of electrical energy were dealing with DC currents and voltages. *Electrical power plants* were built in the centers of communities or close to industrial consumers, and they operated DC generators. Electrical motors were also DC machines. Both the production and application of electrical energy were relying on DC machines, either as generators or as consumers – DC motors. At the time, there were no power converters that would convert low DC voltage of the generator to a higher voltage which is more suitable for transmission. For this reason, energy transmission was carried out with high currents and considerable energy losses, proportional to the generator-load distance. Contemporary transmission networks apply three-phase system of AC voltages. The voltage level is changed by means of power transformers. A *block transformer* transforms the generator voltages to the voltage level encountered at the transmission lines. A sequence of transmission and distribution transformers reduces the three-phase line voltage to the level of 400 V which is supplied to majority of three-phase consumers. The phase voltage of single-phase consumers is 231 V. By using the three-phase system of AC currents, it is possible to achieve transmission of electrical energy to distances of several hundreds of kilometers. Therefore, contemporary power plants could be distant from consumers.

[2] "Root mean square," the thermal equivalent of an AC current, the square root of the mean (average) current squared

[3] In transmission of electrical energy by power lines over very large distances, greater than 1,000 km, transmission by AC system of voltages and currents could be replaced by DC transmission, that is, by power lines operating with DC currents and voltages. At the beginning of a very long transmission line, static power converters are applied to transform energy of the AC system into the energy of the DC system. At the end of the line, there is a similar converter which converts the energy of the DC system into energy of the AC system. In this way, voltage drops across series impedances of the power line are reduced, and the power that could be transmitted is considerably increased.

mills, pumps for various fluids, ventilators, elevators, drills, forklifts, and other equipment and devices involved in production systems and processes. In electrical home appliances, motors are applied in air conditioners, refrigerators, washing and dishwashing machines, freezers, mixers, mills, blenders, record players, CD/DVD players, and computers and computer peripherals. Approximately 8% of the total electrical energy consumption is spent for supplying motors in transportation units like railway, city transport, and electrical cars.

(h) In industrialized countries, 60–70% of the electrical energy production is consumed by electrical machines providing mechanical power and controlling motion in industry, traffic, offices, and homes. Therefore, it can be concluded that most of the electrical energy produced by generators is consumed by electrical motors which convert this energy to mechanical work. Electrical motors are coupled mechanically to machines handling mechanical work and power, carrying and transporting the goods, pumping fluids, or performing other useful operations. Most electrical motors draw the electric power from the three-phase distribution *grid* with line voltages of 400 V and *line frequency* of 50(60) Hz. If the speed of electrical motor has to be varied, it is necessary to use a *static power converter* between the motor terminals and the distribution grid. The static power converters are *power electronics* devices comprising semiconductor power switches. Their role is to convert the energy of line-frequency voltages and currents and to provide the motor supply voltages and currents with adjustable amplitude and frequency, suited to the motor needs.

1.3 Variables and Relations of Rotational Movement

Electrical machines are mainly rotating devices comprising a motionless stator which accommodates a cylindrical rotor. The rotor revolves around the axis which is common to both rotor and stator cylinders. Along this axis, the machine has a steel shaft serving for transmission of the produced mechanical work to an external work machine. There are also linear electrical machines wherein the moving part performs translation and is subject to forces instead of torques. Their use is restricted to solving particular problems in transportation and a relatively small number of applications in robotics.

Position of rotor is denoted by θ_m, and this angle is expressed in radians. The first derivative of the angle is mechanical speed of rotation, $\mathrm{d}\theta_m/\mathrm{d}t = \Omega_m$, expressed in radians per second. Sign of Ω_m depends on the adopted reference direction. It is adopted that positive direction of rotation is counterclockwise (CCW). Besides the rotor mechanical speed, this book also studies rotation of the magnetic field and rotation of other relevant electrical and magnetic quantities.

