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Preface

Electric machines and transformers are found in many different devices used in industry and household appliances. Their users often wish to know what will happen if the working conditions differ from the ratings of the device given by the manufacturer and also how to explain the resulting effects. The fundamentals of applied physics in the domain of electric engineering are usually given in high school. However, the explanations there concern oversimplified structures of certain machinery and apply basic mathematical relationships only.

This book is addressed to students (current and former) of Electrical Engineering and other, similar types of study, who are interested in a deeper insight into a fascinating domain of electromechanical energy conversion. It is assumed that the reader has a basic knowledge of electric circuits together with associated laws governing their behaviour. Two fundamental abstract concepts are extensively used throughout the text – the equivalent circuit of the device and the electromagnetic field inside it. Both of them are able to answer most questions of the type “What if?” related to exploitation conditions, but their properties are rather opposed. The equivalent circuit enables almost immediate results, although with only moderate accuracy. Field analysis allows us to get much more exact information about the details of required parameters of a given device, but may simultaneously be extremely time-consuming. The compromise chosen here is to mostly use the analytical expressions leading to an equivalent circuit; nevertheless, the integral identities necessary for post-processing of numerical results are also given and almost all the illustrations come from field-based solutions.

Such an approach realizes, in the author’s opinion, the easiest way to acquire fundamental knowledge about the principle of operation for those for whom this book will be the first and probably the last contact with the theory of electric machinery. Those readers who desire to expand their expertise in the area of energy conversion will also find explanations of the main concepts used in field treatment and will be familiar with the geometry and material structure of the basic types of electric machines and transformers. Besides, they should be ready to start studying the next, more advanced level of theoretical prediction of the performance of electrical devices.

The exemplary results of calculations presented below were obtained within the Infolytica environment (Magnet and MotorSolve software) and they mostly concern machines of moderate power. This helps to avoid the explanation of a lot of details connected with high voltage, thermal or mechanical strength questions, which must appear when large units are considered. Some of the graphics presenting details of electric machines come from the work of my students, and special thanks are due to Ewa Kubiak, Lukasz Wisniewski and Bartlomiej Krzywiec.

This book covers the scope of the course entitled Electric Machines presented at the Faculty of Electrical, Electronic, Computer Science and Control Engineering, The Lodz University of Technology.

Paweł Witczak, Łódź, January, 2015

Notation System

Some general rules were adopted for symbols used within this book. Thus, a script letter, say u, denotes the instantaneous value of a scalar, time-varying quantity – voltage in this case. The same letter but capitalized is its RMS value and with subscript m represents the magnitude. We may write

$$u = U_m \sin(\omega t) = \sqrt{2}U \sin(\omega t)$$

Letters in bold are reserved for vectors, e.g. the velocity **v** given in 2D coordinate system $\mathbf{0n_1n_2}$ is equal to

$$\mathbf{v} = (\mathbf{n_1}V_{1m} + \mathbf{n_2}V_{2m}) \sin(\omega t)$$

There are a few exceptions to the above, because of the commonly used notation in literature. For example, the flux density vector **B** alternating in time will be

$$\mathbf{B}(\mathrm{t}) = (\mathbf{n_1}B_{1m} + \mathbf{n_2}B_{2m}) \sin(\omega t)$$

Capital letters underlined mean phasors (complex numbers), having sinusoidal variation in time

$$\underline{U} = \sqrt{2}U[cos(\omega t) + jsin(\omega t)]$$

Abbreviations frequently used are as follows:

AC	-	alternating current
DC	-	direct current
EMF	-	electromotive force
Im	-	imaginary part of complex number
MMF	-	magnetomotive force (ampere-turns)
Re	-	real part of complex number
RMS	-	root mean squared
rps	-	revolutions per second
rpm	-	revolutions per minute

The main symbols used in the book are:

B	-	magnetic flux density vector, [T]
B_δ	-	radial component of magnetic flux density in air gap, [T]
B_{re}	-	magnetic remanence, [T]
D	-	electric flux density (electric displacement) vector, [C/m^2]
E	-	electric field vector, [V/m]
e, E	-	electromotive force, [V]
f, F	-	force vector, [N]
$\mathbf{f_S}$	-	surface force density, [N/m^2]
$\mathbf{f_V}$	-	volumetric force density, [N/m^3]
F_R	-	rotor magnetomotive force, [A]
F_S	-	stator magnetomotive force, [A]
f_1	-	network frequency, [Hz]
f_R	-	rotor frequency, [Hz]
f_S	-	stator frequency, [Hz]
H	-	magnetic field vector, [A/m]
H_c	-	coercivity, [A/m]
i, I	-	electric current, [A]
j	-	sign of imaginary part of complex number, $j^2 = -1$
J	-	conducting electric current density vector, [A/m^2]
L	-	inductance, [H]
L_C	-	length of core (usually out of drawing plane), [m]
M	-	moment of force, torque, [Nm]
M_{int}	-	internal torque, [Nm]
M_{em}	-	electromagnetic torque, [Nm]
M_{me}	-	mechanical torque, [Nm]
n_1	-	rotating field speed, [rps]
N	-	number of turns
N_S	-	stator number of turns
N_R	-	rotor number of turns

N_{eff}	-	effective number of turns
p(t), P	-	instantaneous, mean active power, [W]
p	-	pole pair number
q	-	number of slots per pole and phase
Q	-	mean reactive power, [VAr]
R	-	resistance, [Ω]
s	-	slip
S	-	mean apparent power, [VA]
t	-	time, [s]
u, U	-	voltage, [V]
$\mathbf{v}$	-	velocity (speed), [m/s]
$\mathbf{v}_{em}$, V_{em}	-	velocity (speed) of electromagnetic field, [m/s]
$\mathbf{v}_{me}$, V_{me}	-	mechanical velocity (speed), [m/s]
w_{em}	-	magnetic energy density, [J/m^3]
W_{em}	-	magnetic energy, [J]
X	-	reactance [Ω]
α_{geo}	-	geometric angle, [rad]
α_{el}	-	electric (phase) angle, [rad]
δ	-	air gap, [m]
γ	-	conductivity, [S/m]
ε_0	-	permittivity of vacuum, $8.85\ 10^{-12}$ [F/m]
ε_r	-	relative permittivity of material, [-]
μ_0	-	permeability of vacuum, $4\pi\ 10^{-7}$ [H/m]
μ_r	-	relative permeability of material
τ_p	-	pole pitch, [m]
Φ_m	-	magnetic flux magnitude, [Tm^2]
Ψ_m	-	magnetic flux linkage magnitude, [Tm^2]
ω	-	angular frequency, [rad/s]
Ω	-	angular speed, [rad/s]

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Chapter 1
Fundamentals of Energy Conversion

1.1. Power and Energy Flow

Any device serving as an energy converter has specific “terminals” creating the input and output ports, where the energy flows, usually on the outer surface of the given device. In the case of electric energy, such a port is formed by electric wires connecting the device with the network, mechanical energy is transmitted by the shaft, thermal and acoustic energy by the outer surface and so on. An exemplary illustration is presented in Fig. 1.1 using the thermovision photo of an electric motor which shows the temperature distribution on the surface of the motor – the violet colour represents here the ambient temperature.

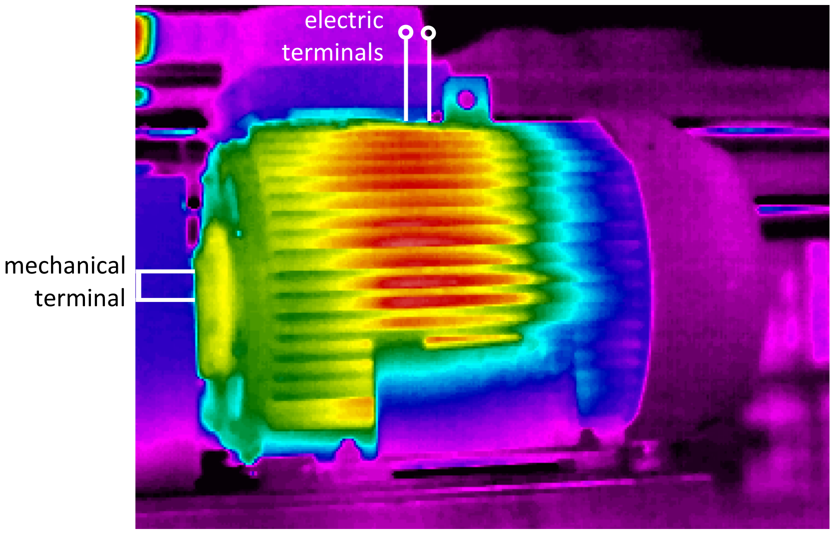

Fig. 1.1. Illustration of “ports” for different kinds of energy present in electric machine using thermovision photography

