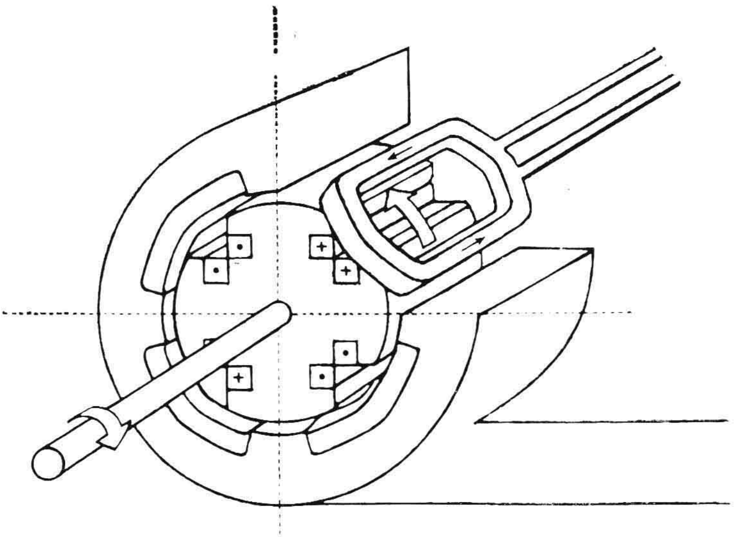
ELECTRICAL MACHINES vol. 1

A. IVANOV-SMOLENSKY

Mir Publishers Moscow

А. В. Иванов-Смоленский

ЭЛЕКТРИЧЕСКИЕ МАШИНЫ



Москва Издательство «Энергия»

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A. IVANOV-SMOLENSKY

Vol. 1

Translated from Russian
by Boris V. KUZNETSOV

MIR Publishers Moscow

First published 1982
Revised from the 1980 Russian edition

На английском языке

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2 A general theory of electromechanical energy conversion by electrical machines

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Preface

The subject matter in the text is presented in the sequence traditionally followed in the Soviet Union. It starts with transformers, passes on to induction and synchronous machines, d.c. machines, and concludes with a.c. commutator machines. Separate chapters are devoted to a general theory of electrical machines, machine design and engineering, and transients in electrical machinery.

The electromagnetic processes that take place in electrical machines are examined from the view-point of electromechanical and mechanoelectrical energy conversion. With such an approach, it has been possible to extend the mathematics used to both conventional and any other conceivable types of electrical machines.

In addition to electromagnetic processes, consideration is given to the thermal, aerodynamic, hydraulic and mechanical processes associated with electromechanical and mechanoelectric energy conversion.

In view of the importance attached to the above accompanying processes, the text discusses general aspects of machine design and engineering.

The chapters on transients are based on the theory of a generalized machine. The material includes the derivation of differential equations for induction and synchronous machines in terms of the d, q, 0 and the α, β, 0 axes, and their transformation to a form convenient for computer-assisted analysis and design.

The chapters dealing with specific types of machine (induction, synchronous, d.c.) are largely concerned with the conventional design. In each case, however, there is a short discourse on the operating principle and arrangement of the most commonly used special-purpose modifications.

The electromagnetic processes occurring in conventional a.c. machines are described in terms of the resultant complex functions of electric-circuit parameters or their projections on the axes of a complex plane. As far as practicable, a unified or generalized approach has been taken to developing equations for and describing the physical processes in the two basic types of machine—the induction machine and the synchronous machine. This concerns electromagnetic torque, electromagnetic active and reactive power, saturable magnetic circuits, machine inductances, etc.

More space is given to thyristor-controlled machines gaining an ever-wider ground, than to a.c. collector machines used on a limited scale.