Speed of rotation of each of the considered variables will be denoted by the upper case Greek letter Ω, whereas the lower case Greek letter ω will be reserved

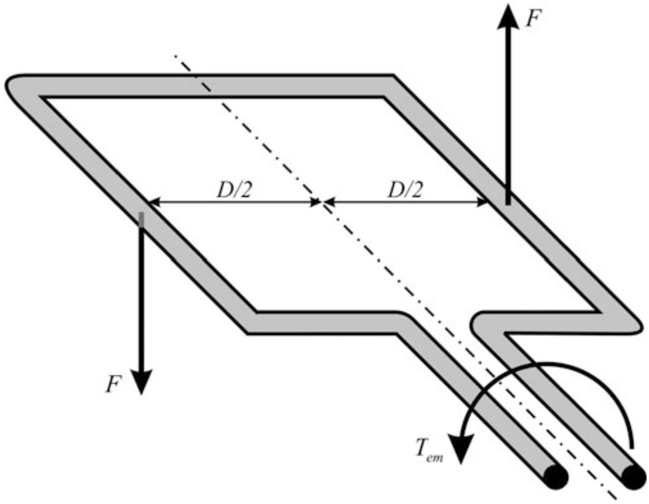

Fig. 1.4 Conductive contour acted upon by two coupled forces producing a torque

for denoting electrical angular frequency. Numerical values of the speed and frequency are usually expressed in terms of the SI system units, s^{-1}, i.e., in radians per second. The value $f = \omega/2\pi$ determines the frequency expressed as the number of cycles per second, Hz. The rotor speed can also be expressed as the number of revolutions per minute (rpm),

$$n = \frac{60}{2\pi}\Omega_m \approx 9.54\ \Omega_m. \tag{1.3}$$

Torque T_{em} generated in an interaction of the magnetic field and the winding currents is called *electromagnetic torque*. The electromagnetic torque produced by electric motors is also called *moving torque* or *driving torque*. Torque T_{em} is a measure of mechanical interaction between stator and rotor. A positive value of T_{em} turns the rotor counterclockwise. The torque contribution of individual conductors is shown in Fig. 1.4. It is assumed in Fig. 1.4 that the field of magnetic induction $\boldsymbol{B}$ extends in horizontal direction. Electrical current in conductors interacts with the field and creates the force $\boldsymbol{F}$ which acts on the conductors in vertical direction. The force depends on the field strength, on the current amplitude, and on the length of conductors. The torque exerted on single conductor is determined by the product of the force F, acting on the conductor, and perpendicular distance of the vector F from the axis of rotation, also called *the force arm*. Figure 1.4 shows a contour subjected to the action of two coupled forces producing the torque $T_{em} = FD$, where $R = D/2$ is the arm of the forces acting on conductors which are symmetrically positioned with respect to the axis of rotation.

The electromagnetic torque T_{em} is counteracted by the load torque T_m, representing the resistance of the mechanical load or work machine to the movement. In the case when the electromagnetic torque prevails, i.e., $T_{em} > T_m$, the speed

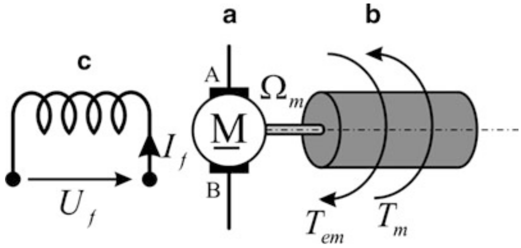

Fig. 1.5 Electrical motor (a) is coupled to work machine (b). Letter (c) denotes excitation winding of the dc motor

of rotation increases. Otherwise, it decreases. Variation of the speed of rotation is governed by Newton equation (1.4):

$$J\frac{\mathrm{d}\Omega_m}{\mathrm{d}t} = Ja = T_{em} - T_m. \tag{1.4}$$

Angular acceleration $a = \mathrm{d}\Omega_m/\mathrm{d}t$ is expressed in radians per square second [rad/s^2] and can be calculated by Newton equation. In steady state, angular acceleration is equal to zero. Then, the electromagnetic torque T_{em} is in equilibrium with the load torque T_m.

Moment of inertia J depends on the masses and shapes of all rotating parts. In case of stiff coupling of the shaft of an electrical machine to rotational masses of a work machine, total moment of inertia $J = J_R + J_{RM}$ is the sum of the rotor inertia J_R and inertia of rotating masses of the work machine J_{RM}. Figure 1.5 shows a work machine coupled to an electrical motor. It is assumed that rotational masses of the machine have cylindrical shapes of radius R and mass m. Moment of inertia of a solid cylinder is determined by expression $J = ½mR^2$.

Question (1.1): A work machine has rotational mass of the shape of a very thin ring of radius R and mass m. Determine moment of inertia of the work machine.

Answer (1.1): $J_{RM} = mR^2$.

