

WARSAW UNIVERSITY OF TECHNOLOGY
FACULTY OF ELECTRICAL ENGINEERING

ELECTRICAL MACHINES

ELECTROMECHANICAL ENERGY CONVERTERS AND TRANSFORMERS

Lectured for IVth semester students by

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REFERENCES - RECOMMENDED BOOKS:

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ELECTRICAL MACHINE DEFINITION

Electrical machine is a converter of energy (or power converter) which converts:

electrical energy (power) into mechanical one,

or

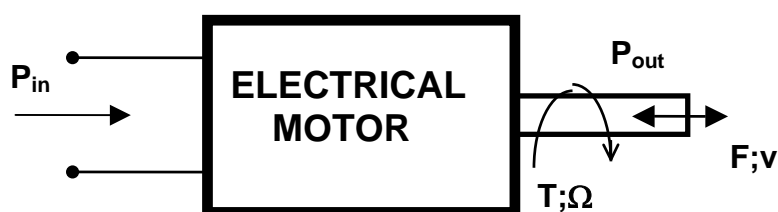
mechanical energy (power) into electrical one,

or

electrical energy (power) into electrical - but usually of different parameters,

with the help of (by means of) magnetic field. Energy conversion in electrical machines is or is not accompanied with mechanical motion.

Machine converters:



INPUT - ELECTRICAL POWER

$$P = UI \text{ (DC circuit)}$$

$$P = UI \cos \varphi \text{ (AC 1-phase)}$$

$$P = \sqrt{3} UI \cos \varphi \text{ (AC 3-phase, line or phase-to-phase values)}$$

$$P = 3 U_{ph} I_{ph} \cos \varphi \text{ (AC 3-phase, phase values)}$$

OUTPUT - MECHANICAL POWER

$$P = T\Omega \text{ (rotational motion)}$$

$$P = Fv \text{ (linear motion)}$$

T - torque (moment) in $N \cdot m$

Ω - angular speed of the shaft in rad/s

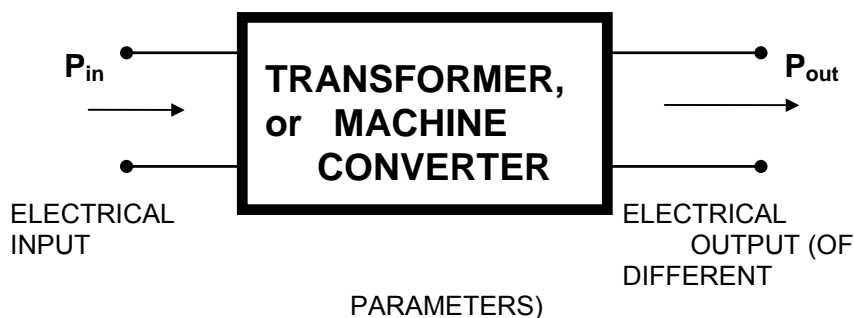
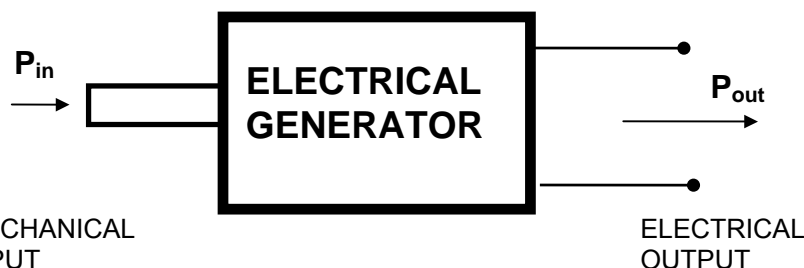
P - power in W (watts)

F - force in linear motion in N

v - speed (linear) in m/s

P_{in} - input power

P_{out} - output power



IMPORTANT NOTICE: OPERATION OF ELECTRICAL MACHINE IS REVERSIBLE. MODE OF OPERATION DEPENDS ONLY UPON THE FORM OF POWER SUPPLIED TO AND ABSORBED FROM THE MACHINE.