In the light of new findings, the effect of core saliency on the harmonics of the airgap flux density has been treated in a more rigorous form. A novel approach has been taken towards the equations for mmfs, emfs, electromagnetic forces, electromagnetic torque, and machine characteristics. Among other things, the equations for the synchronous salient-pole machines are developed in terms of the d, q, 0 axes, the analysis of transients includes the short-circuit condition in the synchronous generator, the starting of the induction motor, and events in the single-phase motor.

The material marked with an asterisk (∗) may be omitted on first reading, without disrupting the integrity of the exposition.

A. V. Ivanov-Smolensky

Introduction

I-1 Basic Definitions

The utilization of natural resources inevitably involves the conversion of energy from one form to another. Quite aptly, devices doing this job by performing some mechanical motion may be called energy converting machines. For example, heat engines convert the heat supplied by the combustion of a fuel into mechanical energy.

In fact, the same name goes for devices converting energy in one form into energy of the same form but differing in some parameters. An example is a hydraulic machine which converts the mechanical energy of a reciprocating fluid flow into mechanical energy further transmitted by a rotating shaft.

A sizeable proportion of the energy stored by nature in chemical compounds, the atoms and nuclei of substances, the flow of rivers, the tides of seas, the wind, and solar radiation is now being converted to electric energy. This form of conversion is attractive because electricity can in many cases be transmitted over long distances, distributed among consumers and converted back to mechanical, thermal, or chemical energy with minimal losses. However, at present thermal, chemical or nuclear energy is converted directly to electricity on a very limited scale, because this still involves heavy capital investments and is wasteful of power. Rather, any form of energy is first converted to mechanical by heat or water machines and then to electricity. The final step in this sequence—conversion of mechanical energy to electricity or back—is done by electrical machines.

From other electromechanical energy converting devices, electrical machines differ in that, with a few exceptions, they convert energy in one direction only and continuously.

An electrical machine converting mechanical energy to electricity is called a *generator*. An electrical machine performing the reverse conversion is called a *motor*. In fact, a generator can be made to operate as a motor, and a motor as a generator—they are reversible. If we apply mechanical energy to the movable member of an electrical machine, it will operate as a generator; if we apply electricity, the movable member of the machine will perform mechanical work.

Basically, an electrical machine is an electromagnetic system consisting of a magnetic circuit and an electric circuit coupled with each other. The magnetic circuit is made up of a stationary and a rotating magnetic member and a nonmagnetic air gap to separate the two members. The electric circuit can be in the form of one or several windings which are arragned to move relative to each other together with the magnetic members carrying them.

For their operation, electrical machines depend on electromagnetic induction and utilize the electromotive forces (emfs) that are induced by periodic variations in the magnetic field as the windings or magnetic members are rotated.

For this reason, electrical machines may be called electromagnetic. This also applies to devices that convert electric energy at one value of current, voltage and/or frequency to electric energy at some other value of current, voltage and/or frequency. The simplest and most commonly used electromagnetic energy conversion device which converts alternating current at one voltage to alternating current at some other voltage is the *transformer*. Its coils and core remain stationary relative to each other, and periodic variations in the magnetic field essential for an emf to be induced in the coils are produced electrically rather than mechanically.

Electromagnetic energy converting devices with moving or, rather, rotating parts are more customarily called *rotary converters*. They do not differ from electrical machines in either design or the principle of operation. In fact, rotary converters can sometimes double as electric-to-mechanical (or mechanical-to-electric) energy converting machines. Therefore, we may extend the term "machine" to transformers and rotary converters as special kinds of electrical machine.

Apart from electromagnetic electrical machines, some special applications involve the use of electrostatic machines in which the electromechanical conversion of energy is based on electrostatic induction and utilizes periodic variations in the electric field of a capacitor in which the plates are free to move relative to one another. However, electrostatic machines are no match for electromagnetic machines in terms of size, weight and cost, and are not used in commercial or industrial applications.

As energy converters, electrical machines are important elements in any power-generating, power-consuming, or industrial installation. They are widely used as generators, motors, or rotary converters at electric power stations, factories, farms, railways, automobiles, and aircraft. They are finding an ever increasing use in automatic control systems.