The general equation representing the theorem of the energy conservation is

$$\delta W_{in} = \delta W_{out} + \delta W_{acc} \tag{1.1}$$

where δW_{in}, δW_{out} and δW_{acc} are portions of input, output and accumulated energies flowing to and from the analyzed device within time δt. The input and output quantities depend on the type of energy conversion – for electric machines it may be the motor, generator or brake regime. The accumulated energy is the sum of the electromagnetic energy and heat stored (both are able to do the work) inside the machine. When the amount of accumulated energy does not change ($\delta W_{acc} = 0$), we say the machine is "at steady conditions". The present lecture will deal only with that kind of exploitation condition, which is in fact the easiest one to explain. Nevertheless, it covers the majority of possible cases in practice.

The intensity of the energy conversion is characterized by the mean power P, also known as active power:

$$\delta W = P\delta t \tag{1.2}$$

which at steady conditions is kept constant. When the time period δt tends to zero, we obtain the instantaneous power p(t):

$$p(t) = \frac{dW}{dt} \tag{1.3}$$

The equation connecting these concepts is

$$P = \frac{1}{\delta t}\int_{0}^{\delta t} p(t)dt \tag{1.4}$$

The power in electromechanical energy converters may be in the form of electromagnetic P_{em}, mechanical P_{me} or thermal power P_{th}. The last one usually appears as the necessary effect of realistic energy exchange and it is called power losses, customarily designated as ΔP. Power losses are generated in particular volumes of the machine (windings, core, bearings etc.) in various ways, but all of them finally leave the outer surface in the form of heat flux, which is proportional to the resultant mean temperature of the device. The general diagram of the power flow is shown in Fig. 1.2. The power losses on the input ΔP_{in} and output ΔP_{out} sides – sometimes called the primary and secondary side – have the same character as the input and output power. The component termed internal power P_{int} represents the amount of power "converted" from one kind of power into another.

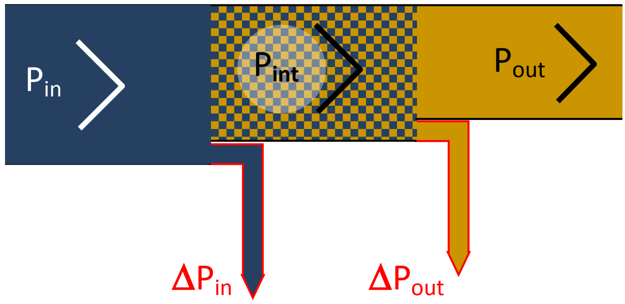

Fig. 1.2. Sankey's diagram of power flow

It must fulfil the equation

$$P_{int} = P_{in} - \Delta P_{in} = P_{out} + \Delta P_{out} \tag{1.5}$$

Depending on the type of device, the nature of the input and output may be electrical or mechanical, as presented in the table below.

Table 1.1. Types of electromechanical converter

Type of Device	Input Power	Output Power
Transformer	electrical	electrical
Motor	electrical	mechanical
Generator	mechanical	electrical
Gear	mechanical	mechanical

The efficiency η is defined as the ratio

$$\eta = \frac{P_{out}}{P_{in}} = 1 - \frac{\Delta P_{in} + \Delta P_{out}}{P_{in}} \tag{1.6}$$

It does not concern the transformer, where the power flow is defined in another way, as will be explained later on.

Each type of power is defined as the product – algebraic or scalar – of two quantities called the state variables. We have in the electromagnetic domain a simple multiplication:

$$p_{em}(t) = u(t)i(t) \tag{1.7}$$

where u(t) and i(t) are instantaneous values of voltage and current, respectively. In mechanical analysis we must remember that there are two kinds of motion:

- linear, when

$$p_{me}(t) = \boldsymbol{f}_{me}(t) \cdot \boldsymbol{v}_{me}(t) \tag{1.8}$$

where $\mathbf{f}_{me}(t)$ and $\mathbf{v}_{me}(t)$ are instantaneous values of mechanical force and speed vectors, and