[A margin for comments and student's own notes]

BASIC PRINCIPLES OF ENERGY CONVERSION IN ELECTRICAL MACHINE

ELECTROMAGNETIC INDUCTION

Assume the coil having N turns. Each turn is linked with the magnetic flux Φ . The total flux linked with the coil is

$$\Psi = N\Phi$$

and is called coil's flux linkage.

According to Faraday-Lenz law when the change of Ψ is taking place the **electromotive force (emf)** is induced in the coil:

$$e = \frac{d\Psi}{dt} = N \frac{d\Phi}{dt}$$

Change of flux linkage may occur in two ways (separately or simultaneously):

- flux is constant, the coil moves through it; in electrical machines it is usually so arranged, that the straight parts of the coil turns move at speed v at right angles to the direction of the flux;
- coil is stationary with respect to the flux, the flux is varying in magnitude.

In general $\Phi = f(x, t)$, and

$$e = N \frac{d\Phi}{dt} = N \frac{\partial \Phi}{\partial x} \frac{dx}{dt} + N \frac{\partial \Phi}{\partial t} = e_r + e_p$$

Motional (rotational) emf in a single conductor of length l cutting across a magnetic field of uniform flux density B at speed v at right angle to the direction of the flux is

$$e = e_r = Blv$$

Pulsational emf (transformer emf) in a coil of N turns, induced due to the flux linked to the coil varying in time sinusoidally

$$\Phi = \Phi_m \sin \omega t = \Phi_m \sin 2\pi f t$$

has the value

$$e = e_p = N \frac{d\Phi}{dt} = 2\pi f N \Phi_m \cos \omega t = E_m \cos \omega t$$

Its root-mean-square (rms) value

$$E = \frac{E_m}{\sqrt{2}} = 4,44 f N \Phi_m$$

ELECTRODYNAMIC INTERACTION OF CURRENT AND MAGNETIC FIELD

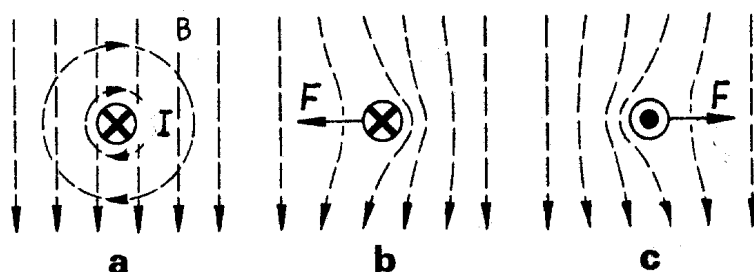
When a current I flowing along the elementary conductor $d\mathbf{L}$ is under influence of magnetic field of density \mathbf{B} , an elementary mechanical force is developed on it, according to Lorentz relation:

$$d\mathbf{F} = I \cdot d\mathbf{L} \times \mathbf{B}$$

The highest value of the force is achieved when the conductor (and current I) is perpendicular to the magnetic field \mathbf{B} . In such a case, for the conductor of total length L , the total force acting at the conductor (current) is

$$F = BIL$$

and is perpendicular to both current and field.



Tendency to align the magnetic field lines (alignment)

DETERMINATION OF EMF AND DYNAMIC FORCE DIRECTIONS

The method of three fingers of the right hand.

AMPER'S RULE FOR MAGNETIC CIRCUIT

$$\oint_L \mathbf{H} \cdot d\mathbf{L} = NI = \Theta$$

or for finite number of the closed magnetic circuit parts of uniform cross-section and assignable length and permeability

$$\sum_x H_x L_x = NI$$

and hence

$$NI = \sum_x H_x L_x = \sum_x \left(\frac{B_x}{\mu_x} L_x \right) = \sum_x \left(\frac{\Phi}{A_x \mu_x} L_x \right) = \Phi \sum_x R_{\mu x}$$

where A_x is a cross-section area of the x -th part of magnetic circuit

H - magnetic field strength in A/m.