1.3.1 Notation and System of Units

Throughout this book, instantaneous values of the considered variables are denoted by lower case letters (u_p, i_p, $p_p = u_p i_p$), whereas steady state values, DC values, and root mean square values are denoted by upper case letters (U_p, I_p, $P_p = U_p I_p$), in accordance with recommendations of the International Electrotechnical Commission (IEC). Exceptions to these recommendations are only notations of the force F, torque T, and speed of rotation Ω. Upper case letter T is used for denoting both instantaneous and steady state values of the torque since lower case letter t is often used to denote other relevant variables of power converters. Speed of rotation is denoted by the upper case Greek letter Ω, whereas lower case letter ω denotes angular frequency. Both variables are expressed in radians per second, i.e., s^{-1}.

Relevant vectors of rotating machines are represented in the cylindrical coordinate system. These are usually planar, since their z components are equal to zero. By introducing complex plane, each vector can be represented by a complex number with real and imaginary parts corresponding to the projections of the plane vector to the axes of the coordinate system.[4] For example, voltage and current vectors are denoted by $\underline{u}_s$ and $\underline{i}_s$. It should be noted that the stated quantities are not constants; thus, $\underline{u}_s$ and $\underline{i}_s$ are not voltage and current phasors. Namely, their real and imaginary parts can vary independently during transient processes. In steady state, quantities $\underline{u}_s$ and $\underline{i}_s$, like other vectors represented in complex numbers, become complex constants and should be treated as phasors. In steady state, notation changes and becomes $\underline{U}_s$ or $\underline{I}_s$. Stationary matrices can be denoted by [A] or $\underline{\mathrm{A}}$. All variables which can assume different numerical values are denoted by *italic*. Operators sin, cos, rot, div, mod, differentiating operator d, and others, as well as the measurement units, cannot be denoted by italic.

Notation of vectors such as magnetic induction, magnetic field, force, and other vectors in equations is usual, $\vec{B}$, $\vec{H}$, $\vec{F}$, etc. When these vectors are mentioned in the text, the upper arrow is not used and the magnetic induction vector is denoted by ***B***, magnetic field vector by ***H***, force vector by ***F***, etc.

Within this book, coupled magnetic forces are called *electromagnetic torque*. In the introductory subjects of electrical engineering, forces acting on conductors in a magnetic field are called *magnetic forces*. The term *magnetic torque* is quite adequate, but the literature concerning electrical machines usually makes use of the term *electromagnetic torque*, so this term has been adopted in this book.

International System of Units (SI), introduced in 1954, has been used in this book. The system has been introduced in most countries. A merit of the SI system is that it allows calculations with no need for using special scaling factors. Therefore, by applying the SI system, remembering and using dedicated multiplication coefficients are no longer needed. For example, calculation of work W made by force F, acting along path l, is obtained by multiplying the force and path.[5] In the case of SI system, the work is determined by expression $W[\mathrm{J}] = F[\mathrm{N}]l[\mathrm{m}]$, without any need for introducing additional scaling coefficients because $1\ \mathrm{J} = 1\ \mathrm{N} \times 1\ \mathrm{m}$. In the case when the force is expressed in kilograms, distance in inches or feet, the result Fl would have to be multiplied by a scaling factor in order to obtain the work in joules or calories. In the analysis of electrical machines, one should check whether the results are expressed in correct units. In doing so, it is useful to know relations between the basic and derived units. Some of the useful relations are

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[4] Representation of a plane vector by complex number is widely used in the technical literature concerning electrical machines. The vectors related to machine voltages and currents are also called *space vector*. Term *polyphasor* is also met. The complex notation is used here without any specific qualifier. A "vector $\underline{\mathrm{V}}$," mentioned in the text, refers to the planar vector and implies that the unit vectors of the Cartesian coordinate system are formally replaced by the real and imaginary units.

[5] Work of the force is $W = Fl$ provided that the force is constant, that it moves along straight line, and that the course and direction of the force coincide with the path.

[Vs] = [Wb], [Nm rad/s] = [W], [Nm rad] = [J], [AΩ] = [V], [AH] = [Wb] = [Vs], etc.

Within this book, the rated values are denoted a subscript n, such as in U_n or I_n.

1.4 Target Knowledge and Skills

Knowledge of electrical machines is a basis for successful activity of an electrical engineer. A large number of applications and systems, designed or used by an electrical engineer, contain one or more electrical machines. Characteristics of these applications and systems are usually determined by the performances of electrical machines, their dimensions, mass, efficiency, peak torque capability, and speed range, as well as control characteristics and dynamic response. For this reason, it is necessary to acquire the knowledge and skills to understand basic operation principles of electrical machines. Basic understanding of mechanical and electrical characteristics of electrical machines is required to specify and design their power supply and controls. The knowledge concerning the origin and nature of energy losses in electrical machines is required to specify and design their cooling and conceive their loss-minimized use.

