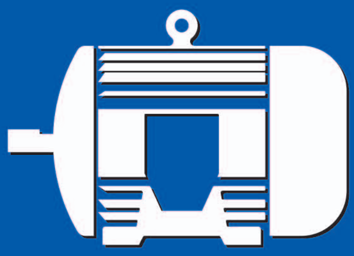
Three Phase Asynchronous Squirrel Cage Motors Manual

VALIADIS
Hellenic Motors



THREE PHASE ASYNCHRONOUS SQUIRREL CAGE MOTORS MANUAL

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INTRODUCTION

This manual contains specifications for electric motors manufactured by “VALIADIS S.A.”, mainly, those of K-Series, i.e. low-voltage, three-phase, squirrel-cage motors.

The most important tests for motors of this type are described in details.
Additional tests for medium-voltage motors are also presented. Initially, reference is made to some of their basic operational characteristics, as these are specified according to International Standards.

Information is provided for the correct motor selection and starting method.

In this second edition of our Engineering Manual we also present the torque test, i.e. the test according to which the torque-speed curve is derived. The motor testing arrangement that is installed and operates in our factory is also presented in this manual below. Special reference is made to the cooling methods according to IEC 34-6. The classification of motors depending on their starting torque is provided according to IEC 34-12.

With this manual, we hope to help our customers in solving problems relating to the specifications of electric motors and their proper operation.

Apart from three-phase, squirrel-cage motors, our production plan also includes slip-ring motors, single-phase motors with brake, explosion-proof motors, hollow-shaft motors, motor-gearbox units and low/high pressure pumping sets.

We also offer high-voltage and direct current (dc) motors in cooperation with a European manufacturer.

We offer inverters and soft starters as well with full after sale service and spare parts.

Finally, we have installed a repair facility in our factory for low and high-voltage motors, dc motors, etc.

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BASIC PARAMETERS

1. Power

With this term we mean the mechanical power provided on the rotor shaft. Unit of measurement: Watt (W). In Greece, the horsepower (HP) is mostly used as a common unit.

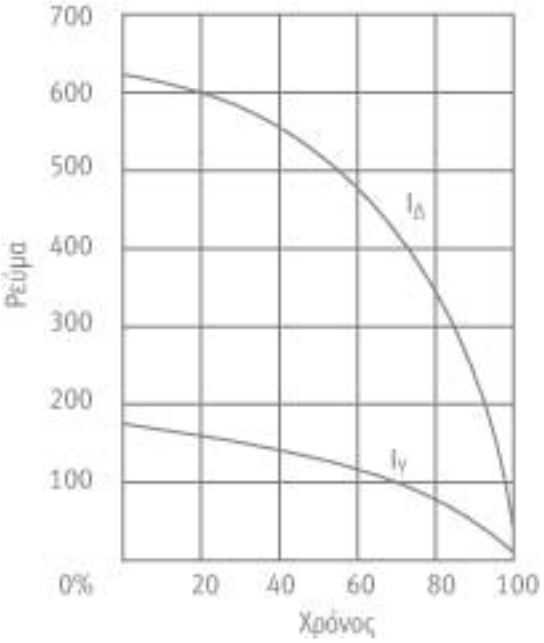
2. Current

The absorbed current of a three-phase motor is: $I = \dfrac{P_m}{\sqrt{3} \times U \times n \times \cos\varphi}$

Where:

I : Absorbed Current (A)
Pm : Power available at the rotor shaft (W)
U : Voltage (V)
cosφ : Power Factor

The current is substantially variable from starting up to the synchronous speed. At starting, the value of current is significantly increased in relation to the rated current of the motor. Depending on the motor size and rotor design, the starting current is 4 to 7 times higher than the rated value.



Current, Speed

Fig.1: *Typical current-speed curve for no-load starting both in delta & star connection of a squirrel-cage motor.*

3. Power Factor (cosφ)

When an alternating, sinusoid current flows in a circuit, both the voltage and current vary in the same sinusoidal mode. During a single period, each one of them takes its maximum and minimum value in succession, i.e. the voltage varies within +V and –V (Volts) and the current within +I and –I (amperes), respectively. However, in general, the maximum voltage (+V) does not occur simultaneously with the maximum current (+I). The same happens with the minimum values as well.

The voltage varies according to the following formula:

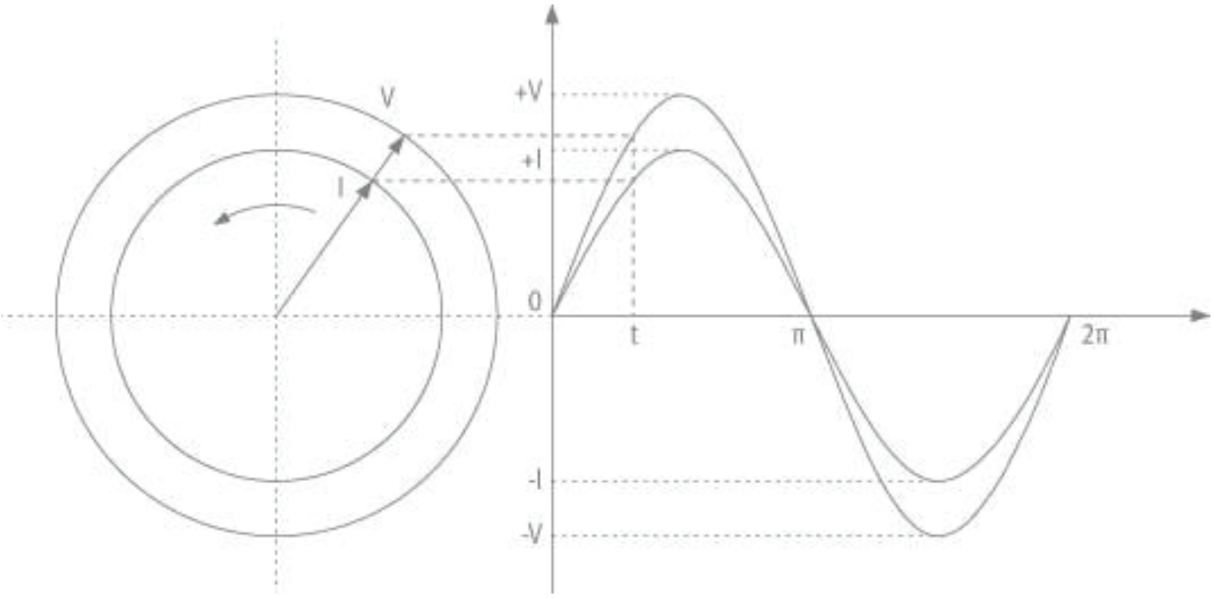
$$v = V \times \sin\omega t$$

The corresponding current varies according to the formula:

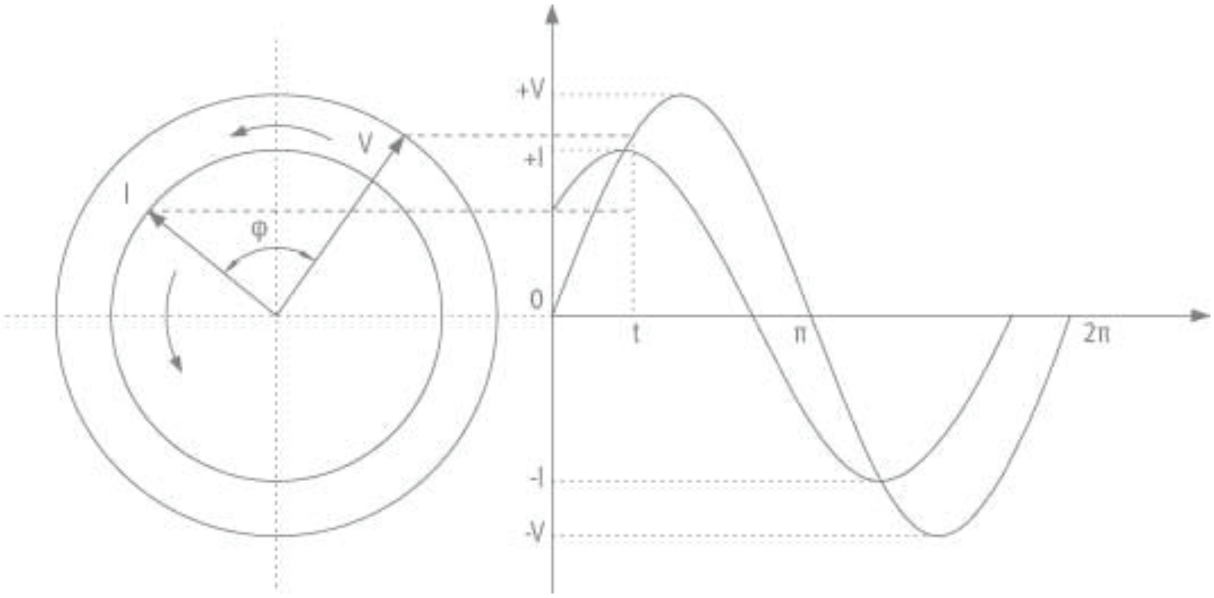
$$i = I \times \sin(\omega t + \phi)$$

The angle φ is called phase deviation angle.

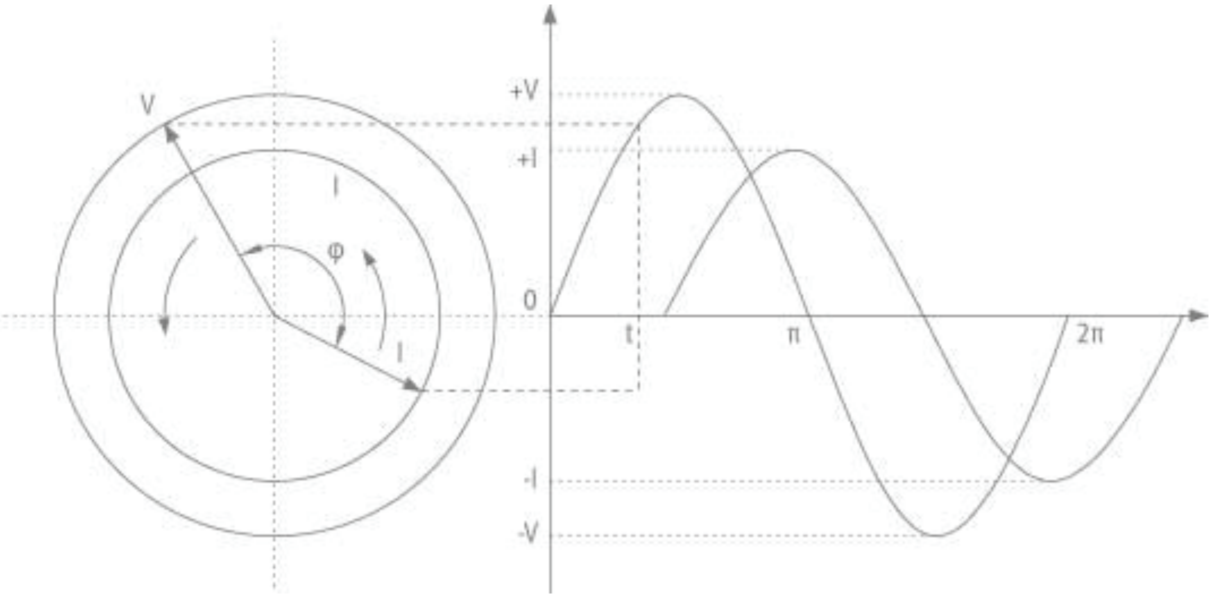
In general, there are 3 types of phase deviation angle, which are described below:



At every moment, the maximum (or minimum) voltage value occurs simultaneously with the maximum (or minimum) value of the corresponding current, respectively, thus ϕ = 0 (see fig.2). In fact, this type of circuit is rare.



Cosϕ leading - the vector of current precedes that of voltage (fig.3). This type of circuit is called capacitive. The term is derived from the characteristic property of capacitors.



Cosϕ lagging - the vector of current follows that of voltage (fig.4). This type of circuit is called inductive. The stator of an asynchronous induction motor is provided with an inductive circuit. The deviation is usually expressed with cosϕ, which is called power factor.

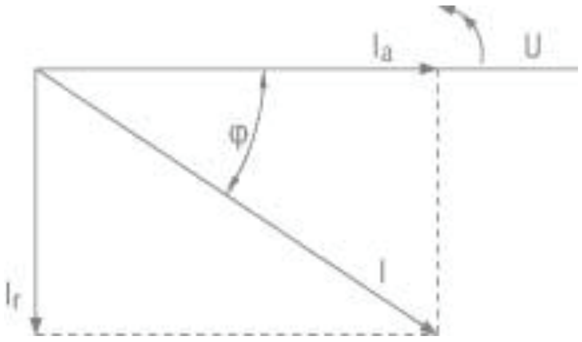


Fig.5

Importance of the Power Factor

Analyzing the vector of current in two geometrical components, the vectors I_a and I_r are derived. I_a is located on the voltage axis, while I_r is deviated by 90^0 in relation to I_a. Thus, I_a is the only current component that is converted to mechanical power in the motor. Therefore, this is called Active Current and the corresponding power is called Active Power.