- rotary, when

$$p_{me}(t) = \boldsymbol{m}_{me}(t) \cdot \boldsymbol{\omega}_{me}(t) \tag{1.9}$$

where $\mathbf{m}_{me}(t)$ and $\boldsymbol{\omega}_{me}(t)$ are instantaneous values of torque (moment of force) and angular speed vectors, respectively. In further analysis we will consider the steady states of rotating electric machines only, when the angular velocity remains constant, even if the torque has a component pulsating in time. This means in practice that the rotor inertia is big enough to keep the velocity pulsations at a negligible level. Therefore, the mean value of torque may also be used. Besides, the rotating machines have one degree of freedom, so the vector discriminants in (1.9) can be dropped, resulting in

$$p_{me}(t) \cong P_{me} = M_{me}\Omega_{me} \tag{1.10}$$

Following these assumptions, electrical power definitions may also be reduced to mean data. The internal power (often called electromagnetic) can be defined in two ways using electric or mechanical quantities:

$$P_{int} = M_{em}\Omega_{em} = EI \tag{1.11}$$

where E and I are RMS (root mean squared) values of electromotive force (EMF) and electric current in the armature winding, M_{em} is the mean value of torque, and Ω_{em} is the angular velocity of the armature against the magnetic field. The instantaneous EMF e(t) differs from the voltage u(t) measured on terminals by the voltage drop on the resistance R of the armature winding:

$$e(t) = u(t) - i(t)R \tag{1.12}$$

The above equation has been written under the so-called receiver convention, where the electric current flows against EMF. We can understand the electromotive force as the voltage measured on terminals of the given circuit when the electric current value is close to zero.

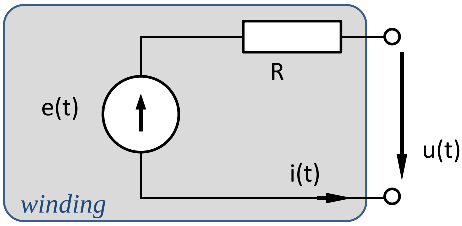

Fig. 1.3. Scheme of elementary circuit

The RMS value, e.g. of electric current, is defined as

$$I = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \tag{1.13}$$

It is clear that the RMS value of a constant in time quantity amounts to that constant value.

1.2. Representation of Sinusoidal Signals by Means of Complex Numbers

The complex number $\underline{z}$ means the following expression:

$$\underline{z} = a + jb \tag{1.14}$$

where a and b are real numbers and $j^2 = -1$. The above relation may be presented in trigonometric form:

$$\underline{z} = \sqrt{a^2 + b^2}(\cos\varphi + j\sin\varphi) = \sqrt{a^2 + b^2}\, e^{j\varphi} \tag{1.15}$$

where the angle (phase) φ is equal to

$$\varphi = \operatorname{atan}\frac{b}{a} \qquad \text{for } a > 0$$
$$\varphi = \pi + \operatorname{atan}\frac{b}{a} \qquad \text{for } a < 0 \tag{1.16}$$

The numbers a and b are named:

- real part of $\underline{z}$ — $Re(\underline{z}) = a$,
- imaginary part of $\underline{z}$ — $Im(\underline{z}) = b$.

The complex numbers are presented on a 2D plane created by axis *Re* and *Im*, where the angle φ is measured starting from axis *Re* towards *Im*, as displayed in Fig. 1.4.

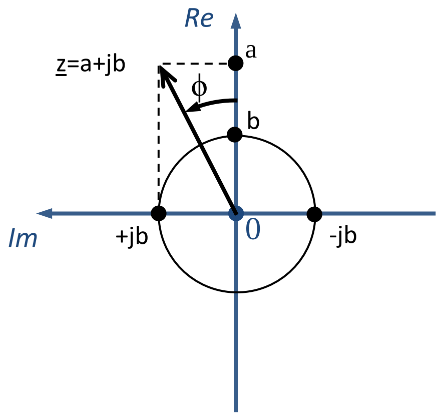

Fig. 1.4. Complex numbers plane

The complex conjugate $\underline{z}^*$ has the phase of the opposite sign to $\underline{z}$:

$$\underline{z}^* = a - jb \tag{1.17}$$

Therefore, the magnitude squared of $\underline{z}$ is given by

$$\underline{z}^*\underline{z} = (a - jb)(a + jb) = a^2 + b^2 = |\underline{z}|^2 \tag{1.18}$$

Equation (1.15) helps also to express the trigonometric functions in terms of exponential ones. By adding $\underline{z}$ and $\underline{z}^*$, one obtains

$$\underline{z} + \underline{z}^* = 2|\underline{z}|\cos\varphi = |\underline{z}|\left(e^{+j\varphi} + e^{-j\varphi}\right) \tag{1.19}$$

which immediately gives

$$\cos\varphi = \frac{e^{+j\varphi} + e^{-j\varphi}}{2} \tag{1.20}$$

Similarly, when subtracting $\underline{z}^*$ from $\underline{z}$, we have

$$\sin\varphi = \frac{e^{+j\varphi} - e^{-j\varphi}}{2j} \tag{1.21}$$

It is obvious that complex numbers have the periodicity property:

$$\underline{z}(\varphi \pm k\,2\pi) = \underline{z}(\varphi) \qquad k = 1,2,\ldots \tag{1.22}$$

