ELECTRICAL POWER GENERATION

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Contents

Summary

EMC is a machine, which converts electrical energy to mechanical energy and vice versa. EMC is basically called an electrical machine. Conversion of energy within EMC occurs owing to interaction of three types of processes: electrical, magnetic and mechanical. EMC processing is explained with the help of the basic laws of electrical engineering. The simplified model of inductive EMC was used to illustrate the main principles and processes of electrical energy conversion. Progress in technology,

computer science, and materials provides new promising opportunities for further electrical engineering development.

During the 1970s and first part of the 1980s the manufactures of turbogenerators have attained outstanding successes: the rating of two pole generators reached 1333 MVA at 3000 rpm and of four poles - 1700 - 1800 MVA at 1500 rpm; hydrogenerators reached a capacity of 700 - 800 MVA at about 100 rpm. This was possible due to rapid development of large nuclear, fossil and hydropower plants. But at the end of the 1980s the accident at Chernobil nuclear plant stirred up a powerful ecological movement. It began to be widely understood that the large power stations of all types are dangerous and it is more effective to put money into energy conservation systems instead of producing extra electricity. Besides, at that time new technologies have appeared - gas turbines together with usual steam turbines gave the possibility to increase the power stations efficiency up to 50 per cent and more importantly, they are substantially cleaner.

For combined power cycles there is no need to use large generators. For the situation of today and of the near future the optimum size, of the gas turbine part of combined cycle is about 150 - 200 MW and that of vapor part - about 300 - 400 MW. It now pays to convert large central boiler stations in which natural gas is used as fuel, into small combined cycle power stations. In such stations the coefficient of the fuel utilization (taking into account both thermal energy and electricity production) can reach about 85 per cent. In this case the power units rating will be in the range of 300 - 10 000 kW.

Therefore these days the most popular turbogenerators ratings for fossil power stations are from some hundreds kW up to approximately 500 000 kW. Concerning nuclear power stations the turbogenerator ratings used also decrease to 1000 MW and less. – This is to increase the security of the nuclear power station which depends on the power station size.

The modern power station cannot operate satisfactory without the special device called the governor which is to provide the power set (power station) operation with stable frequency and adjustable active power.

Modern governors are based on computer technology and must function to ensure overall maximum power station efficiency.

Now there is no need for creation of new very large turbogenerators. But it don't mean that there are no problems which must be solved. According the existing world trends now under development are the following:

The excitation systems together with AVR ensure both normal generator operations and highest possible level of static and dynamic stability. It refers to both independent and self-excited excitation systems with the slip rings on the shaft and also brushless excitation systems. AVR can be based on forced or proportional actions.

Similar to all power installations, they execute the task on power coming in from the upper level and produce a signal for compensation of frequency departure with specified stability. Gas-turbine set governor is all-speed. Gas-turbine sets are highly maneuverable compared to steam power plants. Starting and loading a powerful gas-turbine set may take about 10 minutes.

Induction a.c. machines are most widely used a.c. machines. They are reliable and simple energy converters. But in the generator mode of operation induction a.c. machines are seldom used . This is connected with necessity to feed the generator with reactive power from the grid. In order to decrease the reactive power value the reactance of the an induction generator must have as small reactance as possible. Another question is the regulation both voltage and frequency.

There are many events of short-circuits in power systems followed by overcurrents which can destroy the power system equipment. Special protection systems are introduced to avoid the damages to them. New digital technology based protection systems are developed. In most cases they are integrated with switchgear forming the so called intelligent switchgear.

1. Electromechanical Basis of Electric Machines

1.1. Introduction

We have got into the way of using electric energy in industry and family life, in transport and communication, in office and entertainment. It is not an exaggeration to say that we use it every day. Electric engineering can be considered one of tremendous achievements of humanity, which influences greatly the progress of humankind.