For three-phase currents, the active power equals to:

$$Pa = U \times I_a \times \sqrt{3}$$

Due to the fact that (see fig. 5):

$$I_a = I \text{ x } \cos\phi$$

The active power becomes:

$$Pa = U \times I \times \sqrt{3} \times \cos\varphi$$

The I_r component of the current is called reactive current. The corresponding power is necessary for magnetization but it does not contribute to the conversion of electrical to mechanical power. The resulting power is called reactive power (or magnetization power). For three-phase currents, this equals to:

$$\Pr = U \times I \times \sqrt{3} \times \sin\varphi$$

However, in fact, the motor absorbs a current I from the power supply network that being multiplied by the corresponding voltage results to a power that is called apparent power. This is expressed in volt-amperes (VA) or kilovolts-amperes (kVA). For three-phase currents this equals to:

$$P = U \times I \times \sqrt{3}$$

During the motor design we try to achieve a value of active power as close as possible to the apparent one, i.e. the value of cosϕ is approaching to one, and the phase deviation angle becomes too small.
It is possible to improve the cosϕ of a certain facility by means of capacitors. This is achieved due to the property of capacitors to cause a reverse angle in relation to that of the inductive phase deviation, reducing or eliminating in this way the inductive phase deviation angle of the motor.
This value of cosϕ varies depending on the applied load. In general, by increasing the load, cosϕ is increasing correspondingly. The values of cosϕ for various partial loads are given in the following table. It is noted that these values are only indicative.

Cosϕ for partial loads

1/2Φ	3/4Φ	4/4Φ	5/4Φ	1/2Φ	3/4Φ	4/4Φ	5/4Φ
0.83	0.88	0.90	0.90	0.65	0.75	0.80	0.81
0.80	0.86	0.89	0.89	0.63	0.74	0.79	0.80
0.78	0.85	0.88	0.88	0.61	0.72	0.78	0.80
0.76	0.84	0.87	0.87	0.59	0.71	0.77	0.79
0.75	0.83	0.86	0.86	0.58	0.70	0.76	0.78
0.73	0.81	0.85	0.86	0.56	0.69	0.75	0.78
0.71	0.80	0.84	0.85	0.55	0.68	0.74	0.77
0.69	0.79	0.83	0.84	0.54	0.67	0.73	0.77
0.67	0.77	0.82	0.83	0.52	0.63	0.72	0.76
0.66	0.76	0.81	0.82	0.50	0.62	0.71	0.76

4. Motor Efficiency

The motor efficiency is derived from the following formula:

$$n = \frac{Pm}{Pa}$$

Where:

n = Motor Efficiency (%)
Pm = Power available at the motor shaft, i.e. Output Power
Pa = Power absorbed from the power network, i.e. Active Power

Since, $Pa = UI\sqrt{3}\cos\varphi$, the above formula becomes:

$$n = \frac{Pm}{\sqrt{3}UI\cos\varphi}$$

The result of Pa minus Pm represents the motor losses. In particular, there are 3 types of losses, as stated below:

Iron losses (Pfe): These are caused due to magnetic hysteresis and eddy currents (FOUCAULT currents) created in the magnetic circuits of both the stator and rotor, respectively.
Mechanical losses (Pm+v): These are caused due to mechanical friction in the bearings of the rotor and the necessary power that is consumed for motor ventilation.
JOULE losses: These are caused due to the Joule phenomenon that occurs in the conductors of the motor, such as the stator winding (Pjst), the squirrel cage of the rotor or the winding of the rotor in case of slip ring motors (Pjrot). These are also called copper losses, and are equal to:

$$\mathbf{R \times I^2}$$

Where:

R = Ohmic resistance
I = Current (A)

It is easy to determine the Joule losses of the stator by measuring the Ohmic resistance of each particular phase at a certain temperature and the corresponding current.
According to IEC 34-2, the joule losses of the rotor are derived from the following formula:

Pjrot = Pem x s

Where

Pjrot : Joule losses of the rotor
Pem : Power transferred to the rotor, i.e. the absorbed power minus stator losses
s : slip

The above formula plays a significant role in the operation of asynchronous induction motors.

Additional load losses (Ps):
Such losses are caused when the motor operates at a certain load. They consist of iron losses and losses due to Foucault currents.
According to IEC 34-2 paragraph 9.1.3, the additional losses due to the applied load are approximately equal to 0.5% of the absorbed power.

The efficiency of a certain motor is not constant. It depends on the driven load. In general, effort is taken to achieve the maximum efficiency within a range of 75-100% of the driven load. Some values of the efficiency factor at partial loads are provided in the next table. It is noted that these values are only indicative.

Motor Efficiency at partial loads

1/2Φ	3/4Φ	4/4Φ	5/4Φ	1/2Φ	3/4Φ	4/4Φ	5/4Φ
93.5	95	95	94.5	79	74	74	72
92.5	94	94	93.5	70	73	73	71
91.5	93	93	92.5	68	72	72	70
91	92	92	91.5	67	71	71	69
90	91	91	90	66	70	70	68
89	90	90	89	65	69	69	67
88	89	89	88	64	67.5	68	66
87	88	88	87	62	66.5	67	65
86	87	87	86	61	65	66	64
85	86	86	85	60	64	65	63
84	85	85	83.5	59	63	64	62
83	84	84	82.5	57	62	63	61
82	83	83	81.5	56	60.5	62	60.5
81	82	82	80.5	55	59.5	61	59.5
80	81	81	79.5	54	58.5	60	58.5
79	80	80	78.5	53	58	59	57
77	79.5	79	77.5	52	57	58	56
75.5	78.5	78	76.5	51	55	57	55
74	77.5	77	75	49	54	56	54
73	76	76	74	47	52	55	53
72	75	75	73	46	51	54	52

5. Synchronous Speed

The synchronous speed of a motor is the speed rate of the rotating magnetic field (rpm). It depends on the frequency of the current and the number of pole pairs in each phase of the stator winding. It is derived from the following formula:

$$n_s = \frac{60f}{p}$$

Where:

n_s = Synchronous Speed (rpm)
f = Current Frequency (Hz), i.e. cycles per sec
p = Number of Pole Pairs