Therefore, they are commonly used during the analysis of sinusoidal signals. Replacing φ in (1.20) by ωt, where t is time, ω = 2πf is termed as angular frequency and f is frequency, we may represent the cosine in the time quantity e.g. voltage u(t) as the sum of two so-called phasors rotating on a complex plane in opposite directions:

$$u(t) = U_m \cos \omega t = \frac{U_m}{2} e^{+j\omega t} + \frac{U_m}{2} e^{-j\omega t} = Re\left(U_m e^{j\omega t}\right) \tag{1.23}$$

These relationships are illustrated in Fig. 1.5 for ωt=φ.

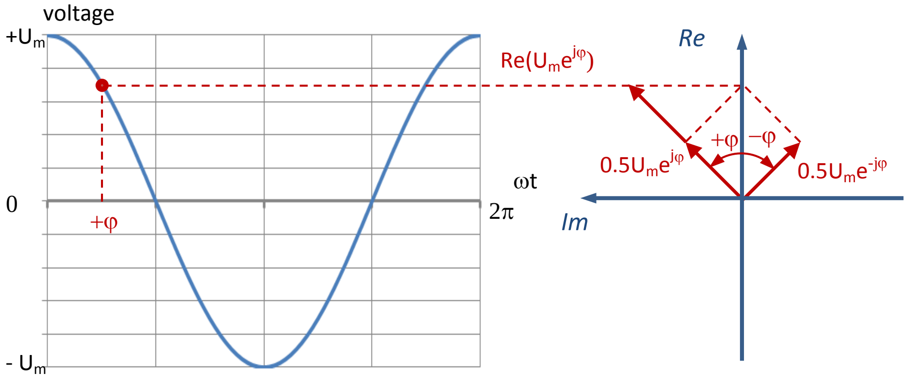

Fig. 1.5. Time signal and its phasor equivalent

Equation (1.23) is also the basis of the spectral analysis (the representation of a non-sinusoidal signal by means of the sum of sinusoidal ones); however, it is outside the scope of this course.

Two signals a(t) and b(t) of the same frequency measured simultaneously may be shifted in phase by an angle, say Δφ. Mathematically, this is obtained by multiplying by exp(jΔφ):

$$a(t) = A_m e^{j\omega t}$$
$$b(t) = B_m e^{j\omega t} e^{j\Delta\varphi} = B_m e^{j(\omega t + \Delta\varphi)} \tag{1.24}$$

We say that b(t) is <u>leading</u> a(t) – the maximum of b(t) appears earlier than that of a(t), or a(t) is <u>lagging</u> b(t) by angle Δφ. A graphical illustration is displayed in Fig. 1.6.

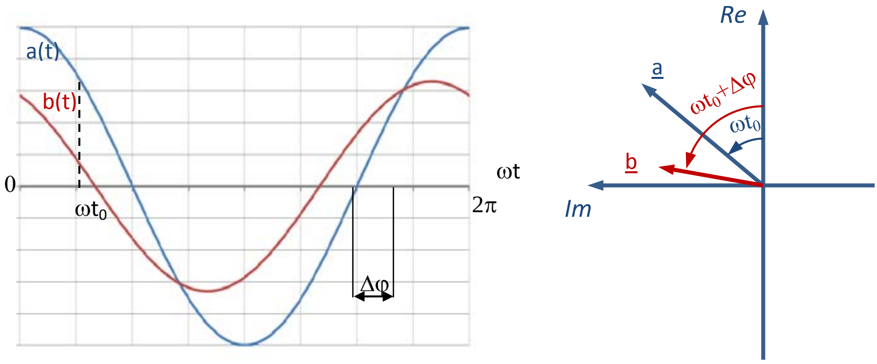

Fig. 1.6. Phase shift between two signals in time and in complex plane

1.3. Apparent, Active and Reactive Power

Let's analyze the simple circuit shown in Fig. 1.7 consisting of two parallel branches supplied from a sinusoidal network having the RMS voltage U. The first branch has resistance R and inductance L connected in series; as will be shown later, this may represent e.g. an induction motor. The second branch contains the capacitor C only. The reactances are: $X_L = \omega L$ and $X_C = 1/\omega C$, respectively. In order to simplify the notation we may set the voltage as a real number – its phasor coincides with the *Re* axis.