The energy conversion is realized due to three-way interaction of electric, magnetic and mechanical processes. The present-day level of technology approved the use of the magnetic field as energy carrier within the electromechanical converter (EMC) as the most technically reasonable solution.According to modern opinions energy conversion in EMC with opposite magnetic poles is possible due to the use of alternating current. EMC are based on the principle of reversibility caused by universal nature of the magnetic field as energy carrier, and the principle of self regulation which follows from the common law of energy conservation.

1.2. Electromechanical converter: Main definitions

EMC is a machine, which converts electrical energy to mechanical energy and vice versa. Consequently EMC is basically called an electrical machine. Conversion of energy within EMC occurs owing to interaction of three types of processes: electrical, magnetic and mechanical. Magnetic field (inductive machines) as well as electric field (capacitor machines) is used as energy carrier. Simultaneous use of these fields is also possible (inductive-capacitor machines). Inductive machines are used more widely.

1.3. Physical basis of electromechanical energy conversion

A simplified physical model of an inductive EMC is presented in Figure 1. A stator with inductor winding (inductor – “*f*”) and a rotor with armature winding (armature – “*a*”) separated by an air gap are the main elements of the system. Windings are shown on the Figure 1 as electric circuits with a number of coils consequently w_f and w_a. Cores of stator and rotor are made from ideal ferromagnetic.

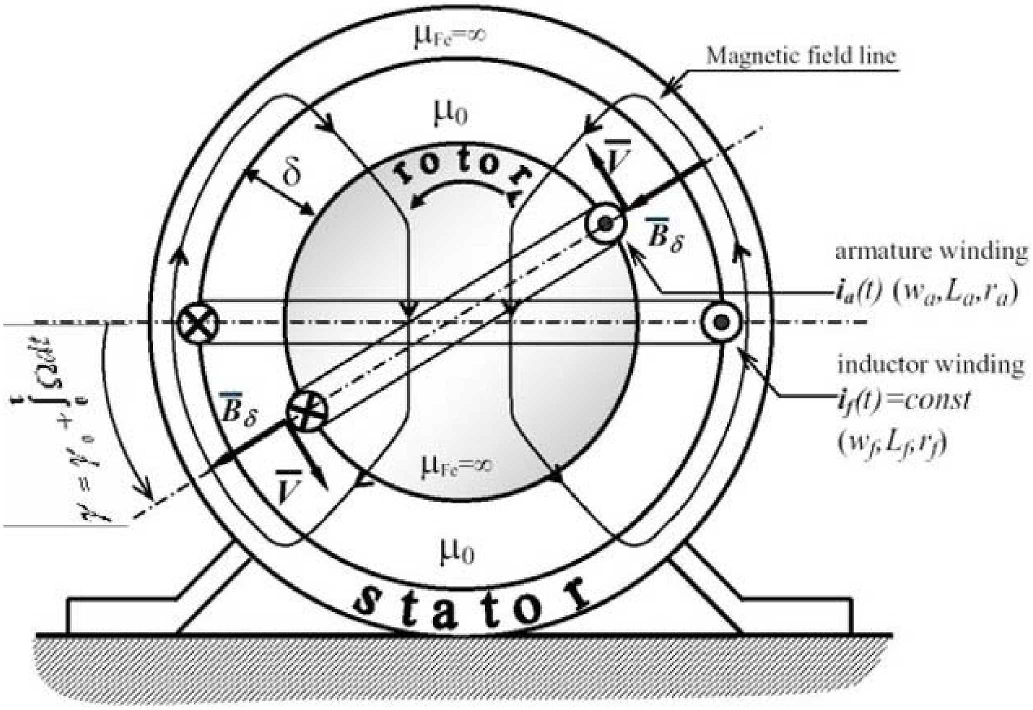

Figure 1. Simplified physical model of electromechanical energy converter

Let us consider that direct current i_f flows through the inductor winding having w_f conductors and creates primary magnetic field in the air gap (magnetic process). This magnetic field is distributed like a rectangular wave in space along the circumference of the air gap. It forms two opposite magnetic poles **N** and **S** with amplitude

$$B_\delta = \mu_0 \frac{i_f w_f}{2} \tag{1}$$

If we move the rotor by external mechanical force M_{1M} and spend for this mechanical energy P_{1M} (mechanical process), a periodically changing electromotive force (EMF) will appear across the armature winding. This EMF can be defined by the law of electromagnetic induction.