From the above formula it is concluded that the speed (rpm) of a motor does not depend on the applied voltage or the number of phases (i.e. single or three-phase motors).
According to the above formula, the following speeds are derived for frequencies of 50Hz and 60Hz, respectively:

Number of poles	Speed at 50Hz (rpm)	Speed at 60Hz (rpm)
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600
14	428	514
16	375	450

When the motor reaches its synchronous speed it stops transferring power.
In fact, we consider that the no-load speed of the motor is its synchronous speed, since the output power compensates only the no-load losses.
Furthermore, the synchronous angular speed of the motor is expressed with the following formula:

$$\Omega_s = \frac{2\pi f}{p}$$

Where:

Ωs = Synchronous Angular Speed (rad/sec)
f = Current Frequency (Hz)
p = Number of Pole Pairs

6. Slip

Asynchronous motors deliver power at speeds lower than their synchronous one. If n_c is the motor speed at a certain load, the corresponding slip is derived from the following formula, expressed in %:

$$s = \frac{n_s - n_c}{n_s}$$

Thus, the motor speed at a certain load is:

$$n_c = n_s\,(1-s)$$

The motor slip is not constant. It depends on the applied load, and it increases with it. Moreover, the slip varies according to the motor type. Large motors operate with low slip values, while motors of low horsepower operate with relatively higher slip. In fact, the slip at full load may vary within 0.3% - 10%, depending on the power.

7. Torque

The torque that is available at the rotor shaft is derived from the following formula:

$$M = 9.55\frac{P}{n_c} = 9.55\frac{P}{n_s(1-s)}$$

Where:

M : Torque (Nm)
P : Power Output (W)
n_s : Synchronous Speed (rpm)
n_c : Speed at a certain load (rpm)
s : Slip

The torque may also be derived from the following formula:

$$M = \frac{P}{\Omega_c} = \frac{P}{\Omega_s(1-s)}$$

Where:

Ωs : Synchronous Angular Speed (rad/sec)
Ωc : Angular Speed at a certain load (rad/sec)

Since:

$$\Omega_s = \frac{2\pi f}{p}$$

Then, we take:

$$M = \frac{P \times p}{2\pi f(1-s)}$$

Where:

p = number of pole pairs
f = current frequency (Hz)

Starting Torque / Breakaway Torque (or minimum torque) / Breakdown Torque

The motor torque at constant voltage varies substantially from the starting point up to the synchronous speed. The characteristic torque-speed curve of an asynchronous squirrel-cage induction motor is presented in fig. 6 below.

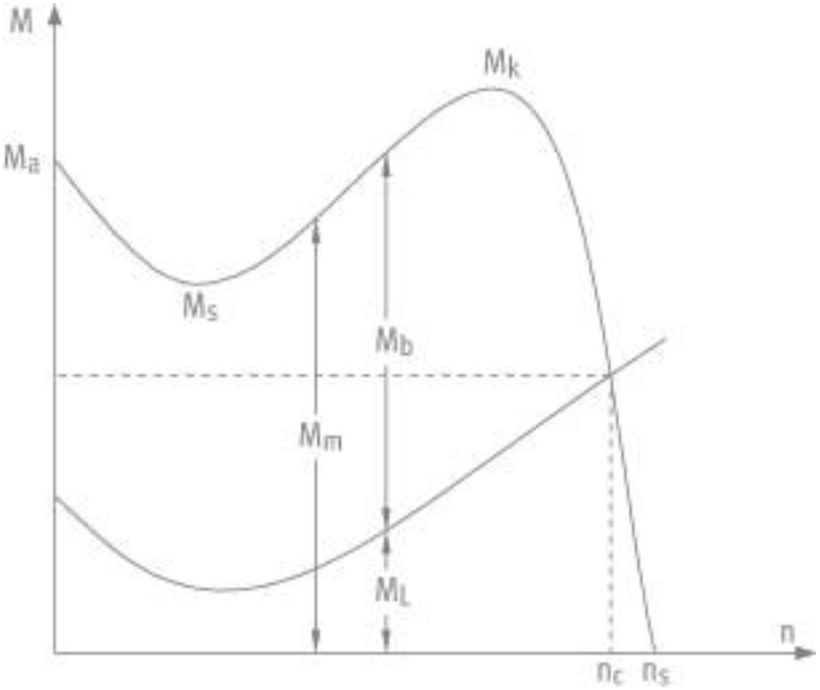


***Fig.6:** This curve is very important for the motor operation. At the moment of starting, with actually zero speed, the so-called Breakaway Torque is equal to Ma. With increasing speed, the torque is reduced up to a minimum value of Ms that is called Pull-up Torque. Then, the speed keeps on increasing with the torque correspondingly increasing up to a maximum value of Mk that is called Maximum Torque or Breakdown Torque. Beyond this point, the torque starts to decrease and becomes zero at the synchronous speed.*

The mechanical overload limit of a motor is determined through its breakdown torque. According to IEC 34-1 paragraph 19.1, induction motors must be able to deliver an output power of up to 1.6 times their rated power at rated voltage and frequency for 15 sec without breaking or any sudden speed drop.

The allowable minimum torque of three-phase induction motors is determined according to IEC 34-1 paragraph 20.1, as follows:

a) For motors of rated power <100kW: 0.5 times the rated torque but in any case not lower than the 50% of the starting torque.
b) For motors of rated power ≥100kW: 0.3 times the rated torque but in any case not lower than the 50% of the starting torque.
c) For single-phase motors: 0.3 times the rated torque (IEC 34-1, paragraph 20.2).

Acceleration torque

The load torque (M_L) vs. speed curve is presented in fig.6.
Taking into account the related tolerances (see chapter “Tolerances”), the starting torque of a motor must be substantially higher than the required starting torque for the specific load. The motor torque must remain substantially higher than the load torque over the entire acceleration period up to the operating speed. The operating speed is determined as the point where the curve of the load torque intersects with the torque curve of the motor. This is the operating point of the system. The difference between the torque values at each point along the curve is called acceleration torque (M_b).

8. Power Balance

Parameters:
Absorbed Power = Stator Input Power = P_a
Stator Output Power = P_{em}
Stator Losses = $\Sigma\upsilon\nu P_{st}$
Rotor Output Power = P_{tot}
Ohmic Rotor Losses (Joule Losses) = P_{jrot}
Total Rotor Torque = M_{tot}
Synchronous Speed = n_s
Speed at a certain load = n_c

The power that is transferred to the rotor is equal to the absorbed one by the stator minus the losses occurring in the stator.