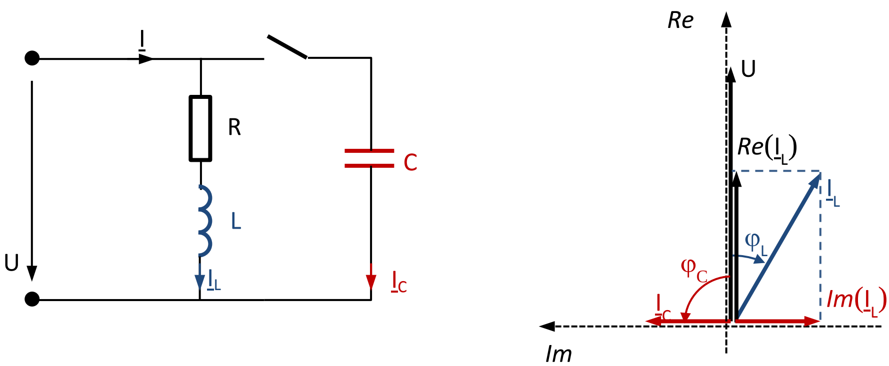

Fig. 1.7. Elementary circuit and its phasor diagram when the switch is on (RMS quantities)

In the first instance we will consider the case when the switch is off – the load current $\underline{I}$ is equal to $\underline{I}_L$.

$$\underline{I}_L = \frac{U}{R + jX_L} = \frac{U}{R^2 + X_L^2}(R - jX_L) \tag{1.25}$$

As expected, the current $\underline{I}_L$ is lagging the voltage – the phase angle φ_L is negative:

$$\varphi_L = \text{atan}\frac{Im(I_L)}{Re(I_L)} = \text{atan}\frac{-X_L}{R} \tag{1.26}$$

Converting the $\underline{I}_L$ current into exponential form, we have

$$\underline{I}_L = \frac{U}{\sqrt{R^2 + X_L^2}} e^{j\varphi_L} = Ie^{j\varphi_L} \tag{1.27}$$

Now we may define the complex or apparent power $\underline{S}$ (against voltage) – see (1.18):

$$\underline{S} = U\underline{I}_L^* = UIe^{-j\varphi_L} = P + jQ = UI[\cos(-\varphi_L) + j\sin(-\varphi_L)] \tag{1.28}$$

The real part P is named *active* power, while the imaginary Q is called *reactive* power. Note that for RL load Q is positive because $\varphi_L < 0$. The units of all these types of power are different: [S] = VA, [P] = W and [Q] = VAr. The ratio P/S is called the power factor, commonly abbreviated as *pf.* When the voltage and current are sinusoidal, the power factor is equal to cos φ_L.

A better understanding of the physical meaning of power components can be obtained by analyzing the instantaneous power p(t). Having at input $u(t) = U_m\cos(\omega t)$ and $i(t) = I_m\cos(\omega t + \varphi_L)$, we obtain

$$p(t) = u(t)i(t) = U_m I_m \cos(\omega t)\cos(\omega t + \varphi_L) \tag{1.29}$$

The results are displayed in Fig. 1.8. We see that the instantaneous power taken from the network has some time intervals when it is returned back, which indicates the negative values of p(t). A clearer insight is possible when we represent the current as the sum of its components:

$$\begin{aligned} i_L(t) &= Re[i_L(t)] + Im[i_L(t)] \\ &= I_m \cos\varphi_L \cos\omega t + I_m \sin(-\varphi_L)\sin\omega t \end{aligned} \tag{1.30}$$

The power signal now has the form

$$p(t) = U_m I_m(\cos\varphi_L \cos^2 \omega t + \sin(-\varphi_L) \sin \omega t \cos \omega t) \tag{1.31}$$