$$e_a = 2 l_\delta B_\delta w_a V \tag{2}$$

where l_δ- active length of winding conductor, w_a - number of armature conductors, V – linear speed of its displacement in the gap. If we close the armature winding to external load, current i_a will appear (electric process), by which the external load will be supplied by electric energy $P_{2,\mathrm{el}}$. Therefore conversion of mechanical energy into electrical energy took place. In the case described above the EMC works as an electrical energy generator. The reverse conversion from electrical energy into mechanical energy can be explained in a similar way, on the same model of EMC: $F = Bil$ where F = maximum force exerted on a conductor of active length l carrying current I, and placed perpendicular to the magnetic field of density B.

1.4. Energy Relations in the electromechanical converter

Let us consider the enegy relations of EMC model. Let us write an expression for the energy of magnetic field in a gap:

$$W_\mathrm{M} = \frac{1}{2} L_\mathrm{f} i_\mathrm{f}^2 + M_\mathrm{af} i_\mathrm{f} i_\mathrm{a} + \frac{1}{2} L_\mathrm{a} i_\mathrm{a}^2 \tag{3a}$$

and for resultant electromotive force in the winding

$$e_\mathrm{f} = -\frac{d\,\Psi_\mathrm{f}}{d\,t} = -\left(L_\mathrm{f} \frac{d\,i_\mathrm{f}}{d\,t} + M_\mathrm{af} \frac{d\,i_\mathrm{a}}{d\,t} \right) - i_\mathrm{a} \frac{d\,M_\mathrm{af}}{d\,\gamma} \Omega \tag{3b}$$

$$e_\mathrm{a} = -\frac{d\,\Psi_\mathrm{a}}{d\,t} = -\left(M_\mathrm{af} \frac{d\,i_\mathrm{f}}{d\,t} + L_\mathrm{a} \frac{d\,i_\mathrm{a}}{d\,t} \right) - i_\mathrm{f} \frac{d\,M_\mathrm{af}}{d\,\gamma} \Omega \tag{3c}$$

The following factors have been taken into account in expressions above: inductions of windings L_f and L_a are constant; angular frequency of rotor rotation Ω depends on angle γ, which defines mutual disposition of windings by correlation:

$$\gamma = \gamma_0 + \int_0^t \Omega dt \tag{4}$$

M_af - mutual induction between windings “a” and “f” depends on angle γ. It is necessary to stress that that the last item in the expression for EMF defines as well so called EMF of rotation, item in the round brackets – transformer EMF. It should be also mentioned here that the value of W_M together with total density of the magnetic energy

$$W_\mathrm{M} = \frac{B_\delta H_\delta}{2} \tag{5}$$

define the power and the size of EMC.

Full electric power on terminals of all windings, regarding that voltage on each is equal to $u_k = -e_k + r_k i_k$, where r_k – active resistance of windings, k=a,f

$$P_{\Sigma} = u_{\mathrm{f}} i_{\mathrm{f}} + u_{\mathrm{a}} i_{\mathrm{a}} = P_{\mathrm{el}} + P_{\mathrm{W}} + P_{\mathrm{M}} \qquad (6)$$

where

$$P_{\mathrm{el}} = r_{\mathrm{f}} i_{\mathrm{f}}^2 + r_{\mathrm{a}} i_{\mathrm{a}}^2 \qquad (6a)$$

- power of electric losses,

$$P_{\mathrm{W}} = L_{\mathrm{f}} i_{\mathrm{f}} \frac{di_{\mathrm{f}}}{dt} + L_{\mathrm{a}} i_{\mathrm{a}} \frac{di_{\mathrm{a}}}{dt} - M_{\mathrm{af}} \left(i_{\mathrm{f}} \frac{di_{\mathrm{a}}}{dt} + i_{\mathrm{a}} \frac{di_{\mathrm{f}}}{dt} \right) + i_{\mathrm{f}} i_{\mathrm{a}} \Omega \frac{dM_{\mathrm{af}}}{d\gamma} = \frac{dW_{\mathrm{M}}}{dt} \qquad (6b)$$

- power which is spent for changing of the electromagnetic field energy.