Thus:

Stator Input Power = Stator Output Power + Stator Losses, i.e.:

$$P_a = P_{em} + \Sigma\upsilon\nu P_{st}$$

The output power of the stator is completely transferred through induction to the rotor circuit. Thus, we have:

Rotor Input Power = Stator Output Power = P_{em}

In addition:

Total Output Power of the Rotor = Rotor Input Power – Rotor Joule Losses

i.e.:

$$P_{o\lambda} = P_{em} - P_{jrot}$$

The total output power of the rotor is converted to mechanical power, creating the total torque of the rotor. A part of this total torque is consumed due to ventilation and friction, and the remaining part constitutes the useful torque that is available at the motor shaft.

Thus, we take:

$$M_{o\lambda} = \frac{P_{tot}}{2\pi n_c}$$

If there are no ohmic losses at the rotor, its output power is equal to the input power and it rotates at the synchronous speed.

Thus, we take:

$$M_{o\lambda} = \frac{RotorInputPower}{2 \times \pi \times n_s}$$

From the two formulas mentioned above, the following are derived:

$$\text{Output Power} = M_{tot} \times 2 \times \pi \times n_c$$
$$\text{Input Power} = M_{tot} \times 2 \times \pi \times n_s = P_{em}$$

The difference between the two values above equals to the ohmic losses of the rotor, i.e.:

$$P_{jrot} = M_{tot} \times 2 \times \pi \times (n_s - n_c)$$

From the last two formulas the following are derived:

$$\frac{P_{jrot}}{P_{em}} = \frac{M_{tot} \times 2 \times \pi \times (n_s - n_c)}{n_c} = \frac{n_s - n_c}{n_s} = s$$

And:

$$P_{jrot} = P_{em} \times s$$

We also take:

Total Output Power of the Rotor = Input Power – Rotor Copper Losses
= $P_{em} - (s \times P_{em})$
= $P_{em} \times (1 - s)$

i.e.:

$$P_{tot} = P_{em} \times (1 - s)$$

From these two formulas the following is derived:

$$\frac{P_{tot}}{P_{jrot}} = \frac{1-s}{s}$$

DEFINITIONS

The definitions of some basic terms and parameters according to IEC 34 – 1 are presented below.

1. Rated operation
Operation mode, according to which all the electrical and mechanical parameters of the motor (regarding both the arithmetic values and the time of application) are exactly the same with the data specified and guaranteed by the manufacturer, as these are mentioned on the name plate of each particular unit (motor).

2. Rated value
The value of a medium characterizing the rated operation

3. Rated power
This is the power value corresponding to the rated operation. Regarding electric motors, this is the mechanical power available on the motor shaft. Unit of measurement: Watt (W). In Greece common power unit is the horsepower (HP).

4. Load
This is the sum of arithmetic values of electrical and mechanical components comprising the total output that is required from a motor at a specific moment.

5. No-load operation
With this term we mean the operation of the motor at rated parameters (voltage, frequency, etc.) but without any power output requirement.

6. Stop or pause (out of operation)
Lack of motion, electric power supply or mechanical drive

7. Operation

The way of load application on a motor is defined with this term, the no-load operation and any possible stop also included, as well as the description of load evolution with the time (duration & succession of events).

8. Operation Mode

Continuous operation or periodic operation in short intervals, at a constant load for a specified time period

9. Thermal Balance

The condition, in which the temperature in various motor components does not increase by more than 2°C within an hour

10. Operation Duration Factor

The ratio of the operation time at a certain load (starting & electric braking time also included) to the duration of an operation cycle, expressed in %

11. Locked Rotor Torque

This is the minimum torque developed when the motor is supplied with rated voltage and frequency with the rotor being locked.

12. Pull-up Torque

This is the minimum value of torque (at rated voltage & frequency) that is found between zero speed and the speed corresponding to the minimum torque of the motor.

13, Maximum or Breakdown Torque

This is the maximum output power of the motor during operation at rated voltage & frequency, in hot condition, without any sudden drop of speed.

14. Cooling Medium

This is the heat transferring medium (gas or liquid).

15. Factor of Inertia

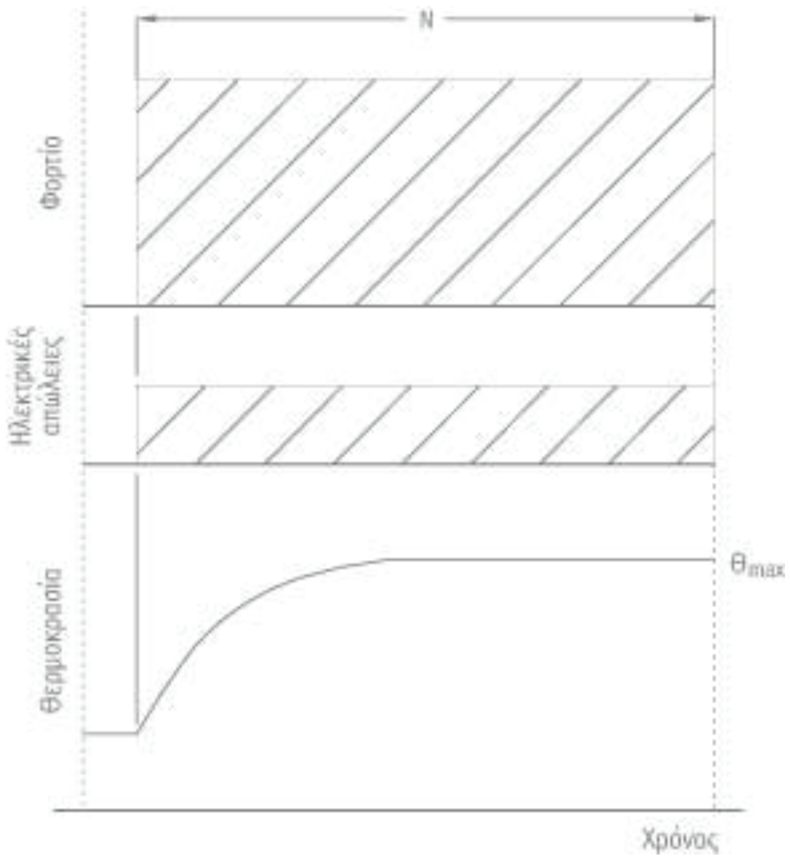
This is the ratio: $FI = \frac{A+B}{A}$

Where:

A : Moment of Inertia of the motor
B : Moment of Inertia of the driven load (reduced in the motor speed)