$NI = \Theta$ - magnetomotive force (mmf) in A (or in A-t)

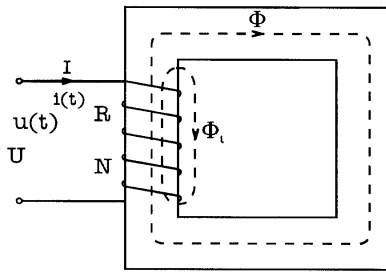
$\mu = \mu_r \mu_0$ - absolute permeability in H/m.

$\mu_0 = 4\pi \times 10^{-7}$ H/m - absolute permeability of vacuum, air or nonmagnetic material

μ_r - relative permeability (in per unit -p.u.)

$R_\mu = \frac{L}{A \cdot \mu}$ - reluctance (magnetic resistance) in H^{-1}

ELECTROMAGNETIC CIRCUIT EXAMPLE



R – winding resistance
 N – number of turns
 Φ – the main flux (A ; l ; μ)
 Φ_l – leakage flux flowing mainly outside the magnetic circuit (A_l ; l_l ; μ_o)

Assume $i = I_m \sin \omega t$ (or $i = \sqrt{2} I \sin \omega t$)

$$\Phi = \Phi_m \sin \omega t \quad \Phi = \frac{N \cdot i}{R_{\mu f}} \quad R_{\mu f} = \frac{l}{A \cdot \mu} = \text{var (saturation effect)}$$

$$\Phi_l = \Phi_{lm} \sin \omega t \quad \Phi_l = \frac{N \cdot i}{R_{\mu l}} \quad R_{\mu l} = \frac{l_l}{A_l \cdot \mu_o} = \text{const}$$

emf induced due to Φ

$$e_f = N \frac{d\Phi}{dt} = N \Phi_m \omega \cos \omega t = N \frac{N I_m}{R_{\mu f}} \omega \cos \omega t = \frac{N^2}{R_{\mu f}} \omega I_m \cos \omega t$$

$$\frac{N^2}{R_{\mu f}} = L_f \quad - \quad \text{inductance of the winding corresponding to the main flux path parameters}$$

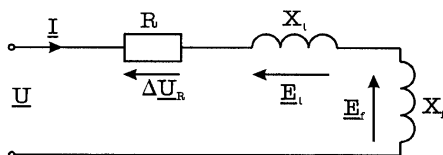
$$\frac{N^2}{R_{\mu f}} \omega = L_f \omega = X_f \quad - \quad \text{so called magnetizing reactance}$$

emf induced due to Φ_l

$$e_l = N \frac{d\Phi_l}{dt} = N \Phi_{lm} \omega \cos \omega t = N \frac{N I_m}{R_{\mu l}} \omega \cos \omega t = \frac{N^2}{R_{\mu l}} \omega I_m \cos \omega t$$

$$\frac{N^2}{R_{\mu l}} = L_l \quad - \quad \text{inductance of the winding corresponding to the leakage flux path parameters}$$

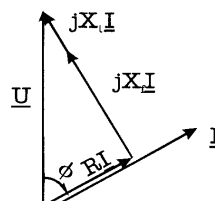
$$\frac{N^2}{R_{\mu l}} \omega = L_l \omega = X_l \quad - \quad \text{so called leakage reactance}$$



Equivalent circuit with rms values of U , I described at complex plane

Voltage balance equation

$$\underline{U} = \Delta \underline{U}_R + \underline{E}_l + \underline{E}_f = R \underline{I} + jX_l \underline{I} + jX_f \underline{I}$$