The most significant challenges in developing novel solutions are design of the magnetic circuit and windings, resolving power supply problems, and devising control laws. Machines should be designed to have the smallest possible dimensions and mass, and to operate with low energy losses. At the same time, machines should be as cheap and robust as possible. At present, the power supply and controls of electrical machines are carried out by using static power converters and digital signal controllers. Some of the goals of generator control are reduction of losses, reduction of electromagnetic and mechanical stress of materials, as well as increasing the power-to-mass ratio, also called *specific power*. Motor control aims at achieving as high as possible accuracy and speed of reaching the torque and speed targets required for performing desired movement of a work machine.

This book contains the basic knowledge concerning electrical machines necessary for future electrical engineers. The approach starts from the basic role and function of the machine. The characteristics of machine electrical and mechanical accesses (*ports*) are analyzed in order to define the mathematical model, equivalent circuits, and mechanical characteristics. This book deals with the elements of machine design, problems of heating and cooling, and also with specific imperfections of magnetic circuits and windings. The depth of the study is suited for understanding the operating principles of main machine types, for acquiring basic knowledge on power supply topologies, and for comprehending essential concepts of machine controls. Rotational electromechanical converters are studied in this book, whereas the power transformers are omitted.

1.4.1 Basic Characteristics of Electrical Machines

Design, specification, and analysis of electrical machine applications require an adequate idea on the size, mass, construction, reliability, and losses. The basic knowledge of electrical machines is required for designing systems incorporating electrical machines and solving the problems of power supply and controls. Basic electrical machine concepts are also required for designing monitoring and protection systems, designing servomotor controllers in robotics, and designing controls and protections for synchronous generators in electrical power plants. The knowledge of electrical machines is required in all situations and tasks likely to be put before an electrical engineer in industry, power generation, industrial automation, and robotics.

1.4.2 Equivalent Circuits

The torque and speed control of an electrical machine is performed by establishing the winding voltages and currents by means of an appropriate power supply. Design or selection of power supply for a given electrical machine requires establishing relations between the machine flux, torque, voltages, and currents. The steady state relations are described by a steady state equivalent circuit. The equivalent circuit is an electrical circuit containing resistors, inductances, and electromotive forces. At steady state, with constant speed and with the given amplitude and frequency of the supply, the equivalent circuit allows calculation of currents in the windings. Based upon the currents determined from the equivalent circuit, it is possible to calculate the steady state flux, torque, power of electromechanical conversion, and power losses.

1.4.3 Mechanical Characteristic

For the given voltage and frequency of the power supply, the calculation of the steady state values of the machine speed and torque requires the torque-speed characteristic of the work machine which is attached to the shaft and acts as mechanical load. The relation $T_m - \Omega_m$ of the work machine is also called *mechanical characteristic* of the load, and it is expressed by the function $T_m(\Omega_m)$. In a like manner, mechanical characteristic of the electrical machine is the relation between the electromagnetic torque T_{em} and the rotor speed Ω_m in the steady state. It is possible to express the mechanical characteristic by function $T_{em}(\Omega_m)$ and present it graphically in the T_{em}-Ω_m plane. Determination of the mechanical characteristic can be carried out by using mathematical model of the machine. The steady state operating point is found at the intersection of the two mechanical characteristics, $T_{em}(\Omega_m)$ and $T_m(\Omega_m)$.

1.4.4 Transient Processes in Electrical Machines

The equivalent circuit and mechanical characteristics can be used for the steady state analysis of electrical machines, i.e., in the operating modes where the torque, flux, speed of rotation, currents, and voltages do not change their values, amplitudes, or frequencies. There are numerous applications where it is required to accomplish fast variations of the torque and speed of rotation. In these applications, it is necessary to have a mathematical representation of the machine which reflects its behavior during transients. This representation is called *mathematical model*. Deriving the mathematical model, one cannot start from the assumption that machine operates in steady state. For this reason, such model is also called *dynamic model*. Examples of electrical machine applications where the dynamic model has to be used are the controls of industrial manipulators and robots and propulsion of electrical vehicles. The motion control implies variations of speed and position along a predefined trajectory of a tool, work piece, vehicle, or an arm of an industrial robot. Whenever the controlled object falls out of the desired trajectory, it is necessary to assert a relatively fast change of the force (or torque) in order to drive the controlled object back to the desired path and annihilate the error. The task of the position (or speed) controller is to calculate the force (torque) to be applied in order to remove the detected position (or speed) discrepancy. The task of electrical motor is to deliver desired torque as fast and accurate as possible. In such *servo applications*, electrical motors are required to realize very fast changes of torque in order to remove the influence of variable motion resistances on the speed and position of the controlled objects. The analysis of operation of an electrical machine used as a servomotor in motion control applications requires thorough knowledge of transient processes within the machine.

