# Preface

Rotating field electric machine is one of the most complex devices in the whole electrical engineering, because physical quantities in it are both a function of space and time, the medium in which they spread is nonlinear and all three dimensions of electromagnetic, mechanical, and thermal fields determine its performance. When fed from AC source(s), rotating field machine windings generate flux density waves which spread at different velocities through the machine, produce time dependent forces between stator and rotor, and dissipate losses which increase the temperature throughout the machine.

Only in an electric machine Faraday's law of electromagnetic induction can show its real nature: the tendency of space to oppose any change of magnetic field. When in a vicinity of a stationary coil the magnetic field is changed, the voltage is induced in the coil, which drives current through it, the magnetic field of which compensates for the primary change of the field. If the coil can move, or rotate, and if it is placed in a space in which the magnetic field rotates, not only the voltage will be induced in it, as is the case with a stationary coil. The coil will start to rotate in the direction of the field, trying to oppose the change of the concatenated flux created by the rotating field. After infinitely long time, neglecting mechanical losses, the coil will reach the synchronous speed and concatenate the magnetic field which in that case does not change relative to it.

Besides generating electromagnetic torques, forces in an electric machine create mechanical stress on its components. Electromagnetic and mechanical losses increase the machine temperature and must be taken out from it by means of a gaseous or fluid coolant. The amount of losses and related temperature increase is crucial when determining the machine rated power, which is a pure thermal quantity, defined as the power transferred to a load at which the dissipated losses increase the machine temperature to the value allowed by the winding class of insulation. Therefore, to design an electric machine is primarily a thermal task which is successfully completed when the losses accompanying the electromechanical energy conversion do not increase the hot spot temperature above the given value.

An exact description of electromagnetic, fluid flow, and thermal effects which simultaneously take place in an electric machine would require enormous computational power, which would barely justify the accuracy of results and time consumed. Therefore, it is designer's job to simplify the bulky mathematical apparatus when solving a particular problem, building a simple physical model of a machine, and solving it with regular mathematical tools. In order to make adequate physical assumptions for a particular problem, the designer has to understand well the tool he is using, which helps him avoid application errors.

Like in almost no other field of engineering, when designing an electric machine there is a high need for proper physical interpretation of mathematical solutions, and especially of conditions under which these are derived. Mathematics is a good servant, but a poor master. This can be illustrated by the example of the probably most misinterpreted equation in electrical engineering, which states that electrical current i through a capacitor is equal to the time derivative of charge Q

$$i = \frac{dQ}{dt}$$

At the latest since the Millikan–Fletcher experiment in the year 1910 the engineering community is aware of the *discrete* character of electrical charge: the amount of electricity can only change in steps of $e^{-} = 1.6 \cdot 10^{-19}$ As, which is the charge of electron. In terms of mathematical analysis, a derivative of a discrete function is not defined; therefore, the expression dQ/dt is mathematically undetermined. At time instants at which the amount of charge in a closed volume V changes, its time derivative is not defined; at all other time instants the derivative of the amount of charge is equal to zero, Fig. 1. Accordingly, an electric current defined as a time rate of change of the amount of charge is either undetermined, or equal to zero.

Such definition of electrical current is a result of misinterpretation of Maxwell's concept of displacement current in dielectrics. Knowing that the divergence of the curl of any vector is equal to zero, and applying operator div to the Ampère's circuital law, one obtains

$$div\left(curl\vec{H}\right) = div\left(\vec{\Gamma} + \frac{\partial \vec{D}}{\partial t}\right) = 0$$

with H denoting the magnetic field strength, Γ the current density, and D the electric displacement. Setting for

$$div\vec{D} = \rho = \frac{Q}{V} = \frac{\sum_{i=1}^{n} q_i}{V}$$

with ρ standing for charge density, and V for volume, one can further write

$$V \cdot div\vec{\Gamma} + \frac{dQ}{dt} = 0$$

which leads to a mathematically correct, yet physically false construction

$$i = \frac{dQ}{dt}$$

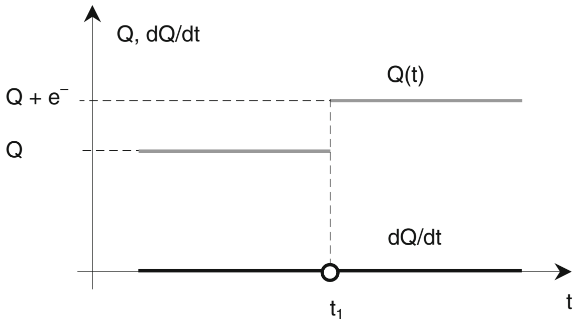


**Fig. 1** Illustrating expression dQ/dt: time rate of change of the amount of charge $e^-$ in a closed volume V is not defined at time instant at which the change takes place; at all other time instants the time rate of change is equal to zero

When correctly interpreted, the displacement current density $\Gamma_d$, defined, e.g. for a parallel plate capacitor as

$$\vec{\Gamma}_d = \frac{\partial\vec{D}}{dt} = \varepsilon\frac{\partial\vec{E}}{dt} = \varepsilon\frac{\partial}{\partial t}(-\nabla\varphi) = \frac{\varepsilon}{d}\frac{du}{dt}$$

helps one express the current $i_c$ through a capacitor by means of voltage drop u across its plates as

$$i_c = S\frac{\varepsilon}{d}\frac{du}{dt} = C\frac{du}{dt}$$

where S denotes the area of plates, d the distance between plates, ε the permittivity of the medium and C the capacitance. The current through a capacitor is proportional to the time derivative of voltage drop across its plates. *Electric current is definitely not equal to a time derivative of charge,* because the amount of charge Q is a discrete quantity and therefore it is not a derivable function.