Phasor diagram

φ - phase angle

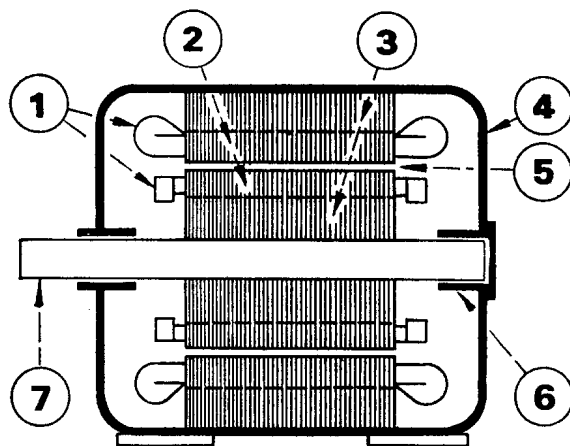
I_m – **amplitude** of sinusoidally varying current
 I – **root-mean-square (rms)** value of current i

amplitude of e_f
 $E_{fm} = X_f \cdot I_m$
 rms value of e_f
 $E_f = X_f \cdot I$

amplitude of e_l
 $E_{lm} = X_l \cdot I_m$
 rms value of e_l
 $E_l = X_l \cdot I$

$X_f + X_l = X$
 (total) reactance of the coil

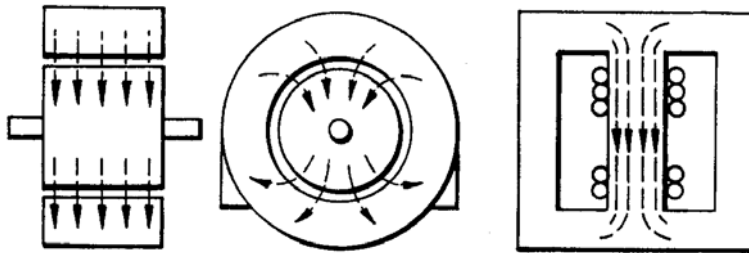
DESIGN AND CONSTRUCTIONAL FEATURES OF A ROTATING MACHINE



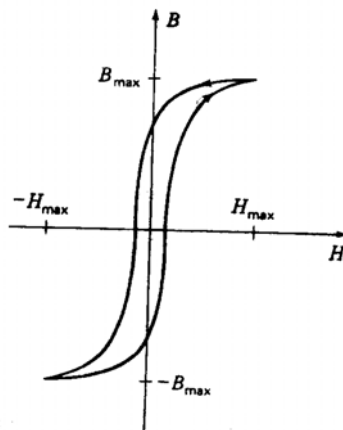
- 1 - windings of stator and rotor embedded in slots
- 2 - slots and teeth
- 3 - magnetic cores of stator and rotor (made of laminations)
- 4 - frame, housing
- 5 - air gap
- 6 - bearings
- 7 - shaft

CORE LOSS

(power loss in magnetic core)



Hysteresis loss - due to the cycling of the material through its hysteresis loop



Specific hysteresis loss (per mass unit of magnetic material)

$$p_h = k_h f B_m^2 \quad [\text{W/kg}]$$

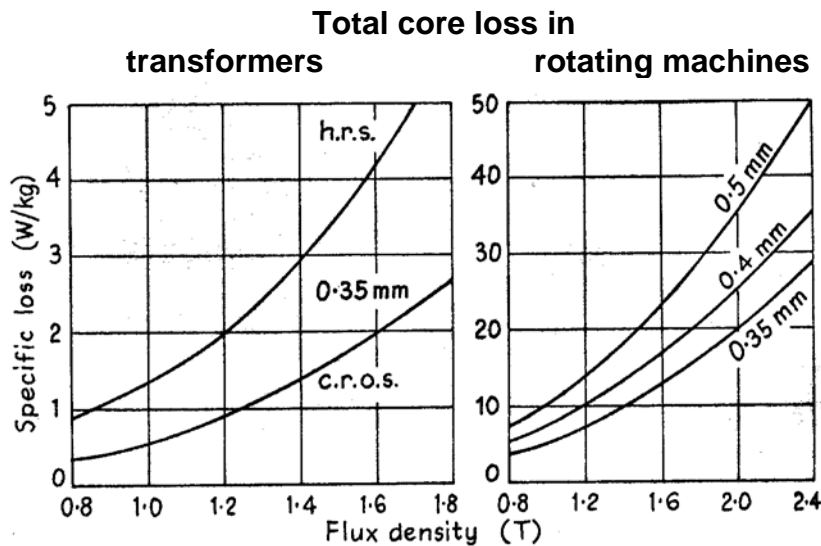
Eddy-current loss - due to the induction of emfs and currents (eddy currents) circulating within the magnetic material.