Essential that the power P_{W} has gone irretrievably, its medium value during the period of current change is equal to zero.

$$P_{\mathrm{M}} = i_{\mathrm{f}} i_{\mathrm{a}} \Omega \frac{dM_{\mathrm{af}}}{d\gamma} \qquad (6c)$$

- power, converted from mechanical one, applied to shaft of EMC, to electrical, appeared in electromagnetic form in the armature winding.

External mechanical forces create mechanical moment on the shaft:

$$M_{\mathrm{1M}} = \frac{P_{\mathrm{1M}}}{\Omega} \qquad (7)$$

Electromagnetic interaction of armature current i_a with the magnetic field creates braking electromagnetic moment:

$$M_{\mathrm{EM}} = \frac{dW_{\mathrm{M}}}{d\gamma} \Bigg|_{\substack{i_{\mathrm{f}} = \mathrm{const.} \\ i_{\mathrm{a}} = \mathrm{const.}}} = i_{\mathrm{f}} i_{\mathrm{a}} \frac{dM_{\mathrm{af}}}{d\gamma} \qquad (8)$$

Electromagnetic power

$$P_{\mathrm{EM}} = M_{\mathrm{EM}} \cdot \Omega = i_{\mathrm{f}} i_{\mathrm{a}} \Omega \frac{dM_{\mathrm{af}}}{d\gamma} = P_{\mathrm{M}} \qquad (9)$$

is carried in the armature winding just to create M_{EM}. This power is defined only by rotating EMF and doesn't depend on transformer EMF. The scheme of energy conversion for generator mode of EMC is shown on Figure 2.