Another case where the mathematical model is required is the analysis of transient processes in grid-connected synchronous generators operating in electrical power plants. Sudden rises and falls of electrical consumption in transmission networks are caused by switching on and off of large consumers, or quite frequently by short circuits. They affect generators as an abrupt change of their electrical load. The analysis of generator voltages and currents during transients cannot be performed by using the steady state equivalent circuit. Instead, it is required to have a mathematical model depicting the transient phenomena within the machine.

1.4.5 Mathematical Model

The mathematical model is represented by a set of algebraic and differential equations describing behavior of a machine during transients and in steady states. The *voltage balance equations* express the equilibrium of voltage in the machine windings, and they have the form $u = Ri + \mathrm{d}\Psi/\mathrm{d}t$. The change of the rotor speed is determined by Newton differential equation $J\,\mathrm{d}\Omega_m/\mathrm{d}t = T_{em} - T_m$. Quantities such as J and R are parameters, while Ω_m and Ψ are variables describing the state of the machine (*state variables*). An electrical engineer needs the model of electrical machine for performing the analysis of the energy conversion processes, for the analysis of conversion losses, for designing of the machine power supply and controls, as well as for solving the problems that may occur during machine applications. For this reason, it is necessary to have a relatively simple and intuitive model so that it can present the processes and states of the machine in a concise and clear way. *A good model* should be thorough and concise outline of the relevant phenomena within the machine, suitable for making conclusions and taking decisions as regards power supply, controls, and use of the electrical machines.

There are aspects and phenomena within the machine which are not relevant for problems under the scope because they influence operation of an electrical machine to a very limited extent. They are called *secondary* or *parasitic* effects, as they are usually neglected in order to obtain a simpler, more practical mathematical model. As an example, the energy density $w_e = \varepsilon E^2/2$ of electric field E within electrical machines can be neglected. It is lower than the energy density of magnetic field by several orders of magnitude. In the process of modeling, other justifiable omissions are adopted in order to obtain a simplified model which still matches the purpose. For the problem under consideration, the most appropriate model is the simplest one, yet depicting all the relevant dynamic phenomena. Justifiable omissions of secondary effects lead to mathematical models that are less complex and more intuitive. With such models, it is easier to overview the main features of the system. The problem solving and decision-making process becomes quicker and straightforward.

In electrical engineering, the model is usually a set of differential equations describing behavior of a system. Model of an electrical machine, or a transformer, can be reduced to the equivalent circuit describing its steady state operation. On the basis of the model, it is possible to determine the mechanical characteristic of the machine.

1.5 Adopted Approach and Analysis Steps

In general, the material presented in this book is intended for electrical engineering students. The basic knowledge of mathematics, physics, and electricity is practically applied in studying electrical machines, by many students met for the very first time. The approach starts with general notion and then goes to detail. It allows the beginners to perceive at first the basic purpose, appearance, and fundamental characteristics of electrical machines. Following the introductory chapters, this book investigates operating modes in typical applications and studies equivalent circuits, mechanical characteristics, power supply topologies and controls, as well as the losses and the problems in exploitation. Later on, the focus is turned to details related to the three main types of electrical machines.

The attention is directed toward DC, asynchronous, and synchronous machines. In this book, other types of electrical machines have not been studied in detail. The problems associated with design of electrical machines are briefly mentioned. The winding techniques, magnetic circuit design, analysis of secondary phenomena, the secondary and parasitic losses, and construction details have been left out for further studies. The main purpose of this book is introducing the reader to the role of electrical machines and studying their electrical and mechanical properties in order to acquire the ability to specify their electrical and mechanical characteristics, to define their power supplies and control laws, and to design systems with electrical motors and generators.