Eddy-current specific loss

$$p_e = \frac{1}{\rho} k_e d^2 f^2 B_m^2 = k'_e f^2 B_m^2 \quad [\text{W/kg}]$$

ρ - resistivity of magnetic material

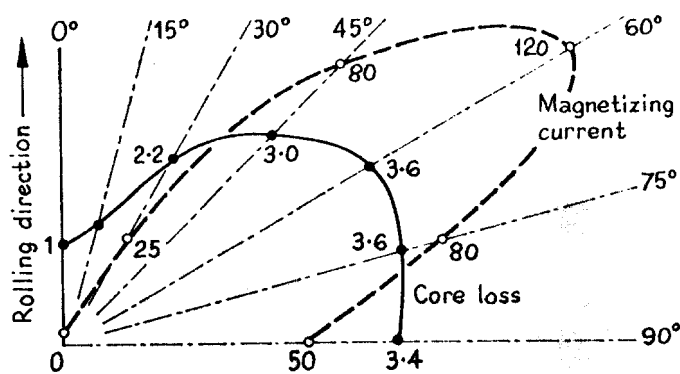
d - thickness of lamination



h.r.s. - hot-rolled steel (4-5% silicon content)

c.r.o.s. - cold-rolled grain-oriented steel

Directional properties of cold-rolled grain-oriented steel



Magnetic properties in the rolling direction are far superior to those on any other axis.

Power loss and magnetising current in the rolling direction are each taken as unity.

COPPER (I^2R) LOSS

When current I (rms value or DC) flows in a conductor (winding) of resistance R , the I^2R loss appears.

Copper & aluminium - most common conducting metals used for electrical machine windings.

Total loss $\Delta P = \Delta P_{Cu} = I^2 R$

$$R = \rho \frac{l}{S_{Cu}}$$

Specific I^2R loss (per volume unit of conducting material (or per unit cube of conducting material))

$$\Delta p = J^2 \rho$$

The resistance depends on temperature

$$R_{\vartheta} = R_{20}(1 + \alpha \cdot \Delta \vartheta) \quad \Delta \vartheta = (\vartheta - 20)$$

Conducting materials properties

Metal	ρ Resistivity [$\mu\Omega \cdot m$]	α Resist - temper. coefficient [1/K]	Density [kg/m ³]
Copper	0.0172	0.00393	8 900
Aluminium	0.045	0.00393	2 700

l - length of conductor (winding)

ρ - resistivity ($\Omega \cdot m$)

S_{Cu} - cross-section area of the conductor

J - current density (A/m^2)

ϑ - temperature

$\Delta \vartheta$ - temperature rise

α - resistance-temperature coefficient

R_{20} - resistance determined (measured) at 20°C

MECHANICAL LOSS ΔP_m

Power loss due to:

- bearing friction
- windage (fan - ventilator action, friction of rotating parts against coolant, f.e. air)
- brush friction

EFFICIENCY OF ENERGY CONVERSION

Efficiency of power conversion is usually the most important parameter of electrical machine.

$$\frac{P_{out}}{P_{in}} = \eta \quad \text{efficiency}$$

$$P_{in} - P_{out} = \Sigma \Delta P \quad \text{total power loss}$$

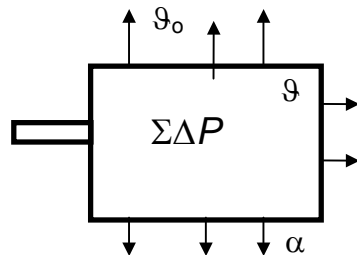
$$\Sigma \Delta P = \Delta P_{Fe} + \Delta P_{Cu} + \Delta P_m$$

$$\eta = \frac{P_{out}}{P_{out} + \Sigma \Delta P} = \frac{P_{in} - \Sigma \Delta P}{P_{in}} \quad \text{can be also expressed in \%}$$