DUTY TYPES

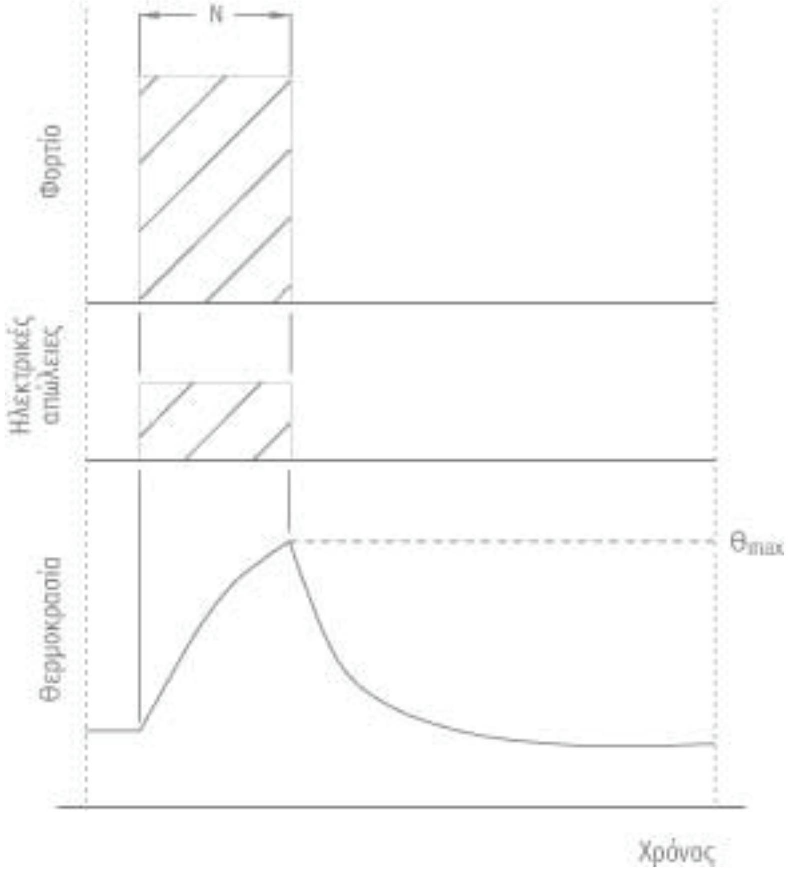
The correct specification of the operation mode is very important in order to meet customers' requirements and achieve smooth operation conditions.
The standard duty types (according to IEC 34-1) which cover most of the cases are mentioned below. Experience, knowledge and correct estimation will help to describe as correctly as possible the operation of a motor and to classify it in one of the following operation modes:



Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Χρόνος = **Time**

Continuous running duty (S1)

The motor operates at constant load for a time period, sufficient enough to establish a thermal equilibrium.



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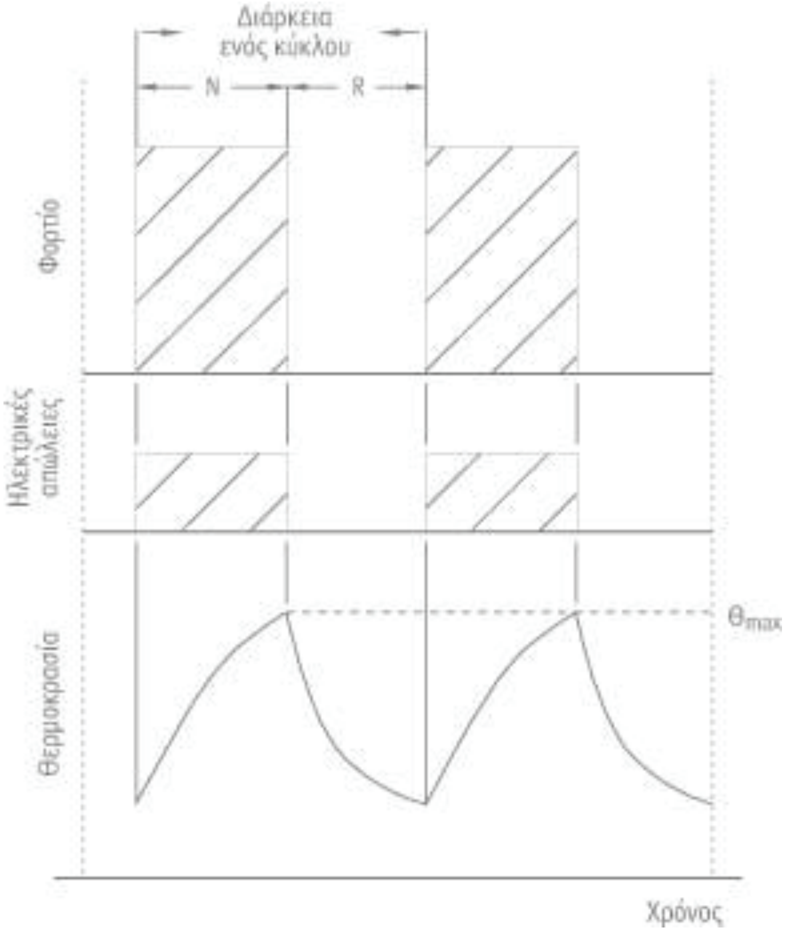
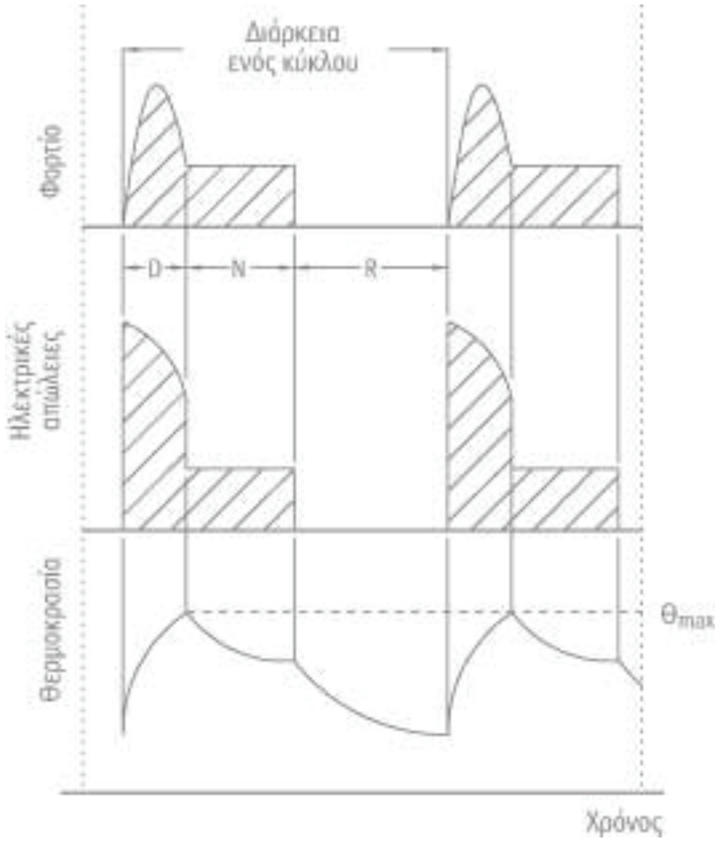
Short-time duty (S2)
The motor operates for a short period that is not enough to establish a thermal equilibrium, while it is stopped for too long that the temperature inside the motor nears the ambient temperature again. Standard times for this mode: 10min, 30min, 60min, and 90min.