Electrical machines are classed into alternating-current (a.c.) and direct-current (d.c.) machines, according as they operate into or from an a.c. or a d.c. supply line.

I-2 Conversion of Electric Energy by the Transformer

In sketch form, the arrangement of a simple single-phase two-winding transformer is shown in Fig. I-1. As is seen, it consists of two windings, *1* and *2*, with turns w_1 and w_2,

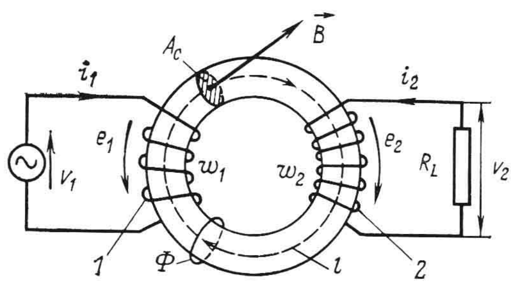

Fig. I-1 Electric and magnetic circuits of a transformer

which are wound on a magnetic core. For better coupling between the coils, the core is assembled from laminations punched in electric-sheet steel having a high relative permeability, μ_r, with no air gap left around the magnetic circuit. The laminations or punchings are made thin in order to reduce the effect of eddy currents on the magnetic field which alternates at an angular frequency ω. Let us open, say, coil *2* and connect coil *1* to a source of a sinusoidal alternating current of frequency $f = \omega/2\pi$ and of voltage $v_1 = \sqrt{2}\,V_1 \cos \omega t$, where V_1 is the rms value of voltage. This will give rise to an alternating current, $i_1 = i_0$, in the coil, which can be found from the voltage equation for the circuit where it is flowing:

$$v_1 = -e_1 + R_1 i_0 \tag{I-1}$$

where R_1 = resistance of winding *1*
$e_1 = -\mathrm{d}\Psi_{11}/\mathrm{d}t$ = emf of self-induction
$\Psi_{11} = w_1\Phi$ = flux linkage
$\Phi = BA_c$ = magnetic flux
B = magnetic induction (magnetic flux density)
A_c = cross-sectional area of the core.

On setting μ_r constant and applying Ampere's circuital law to the magnetic circuit

$$\oint H_l \,\mathrm{d}l = \oint (B/\mu_r\mu_0)\,\mathrm{d}l = \Phi/\Lambda_\mu = i_0 w_1 \tag{I-2}$$

where $\Lambda_\mu = \mu_r\mu_0 A_c/l_c$ is the permeance of the core and l_c is the mean core length, it is an easy matter to find the inductance of winding *1*

$$L_{11} = w_1\Phi/i_0 = w_1^2\Lambda_\mu$$

and the mutual inductance

$$L_{12} = w_2\Phi/i_0 = w_1 w_2\Lambda_\mu$$

and to express in their terms the flux linkage

$$\Psi_{11} = i_0 L_{11}, \qquad \Psi_{21} = i_0 L_{12}$$

and the emf

$$e_1 = -L_{11}\,\mathrm{d}i_0/\mathrm{d}t$$

Using Eq. (I-1) and neglecting $R_1 i_0$, we obtain the magnetizing current

$$i_0 = \sqrt{2}\, I_0 \cos(\omega t - \pi/2)$$

which produces an alternating magnetic flux

$$\Phi = i_0 w_1 \Lambda_\mu$$

Variations in the flux Φ linking coil *2* induce in the latter a sinusoidal emf of mutual induction

$$e_2 = -\mathrm{d}\Psi_{21}/\mathrm{d}t = -L_{12}\,\mathrm{d}i_0/\mathrm{d}t$$

Thus, coil *2* can be used as a source of an alternating current of the same frequency f, but at another voltage, $v_2 = e_2$.

As is seen, the ratio of the instantaneous and the rms emfs across windings *1* and *2* and of the respective rms vol-