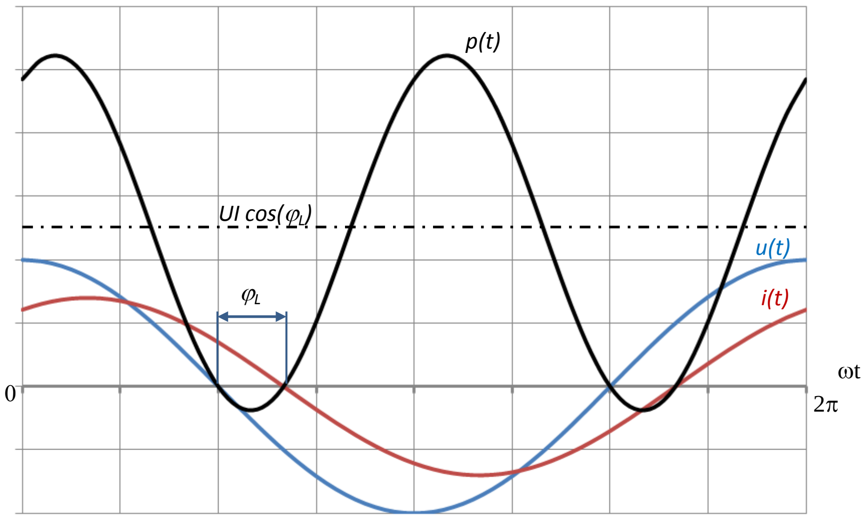

Fig. 1.8. Time functions of voltage u(t), current i(t) and power p(t) in RL load, $\varphi_L = \pi/6$

and after simple manipulations it gives

$$p(t) = UI[\cos\varphi_L (\cos 2\omega t + 1) + \sin(-\varphi_L) \sin 2\omega t] \tag{1.32}$$

Denoting

$$\begin{aligned} I_{Re} &= I \cos\varphi_L \\ I_{Im} &= I \sin(-\varphi_L) \end{aligned} \tag{1.33}$$

we have

$$p(t) = UI_{Re}(\cos 2\omega t + 1) + UI_{Im} \sin 2\omega t \tag{1.34}$$

The first component is always positive and it stands for the power taken from the network and converted into another type of power – mechanical or heat. We earlier referred to this as the active power. The second component has the mean value equal to zero and represents some amount of electric power oscillating to and from the network. It is the reactive power necessary to create the magnetic field inside the load. The time distributions of electric power and its components are shown in Fig. 1.9.

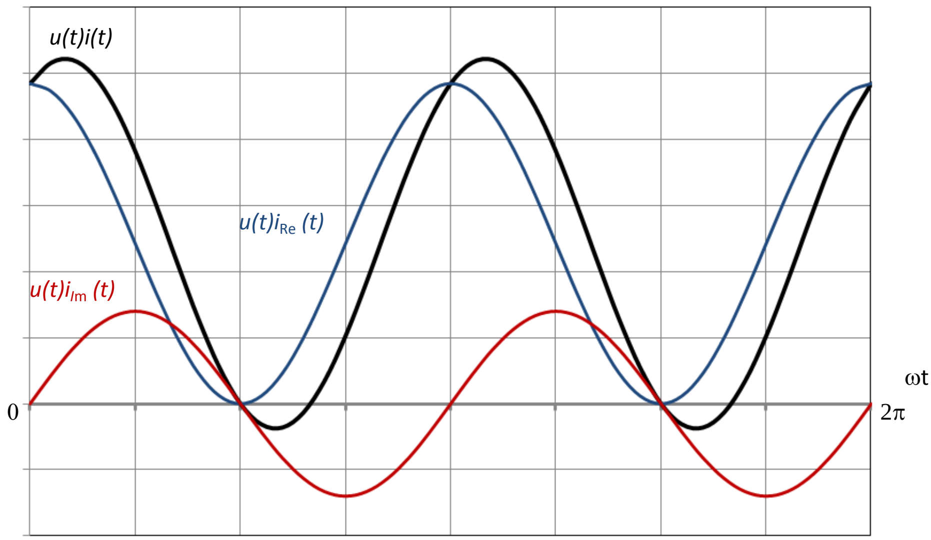

Fig. 1.9. Time functions of electric power components in RL load, $\varphi_L = \pi/6$

Having R and L elements connected in series, we may create two kinds of phasor diagram: related to the voltage on the terminals (as in Fig. 1.7) or related to the current flowing through both of them. The mutual position of the voltage and current phasors remains unchanged – the voltage leads the current in φ_L, but they differ in terms of the starting time instant when t = 0. Following Fig. 1.10.b, we may write

$$\begin{aligned} U_{Re} &= U\cos\varphi_L = I_L R \\ U_{Im} &= U\sin\varphi_L = I_L X_L \end{aligned} \tag{1.35}$$

And, according to (1.12),

$$\underline{U} = U_{Re} + jU_{Im} = I_L R + jI_L X_L = I_L R + \underline{E} \tag{1.36}$$

where E is the RMS value of electromotive force – each voltage drop on the inductance in the circuit can be interpreted as the EMF. It is easy to prove that $i_L(t)^2R$ and $e(t)i_L(t)$ produce the same power pictures as in Fig. 1.9. In other words, the product e(t)i(t) carries no active power here – the analyzed device has input terminals only and the presence of EMF limits the magnitude of current taken from the network.