The study of electrical machines starts by an introduction to the basic principles of operation and with a survey of functions of electrical generators and motors in their most frequent applications. The analysis steps include the principles of electromechanical conversion and study the conversion process by taking the example of an electrostatic machine. Energy of the coupling electrical field is analyzed along with the process of energy exchange between the field, the electrical source, and the mechanical port. The study proceeds with the analysis of a simple electromechanical converter with magnetic coupling field. Construction of the magnetic circuit and windings of the machine are followed by specification of conversion losses. Subsequently, rotational electromechanical converters with magnetic coupling are considered, along with the rotating electrical machines which are the main subject of this study. The basic notions and definitions include the magnetic resistances and circuits, concentrated and distributed windings, methods of calculating the flux per turn and the winding flux, and the expressions for the winding self-inductances, mutual inductances, and leakage inductances. Magnetomotive forces of the winding are explained and analyzed, as well as electromotive forces induced in concentrated and distributed windings. The magnetic field in the air gap is analyzed and applied in modeling the electromechanical conversion in cylindrical machines. The electromagnetic torque and the power of electromechanical conversion are expressed in terms of flux vectors and magnetomotive forces. The concept and creation of rotating magnetic field are detailed and used to describe the difference between direct current (DC) machines and alternating current (AC) machines. The mathematical model of a cylindrical machine with the windings having N coils is derived, along with the expressions for electrical power, mechanical power, and power losses in the windings, magnetic circuit, and the mechanical subsystem. The secondary phenomena that are usually neglected in the analysis of electrical machines are specified and explained. At the same time, some sample applications and operating conditions are named where the secondary phenomena cannot be excluded from the analysis.

The introduction is followed by the chapters dealing with DC machines, asynchronous machines (AM), and synchronous machines (SM). Each chapter starts with basic description and the operating principles of the relevant machine, followed by the most significant aspects of its construction, description of its merits, the most frequent applications, and meaningful shortcomings. The expressions are derived for the magnetomotive force, flux, electromotive force, torque, and conversion power. Mathematical model is derived for the machine under consideration, describing its behavior during transient processes and providing the grounds for obtaining the equivalent circuits and mechanical characteristics. In the case of AC electrical machines, the modeling includes introduction of the three-phase/two-phase coordinate transformation (Clarke transform) and coordinate transformation from the stationary coordinate frame to the revolving coordinate frame (dq or Park transform).

The equivalent electrical circuits of the machine are derived from the steady state analysis. They are used to calculate the currents, voltages, flux, torque, and power at steady states, where the supply voltage, the load torque T_m, and the speed of rotation are known and unchanging. The mathematical model is also used to obtain the mechanical characteristic which gives the steady state relation of the machine speed and torque delivered to the shaft. For each electrical machine, the operating regimes sustainable in the steady state are analyzed and formulated as the *steady state operating area* in the T_{em}-Ω_m plane. Likewise, the *transient operating area* of the T_{em}-Ω_m plane is defined, representing the transient operating regimes attainable in short time intervals.

Particular attention is paid to conversion losses. The losses in the windings and magnetic circuits are analyzed in depth, along with heating of electrical machines and the methods of their cooling. The highest sustainable values of the current, power, and torque are defined and explored. These values and the highest sustainable values of other relevant quantities are called *the rated values*.[6] The need for operation in the region of field weakening is emphasized, and the relevant relations and characteristics are derived.

The transient operating area is analyzed for DC and AC machines. It is derived from the short-term overload capabilities of mechanical and electrical ports of electrical machines. The analysis takes into account the impact of peak current and peak voltage capabilities of the electrical power supply on the machine transient performance. Basic information concerning the supply, controls, and typical power converter topologies used in conjunction with the electrical machine is given for DC, asynchronous, and synchronous machines.

[6] The *rated* values are the highest permissible values of the machine currents, voltages, power, speed, and torque in a continuous service. Permanent operation with higher values will damage the machine's vital parts due to phenomena such as overheating. They are usually the result of engineering calculation, and they also represent an important property of the machine. The rated values are usually related to specified ambient temperature. Typically, the rated power is the maximum power the electrical machine can deliver continuously at 40°C ambient temperature. The values written on the machine plate or in manufacturer's specifications are called *nameplate* or *nominal* values. The nominal and rated values are usually equal. In rare cases, manufacturer may have the reason to declare the nominal values lower than the rated values. Within this book, it is assumed that the nominal values correspond to the rated. They are denoted by a lowercase subscript *n*, such as in U_n or I_n.