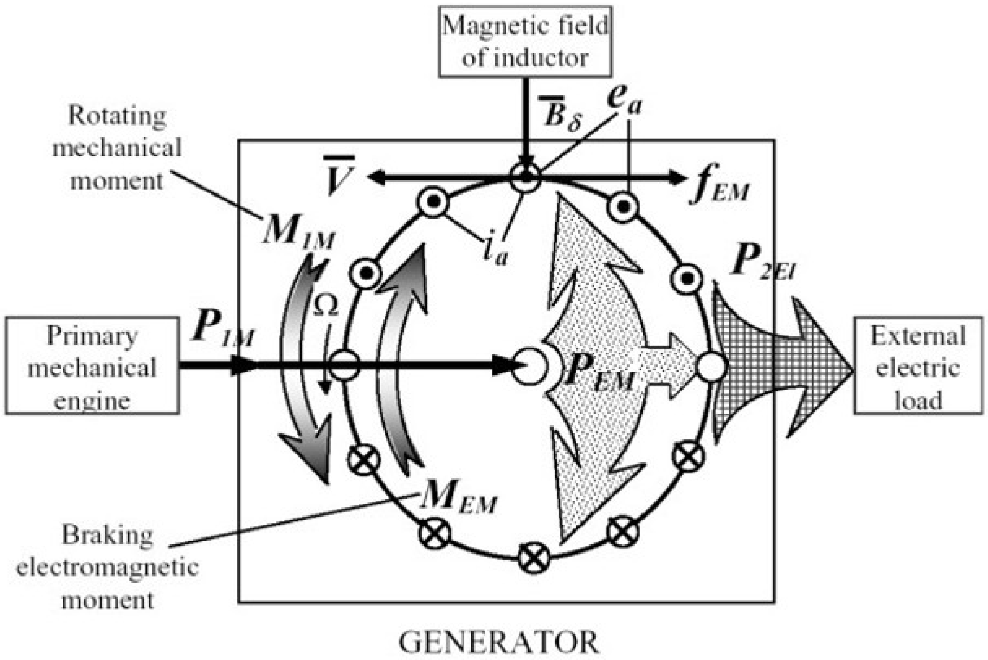

Figure 2. Scheme of energy conversion in EMC

1.5. The conditions of single-directed conversion of energy

The conditions of single-directed transformation of energy are

$$\frac{1}{2\pi}\int_{0}^{2\pi} P_{\mathrm{EM}}\, d\gamma \neq 0 \qquad (10)$$

If follows from (10) that, firstly, it is necessary to have $dM_{\mathrm{af}}/d\gamma \neq 0$. It means that mutual induction M_{af} must change periodically. This requirement is realized in model of rotating EMC. Secondly, armature current i_{a} must also change periodically with frequency of change of induction M_{af}. It means that in EMC with opposite magnetic poles in a gap clearance conversion of energy can be realized only by means of alternating current. For producing direct current it is necessary to install additional equipment.

1.6. The mechanisms of electromechanical energy conversion

The curves of functional dependencies for M_{af}, i_{a} and M_{EM} for model of EMC are shown on Figure 3. They show the mechanism of transformation from mechanical energy to electrical energy in accordance with Figure 2. The permanent inflow of electromagnetic energy occurs owing to the moment M_{1M} of primary mover. At the same time permanent outflow of energy from the magnetic field of air gap also takes place. It is provided by current i_a. As a result of this the braking moment appears. Since these moments are equal in the balanced conditions of EMC operation (Ω= const.) the energy inflow in the air gap should be equal to the energy outflow from it. Magnetic field becomes here the common energy carrier, transferring energy from rotor shaft to the armature winding. This balance is ensured by physical processes within EMC – magnetic, electric and mechanical, by appropriate parameters for each of these processes - B_δ, i_a ,Ω.