TEMPERATURE RISE OF THE MACHINE

Simplifying assumptions:

- machine is an ideal homogeneous body,
- machine is internally heated by total power loss $\Sigma \Delta P$,
- machine is surface (externally) cooled (f.e. by means of external fan):



The energy balance equation for heated machine when running

$$\Sigma \Delta P \cdot dt = M \cdot c \cdot d\Theta + A \cdot \alpha_h (\Theta - \Theta_o)$$

and its solution for temperature rise (above the ambient temperature) $\Delta\Theta = \Theta - \Theta_o$

$$\Delta\Theta = \Delta\Theta_{\max} \left(1 - e^{-\frac{t}{T_h}} \right) \quad \Delta\Theta_{\max} = \frac{\Sigma \Delta P}{A \cdot \alpha_h} \quad T_h = \frac{M \cdot c}{A \cdot \alpha_h}$$

The energy balance equation for cooling down (machine at rest)

$$0 = M \cdot c \cdot d\Theta + A \cdot \alpha_c (\Theta - \Theta_o)$$

and

$$\Delta\Theta = \Delta\Theta_i e^{-\frac{t}{T_c}} \quad T_c = \frac{M \cdot c}{A \cdot \alpha_c}$$

where $\Delta\Theta_i$ is initial temperature rise (at the beginning of cooling)

Θ_o - ambient temperature
(coolant temp.)

Θ - machine temperature

α - heat transfer
coefficient [W/(m².K)]

M - mass of the machine

c - specific heat of the
machine body
[J/(kg.K)]

A - area of machine
surface at which the
heat exchange occurs
(cooling surface)

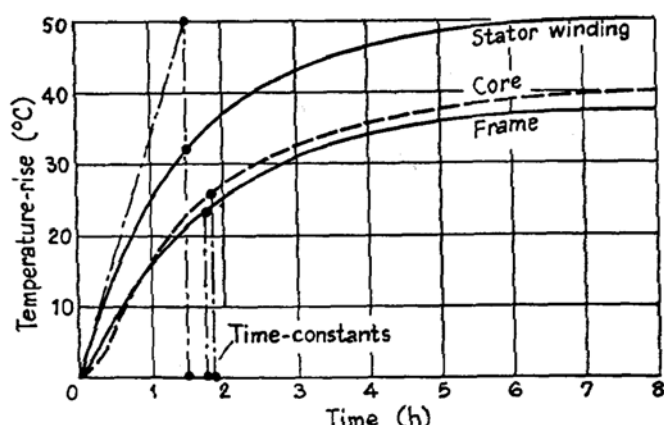
α_h - heat transfer coeff.
of running machine

T_h - heating time
constant

α_c - heat transfer coeff. of
resting machine
(while cooling at
rest)

T_c - cooling time constant
(at rest)

When we don't regard a machine as a homogeneous body, the temperature rises of the winding, core & frame can be different:



What maximum temperature (or temperature rise) can be allowed for any machine part?

Too high temperature (overheating) can damage the material or can shorten the material life expectancy (material life time).

Insulating materials are most sensitive to temperature. Therefore, almost all usable materials are subject to temperature limitations. They are classified in accordance with limits of operating temperature:

Insulation class	A	E	B	F	H
Max temperature °C	105	120	130	155	180

or, when we assume the ambient temperature $\vartheta_0 = 40^\circ\text{C}$ and take into consideration the average temperature rise (for example the temperature rise of the entire winding determined by means of its resistance increase), we can describe the maximum temperature rise:

Insulation class	A	E	B	F	H
Max temp. rise, K	60	75	80	105	125

IEC and European Standard **60034-1 Edition 11: "Rotating electrical machines – Part 1: Rating and performance"** provides three degrees of thermal classification:

Thermal classification	130	155	180
Max temp. rise, K	80	105	125

For large machines the life expectancy is about 30 years, providing the maximum temperature of insulating material used in the machine is not exceeded. Increased temperature above the permissible value causes the quicker degradation of insulating material.