Διάρκεια ενός κύκλου = **Duty Cycle Duration** // Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Χρόνος = **Time**

Intermittent periodic duty (S3)

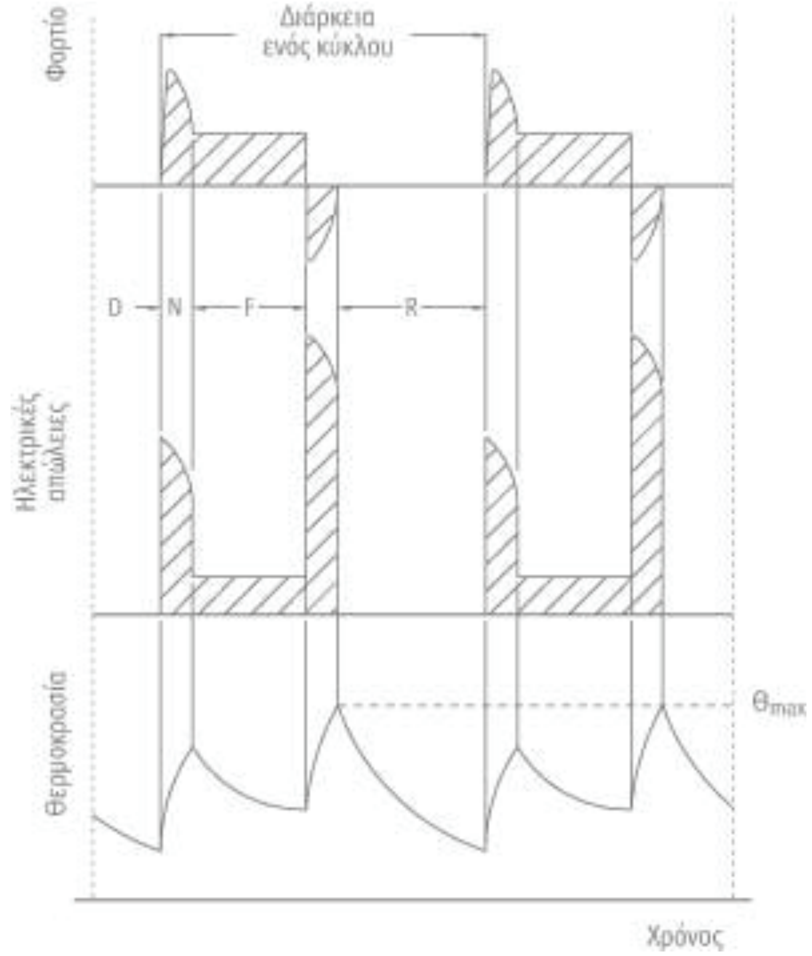
The motor performs identical duty cycles (at constant load) and stopping, the duration of which is not sufficient enough to reach the maximum allowable temperature and the starting current does not affect the temperature inside the motor. Standard values for the operation duration coefficient: 15%, 25%, 40%, 60%.



Διάρκεια ενός κύκλου = **Duty Cycle Duration** // Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Χρόνος = **Time**

Intermittent periodic duty affected by the starting current (S4)

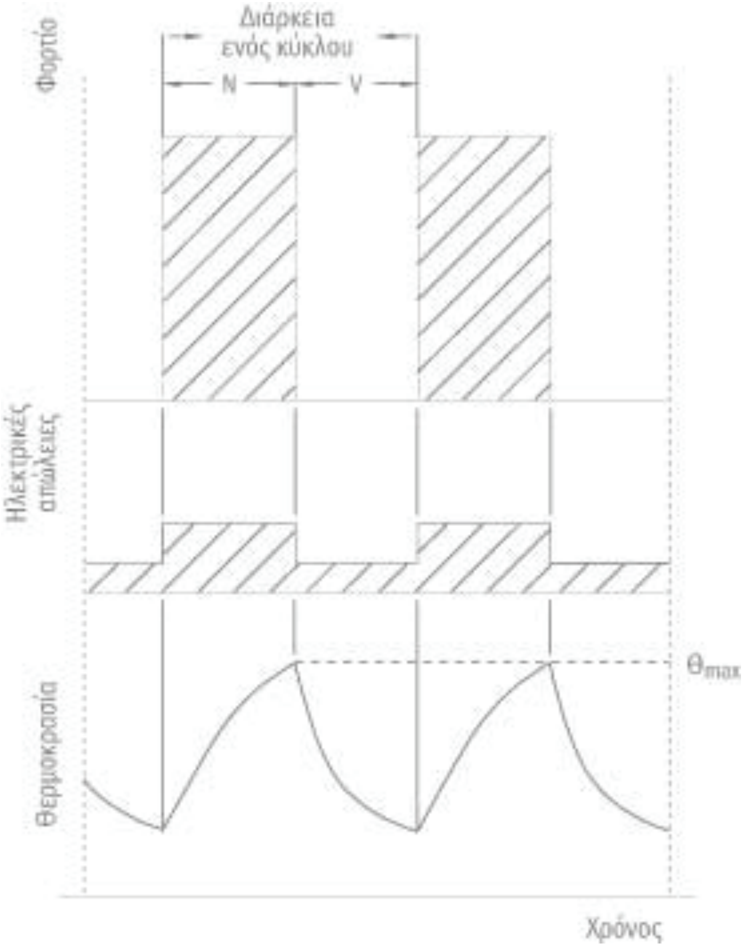
The motor performs identical duty cycles (at constant load) and stopping, while the temperature inside the motor is affected by the starting current. Standard values for the operation duration coefficient: 15%, 25%, 40%, 60%.