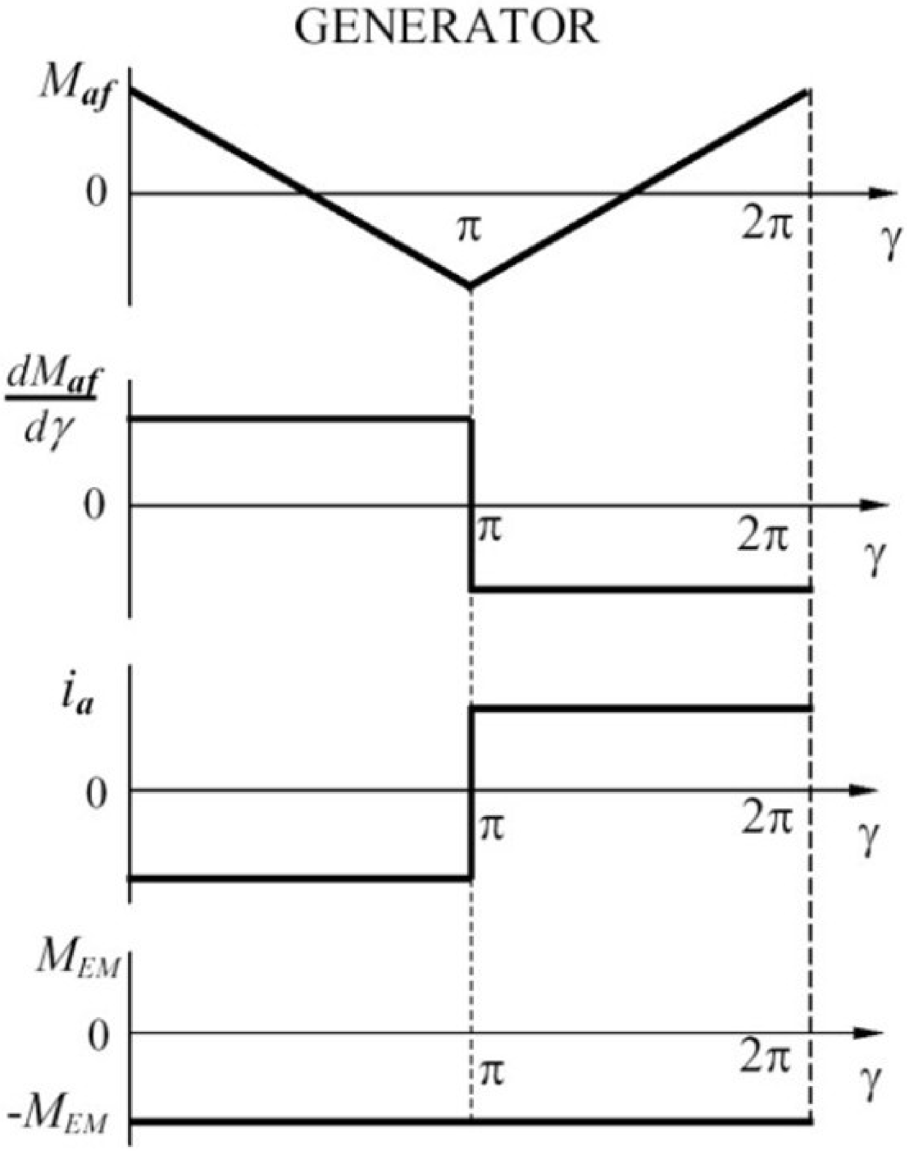

Figure 3. Functional dependencies for M_{af}, i_a & M_{EM} for examined model of EMC

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Biographical Sketches

Oleg I. Bashnin graduated from St.-Petersburg Shipbuilding Institute in 1961. He also graduated from St.-Petersburg State University in 1967. In 1968 he received his PhD degree from Russian Academy of Sciences (RAS) and in 1988 Dr.Sc. (eng) degree. For long time he has been working in RAS. Now he is with a stock company "*Promstrojavtomatika*". Dr Bashnin is the author and co-author more than 100 scientific paper, 25 patents in the field of turbines governors.

Igor A. Glebov graduated from Leningrad Polytechnic Institute with honors in 1938. He served as an engineer in power systems and for some time was head of chair in Technological Institute. From 1971 he is the director of Russian Research Institute for Electric Machinery. In 1976 he was elected as full member (academician) of Russian Academy of Sciences. He is Doctor of Technical Sciences (1964) and Professor (1966). Prof. Glebov is the specialist in the field of electrodynamic modeling (simulation), large electric machines and their excitation and regulation systems.

Boris E. Kirichenko was born in St.-Petersburg in 1950. He graduated from State Marine Academy, St.-Petersburg in 1972. He joined RAS in 1995. Now he serves as scientific secretary of the Division for Basic Researches in Electric Power Engineering and is the laboratory chief "Unconventional Energy Sources and Ecology" in the same division.

Victor V. Popov graduated from Leningrad Polytechnic Institute (now St. Petersburg State Technical University) in 1955. From 1957 till now he works at the Electrical Machines Department of the same university. From 1985 till 1996 he was the Dean of the Electromechanical faculty, from 1988 - the Chair of the Department. He is Dr. Sc., Professor, the Real Member of the Russian Academy of Electrical Engineering and International Energy Academy, the member of IEEE. He is the head of a number of programs directed on investigation of interrelated physical fields and processes in electrical machines. He is the author and co-author of more than 220 scientific publications which include books such as "Electrical machines" (1996), "Methods of Thermal Examination of Electrical Machines".

Vasily V. Semenov graduated from St.-Petersburg Politechnical Institute with honors. He worked in some hydro power stations and then joined Research Institute for Electric Machinery, St.-Petersburg. He is author and co-author more than 200 scientific publications and holds patents in the field of governors for hydro power sets and stations. Mr. Semenov has scientific degree of Dr. Sc. (eng.) and Professor (eng.).