Machine life expectancy (time to failure) is halved for each 8°C temperature rise above that maximum permissible value (continuously).

Thermal life expectancy

Temperature of winding measured by means of resistance measurement method

A, E, B, F, H – previously used abbreviations of machines' insulation classes (still in application in machines of older manufacturing)

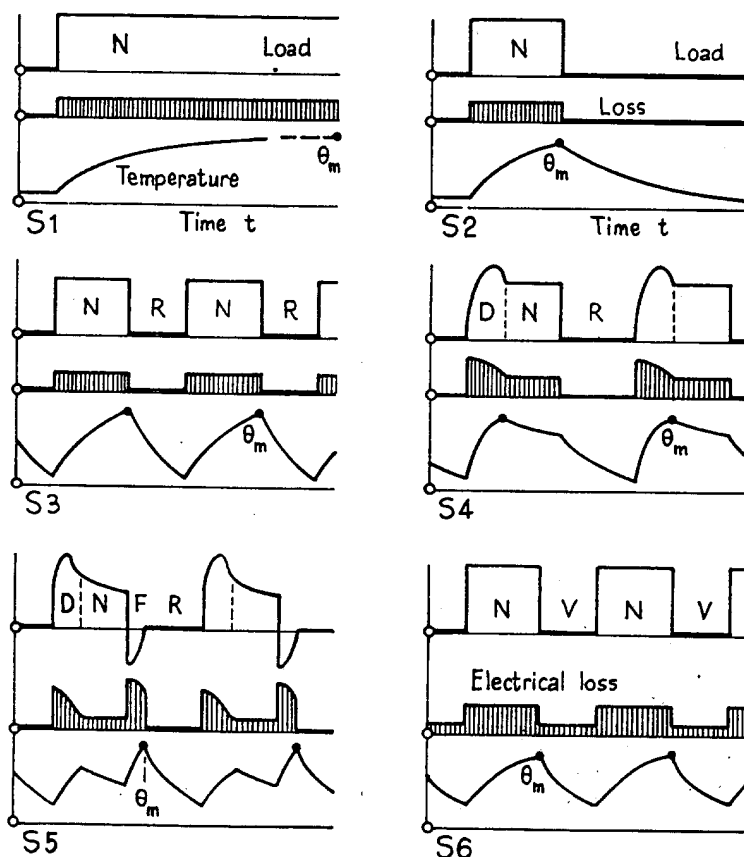
Most actual system of thermal classification

8°C rule

Montsinger's rule

DUTY TYPES OF THE MACHINE

There are various applications of the machines. Standard motors & transformers are rated in terms of continuous operation. But there are also other possible types of operation - *duty types*:



- S1 - continuous running duty
 S2 - short-time duty
 S3 - intermittent periodic duty
 S4 - intermittent periodic duty with starting
 S5 - intermittent periodic duty with electric braking
 S6 - continuous-operation periodic duty

....

Maximum temperature rise must not exceed the appropriate permissible value for the given insulation class of the machine.

Insulation class (thermal classification) of the machine is always given at the machine nominal plate.

The rated (nominal) power of the machine is referred to (corresponds to) the chosen duty type which should also be given at the machine nominal plate by means of: duty type symbol (S1 ... S10), corresponding cyclic duration factor and moments of inertia of machine and of the load.

N - operation under rated condition of load

R - machine at rest and de-energised

D - starting time

F - braking time

V - operation at no-load but rotating

Cyclic duration factors

$$S3: N/(N+R)$$

$$S4: (D+N)/(D+N+R)$$

$$S5: (D+N+F)/(D+N+F+R)$$

$$S6: N/(N+V)$$

(usually expressed in %: 15, 25, 40 or 60%)

Cycle duration - 10 min

$$S2: N=10, 30, 60 \text{ or } 90 \text{ min}$$