Any discussion about physically proper description of electric current inevitably leads to the question about its real nature. The answer to this question is astonishingly simple: electric current is a state of continuum characterized by thermal, light, chemical, and magnetic effects. Whereas thermal, light, and chemical effects do not always accompany electric current, magnetic field is *always* generated when a current flows. Therefore, electric current can be defined as the source of magnetic field (Fig. 2).

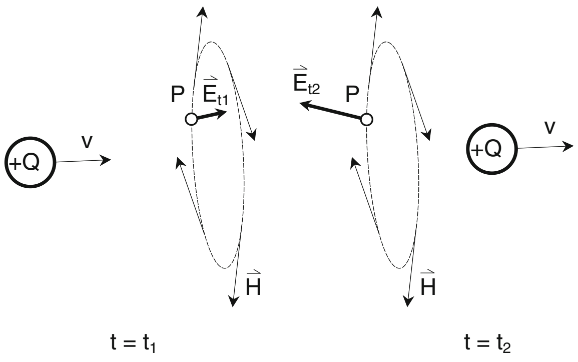


**Fig. 2** Illustrating effects of motion of charge +Q, which travels at finite velocity v, as a source of magnetic field. The charge +Q creates at point P the electric field $E_{t1}$ at time instant $t_1$, and the electric field $E_{t2}$ at time instant $t_2$. The change of electric field distribution in time interval $[t_1, t_2]$, which spreads through space with the speed of light, gives rise to displacement current density $\varepsilon \frac{\partial E}{\partial t}$, which is a source of magnetic field H

The emphasis in the definition of electric current is on the state of continuum, which, according to the currently valid physical model of the universe, spreads with the maximum possible speed through space. For example, when a body with mass m changes its position, a new distribution of gravitational field is generated which spreads with the speed of light through the universe. In the same manner when a charge Q changes its position in space, the effect of the change—a new distribution of electromagnetic field—spreads with the speed of light throughout the whole universe.

Since every change of electric field distribution is accompanied by a creation of magnetic field, a charge which changes its position creates magnetic field in space. Independent of how slow a charge moves, the electric field distribution created at its every new position spreads with the speed of light through space. Therefore, one can state that no matter how fast or slow a charge moves, the state of continuum described by electric current spreads at the speed of light.

Previously discussed topics illustrate the tenor of the book: thorough understanding of physical (electromagnetic, mechanical, and thermal) processes in rotating field electric machines by using sophisticated computational tools, along with correct physical interpretation of mathematical results.

A reader who expects to find a compilation of recipes on how to design a rotating field electric machine in this book will be disappointed, because this is a book on "why", rather than on "how". Alexander Gray, one of the pioneers in the field of electric machines design, stated more than one hundred years ago "Since the design of electrical machinery is as much an art as a science, no list of formulae or collection of data is sufficient to enable one to become a successful designer." The art in this statement relates to balanced trade-offs of often contradictory requests. Technical specifications for a particular machine can be fulfilled in many different ways, none of them being absolutely the best. There exists no recipe on how to design a perfect electric machine—it is more a question of experience and manufacturing capabilities, with a strong influence of engineering talent. Nevertheless, one should always keep in mind the simplicity of the solution, as a dominating design goal which guarantees longer mean times between failures and decreases the machine price.

One of the basic ideas followed in this book is a wide use of lumped circuit approach when solving field problems. Electrical engineers think in terms of circuits. Ohm's law, one of the most pronounced laws in the nature, states that the output is proportional to the input. Just like for electric circuits, similar laws of proportionality can be written for pressure and mass flow, temperature and heat flow, as well as for magnetic flux and MMF drop.

Despite various nonlinearities which dominate the physics of electric machines, an emphasis in the book is given to an analytical solution of a particular problem. An analytical solution helps designer to get insight into the nature of processes in a machine and estimate the influence of each parameter on its overall performance. A numerical solution, on the other hand, is valid only for a particular set of parameters. A single numerical solution might deliver correct numbers, but it does not help the designer to understand the relationships between the quantities involved.

The book is organized in eight chapters. In the first seven chapters, a thorough analysis of electromagnetic and thermal effects which dominate the operation of electric machines is given. In the last chapter important steps in the design of induction and synchronous machines are sketched. In each chapter several case studies are presented, dealing with a topic relevant to the chapter contents.

Properties of permanent magnet machines are discussed thoroughly in the first chapter and in the Appendix. Considering inferior performance of a permanent magnet AC machine as compared to a wound rotor synchronous machine, the design procedure for the former machine type is not carried out separately in the book. Nevertheless, permanent magnet machines have been referred to in several case studies. The interested reader can obtain the performance curves of a permanent magnet machine simply by setting the field current of an equivalent wound rotor synchronous machine down to its no-load value.

Paraphrasing the statement "Never trust a statistics you didn't make yourself," one might find it a good idea not to use commercial machine design software packages, the vendors of which consider the applied methods and procedures their intellectual property. When applying such software packages it could happen that the user, without being aware of assumptions and limitations made when creating such a package, obtains physically meaningless results, like current flowing from a conductor into air, overall power factor larger than one, or even sum of all power components different from zero, etc. Having this in mind, the intention of this book is to support those engineers who want to design an electric machine standing on their own two feet.

Last but not least, the text of the book was checked, rechecked, and checked again in order to eliminate possible errors. If despite the careful preparation certain expression turns out to be incomplete or misleading, one should keep in mind that this was done on purpose, because those readers, who desperately look for an error in a work like this, should also be satisfied after having found it.

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