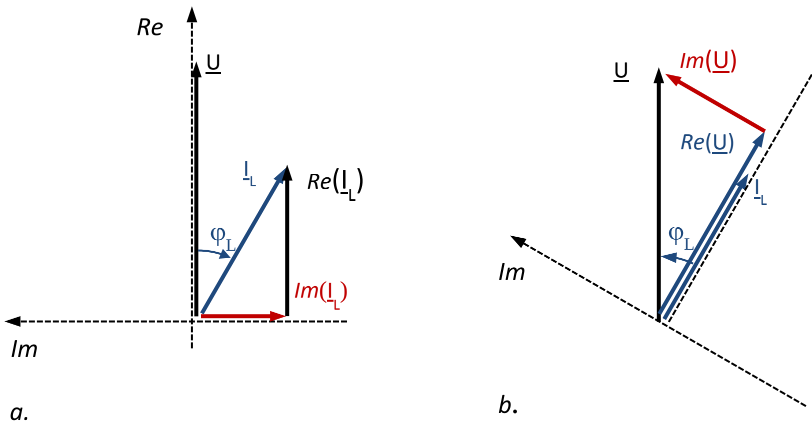

Fig. 1.10. Two types of phasor diagrams for RL load, $\varphi_L=\pi/6$
a. voltage-related,
b. current-related

Now let's observe the changes introduced by the capacitor connected in parallel to the RL load. The currents $i_L(t)$ and $i_C(t)$ are added on to the network terminals. It is possible at a given frequency ω to adjust the values of L and C in such a way that $\underline{I}_C = -Im(\underline{I}_L)$. The equation linking these quantities is

$$\omega^2 = \frac{1}{LC} \tag{1.37}$$

Thus the resultant current $\underline{i}(t)$ has the real component only, but the current flowing through and the incoming power to the RL load have not changed. At present, the reactive power comes here from the capacitor and not from the network. When the resistance is negligible (R ≈ 0), the currents in parallel branches are in anti-phase (so-called current resonance) and the network current is equal to zero. Such a situation is possible when there was an electric charge inside the capacitor just before switching it to the RL impedance.

1.4. Equivalent RL Circuit

The idea of an equivalent circuit of a device comes from well-defined calculation methods of complex electric circuits consisting of R, L and C elements, which enable fast analysis of steady and transient voltage and current signals. The equivalent circuit usually consists of two ports where the power (electrical or mechanical) may flow in and out. In such a case, the meaning of the RL elements building the circuit is more general. The resistance represents the active power consumed or passed away, and the inductance is the measure of reactive power stored inside the device in the form of magnetic field. The scheme of RL components does not follow the actually existing electric connections, but it rather subdivides the device volume into particular parts where the power is stored or exchanged. An exemplary equivalent circuit of an induction motor is presented in Fig. 1.11. Its details are extensively explained in Chapter 7.

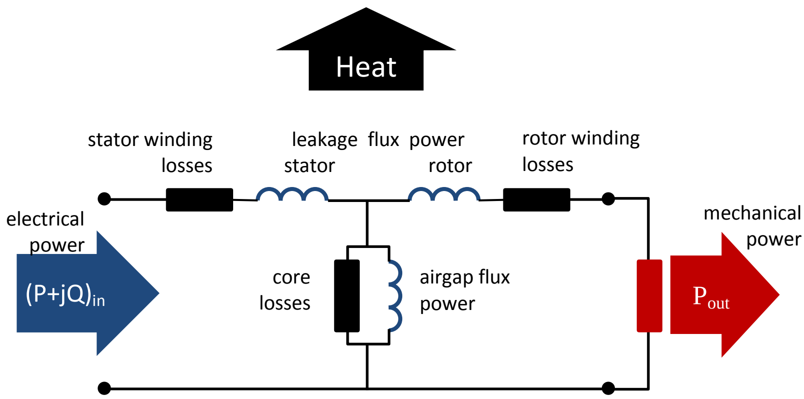

Fig. 1.11. Functionality of equivalent scheme of induction motor