1.5.1 Prerequisites

Precondition to understanding analysis and considerations in this book, accepting the knowledge, acquiring the target skills, and solving the problems is the knowledge of mathematics, physics, and basic electrical engineering which is normally taught at the first year of undergraduate studies of engineering. It is required to know the basic laws of motion and practical relations concerning rotation and translation. Required background includes the steady state electrical and magnetic fields, the basic characteristics of dielectric and ferromagnetic materials, and elementary boundary conditions for electrostatic and magnetic fields. Chapter 2, *Electromagnetic Energy Conversion*, deals with the analysis of the energy and forces associated with electrostatic and magnetic fields in dielectrics, ferromagnetics, and air. Further on, analysis includes solving simple electric circuits with DC or AC currents. In addition, the analysis extends on the magnetic circuits involving magnetomotive forces (*magnetic voltages*), flux linkage, and magnetic resistances. The basic laws of electrical engineering should be known, like Faraday law on electromagnetic induction, Ampere law, Lorentz law, and Kirchhoff laws and similar. The study includes spatial distribution of the current, field, and energy. Therefore, coordinates in the Cartesian or in the cylindrical coordinate systems will be used along with the corresponding unit vectors. A consistent effort is sustained throughout this book to make the developments material accessible to readers not familiar with spatial derivatives, such as rotor (**curl**, **rot**) or divergence (**div**). Therefore, familiarity with Maxwell differential equations is not inevitable. Instead of differential form of Maxwell laws, it is sufficient to know their integral form, such as Ampere law. The skill in handling complex numbers and phasors is required, as well as dealing with scalar and vector products of vectors. For determining direction of a vector product, one should be familiar with the right-hand rule. Also required are the abilities of representing and perceiving relations between three-dimensional objects, of identifying closed surfaces defining a domain, and of contours defining a surface and surface normals. Within this book, the problem solving involves relatively simple line and surface integrals and solution of first-order linear differential equations. An experience in reducing differential equations to algebraic equations by applying Laplace transform and the ability of performing basic operations with matrices and vectors are also useful.

1.6 Notes on Converter Fed Variable Speed Machines

This book has not been written with an intention to prepare a reader for designing electrical machines. The main goal is studying the electrical and mechanical characteristics of electrical machines from the user's point of view, with an intention to prepare a reader for selecting an adequate machine, for solving the problems associated with the power supply and controls, and for handling the problems that may appear during operation of electrical motors and generators. The specific knowledge required for designing electrical machines is left out for further studies. The prerequisite for exploring further is a thorough acceptance of the knowledge and skills comprised within this book. The need for skilled designers of electrical machines is higher than before. Some of the reasons for this are the following:

- During the last century, electrical machines were designed to operate from the grid, with constant voltages and with the line frequency. Development of static power converters, providing three-phase voltages of variable frequency and amplitude, permits the power supply of an electrical motor to be adjusted to the speed and torque. Most new designs with electrical motors include static power converters that convert the energy received from the grid into the form best suited to the actual speed and torque. The voltage and frequency can be adjusted to reduce the power losses while delivering the reference torque at given speed. Therefore, there is an emerging quest for electrical machines designed to operate in conjunction with static power converters and variable frequency power supply.
- Applications of electrical motors for propelling electrical vehicles or driving industrial robots often require the rotor speed exceeding several hundreds of revolutions per second, which requires the power supply frequencies of the order of $f > 500$ Hz. Therefore, within contemporary servomotors and traction motors, electrical currents and magnetic induction pulsate at the same frequency. Fast variation of magnetic field requires application of new magnetic materials and novel design solutions for magnetic circuits. The increased frequencies of electric currents demand new solutions for making the windings.
- Propelling industrial robots requires electrical motors having a fast response and low inertia. Therefore, it is required to design synchronous motors having permanent magnets in their rotors, with the rotor shape and size resulting in a low inertia and fast acceleration, such as a disc or a hollow cylinder with double air gap.
- An increased interest in alternative and renewable power sources requires design of novel synchronous generators, suitable for the operation in conjunction with wind turbines, tidal turbines, and similar. The speed and the operating frequency are variable, while in some cases, generators operate at a very low speed. At the same time, the inertia and weight of generators should be low, with the lowest possible power losses.
- Construction of thermal electric power plants with supercritical steam pressure enables design of a single block in excess of 1 GW. Mechanical power of the block, obtained from a steam turbine, is converted to electrical energy by means of a synchronous generator operating at the line frequency of 50 Hz. Designing generators of this high power demands application of new design solutions, new insulating and ferromagnetic materials, and new cooling methods and systems.

The need to increase the production of electrical energy and the need to reduce the heat released to the environment can be alleviated by reducing the losses and increasing the *energy efficiency* η of electrical machines. The efficiency of generators and motors can be increased by adequate control, but also by designing novel electrical machines and applying new materials in their construction.

1.7 Remarks on High Efficiency Machines

Reduction in power losses increases the energy efficiency of electrical machines and relieves the problem of their cooling. As all the machine losses eventually turn into heat, the loss reduction diminishes the heat emitted to the environment. The heat released by electrical machines is a form of environmental pollution, and it should be kept low. Considering the fact that industrial countries use more than 2/3 of their electrical energy in electrical motors, the loss reduction in electrical machines has the greatest potential of energy saving. In addition, an efficient heat removal (cooling) often requires specific engineering solutions, increasing in this way the cost and complexity of the design. For these reasons, there is an increasing need for designing new, more efficient electrical machines and to devise their controls that would reduce the losses. Designing new solutions for electrical generators and motors requires a thorough basic knowledge on their operating principles, and it is bound to use novel ferromagnetic materials and new design concepts. One example is the use of permanent magnet excitation which eliminates the excitation winding and cuts down the rotor losses of synchronous machines. Besides, an efficient electromechanical conversion requires as well new solutions for the machine supply. Most of contemporary machines do not have a direct connection to the grid and do not operate with line-frequency voltages and currents. Instead, they are fed from static power converters which transform the grid supply to the form which is consistent with an efficient operation of the machine. Supply from a static power converter allows for the flux changes and selection of the flux level which results in the lowest power losses. Successful design of electrical machines supplied from static power converters requires a thorough knowledge on electrical and magnetic fields within the machine, as well as the knowledge on the energy conversion processes taking place within switching power converters.

1.8 Remarks on Iron and Copper Usage

On a wider scale, the energy efficiency of electrical machines includes as well the amount of energy consumed in the course of the machine production. Manufacturing of electrolytic copper and aluminum and making of laminated steel sheets require large amounts of energy. For this reason, the machine that uses fewer raw materials is likely to be the more efficient one. Construction of electrical machines has certain similarities with the construction of power transformers. In both cases, the appliance has a magnetic circuit and some electrical current circuits. Traditionally, magnetic circuits are made of laminated steel sheets, whereas electric circuits (windings) are made of insulated copper conductors. Both transformers and electrical machines are used within systems comprising energy converters, semiconductor switches, sensors, microprocessor control systems, and the associated software. The decisive factor which governs the price of the whole system is the iron and copper weight involved. Namely, production of semiconductor devices requires relatively small quantities of raw materials, such as the silicon ingot, some donor and acceptor impurities, and relatively small quantities of ceramic or plastic materials for the casing. Moreover, development, design, and software production costs have an insignificant contribution to the cost in series production. Therefore, it is significant to design and manufacture units and systems with reduced consumption of iron and copper. Reducing the quantities of raw materials can be accomplished in three ways:

In the system design phase, the operating conditions of electrical machines involved in the system can be planned so as to manufacture them with a reduced consumption of iron and copper.

In the electrical machine design phase, it is possible to make the magnetic and electric circuits in a manner that saves on raw materials. As an example, four-pole[7] machines make a better use of the magnetic circuit than two-pole machines.

During the operation of electrical machine supplied from a static power converter, it is possible to use the control methods that maximize the torque and power available from the given magnetic and electric circuits. In this way, there is an increase in the specific torque and specific power.[8] Given the torque and power requirements, it is possible to design and make the electrical machine with less iron and less copper.

Contemporary computer tools for design of electrical machines allow anticipation of their characteristics prior to making and testing a prototype. This facilitates and speeds up the design process. Moreover, it becomes possible to test several different solutions and approaches over a relatively short period of time. Most of the software packages make use of the finite element analysis (FEM) of electrical, magnetic, mechanical, and thermal processes. Designing with computer tools brings up the risk of inadvertent errors. The problems arise in cases when designer pretends that the tool performs the creative part of the job. A computer tool will give an output for each set of input data, whether the input makes sense or not. Therefore, a user has to possess certain experience in design, in order to interpret properly the obtained results and notice errors and contradictions. A conservative use of computer tools consists of using computer for quick completion of automatic tasks and calculations which the designer would have performed himself if he had sufficient time.

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[7] The operation of electrical machines involving multiple pairs of magnetic poles will be explained in chapter on asynchronous machines.

[8] For the given electrical machine, specific torque is the ratio between the available torque and the mass (or volume) of the machine. Hence, it is the torque per unit mass (or volume). The same holds for the specific power. With higher specific torque (or power), electrical machine is smaller and/or lighter for the same task.