Διάρκεια ενός κύκλου = **Duty Cycle Duration** // Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Χρόνος = **Time**

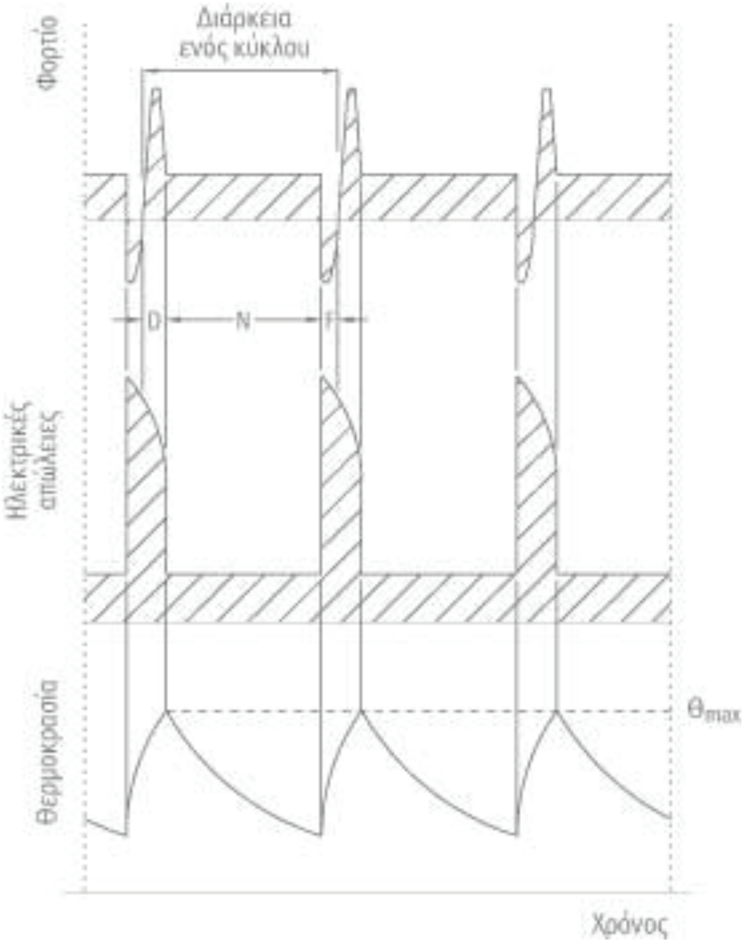
Intermittent periodic duty affected by the starting current and the electrical braking (S5)

The same as the S4 one but with intervening electrical braking



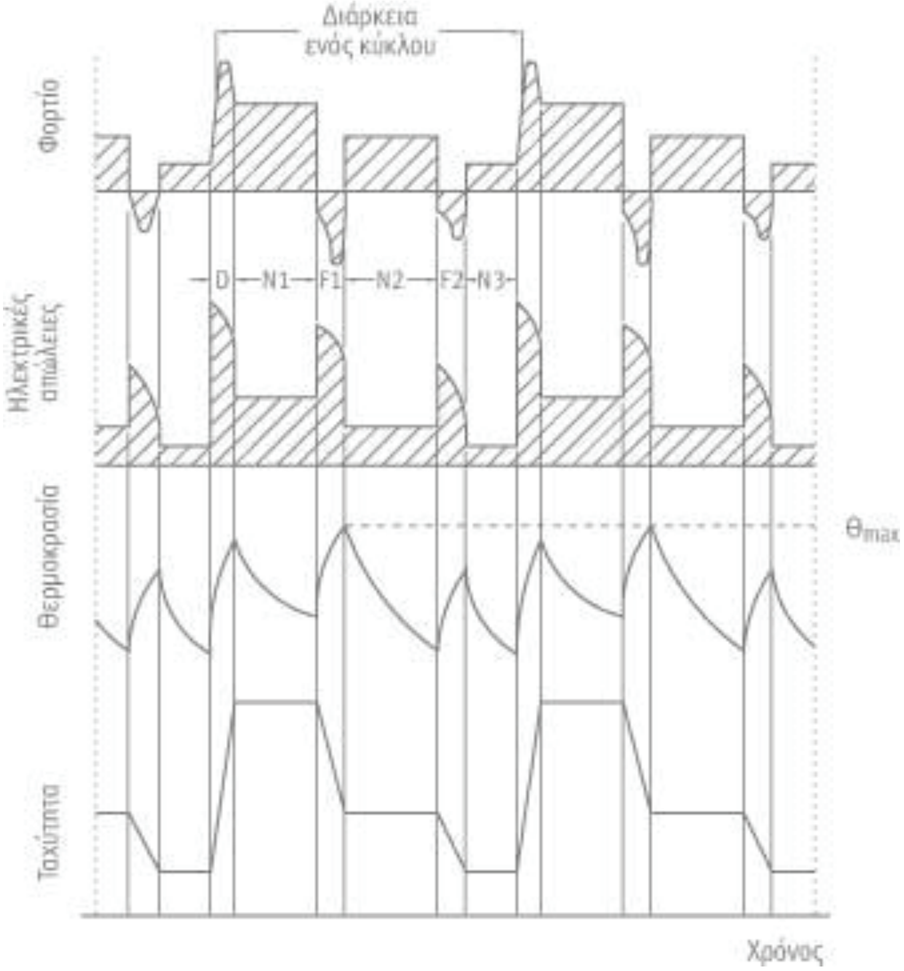
Διάρκεια ενός κύκλου = **Duty Cycle Duration** // Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Χρόνος = **Time**

Continuous-operation periodic duty (S6)
The motor operates continuously, performing periodic duty cycles at constant load and no-load, successively. There is no pausing period between successive cycles. Standard values for the operation duration coefficient: 15%, 25%, 40%, 60%.



Διάρκεια ενός κύκλου = **Duty Cycle Duration** // Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Χρόνος = **Time**

Continuous-operation periodic duty with electric braking (S7)
The motor operates continuously, performing periodic duty cycles at constant load and braking, successively. There is no pausing period between successive cycles. Standard values for the operation duration coefficient: 1.



Διάρκεια ενός κύκλου = **Duty Cycle Duration** // Φορτίον = **Load** // Ηλεκτρικές απώλειες = **Electric Losses** // Θερμοκρασία = **Temperature** // Ταχύτητα = **Speed** // Χρόνος = **Time**

Continuous-operation periodic duty with related speed / load changes (S8)
The motors operates continuously performing identical cycles, each one of them consisting of a period at constant load and a certain rotation speed, followed by one or more periods at various loads –kept constant within each period- and various speed rates. There is no pausing period in between.

The specified time period for the operation modes S3, S4 and S6 (operation cycle duration) is 10min.

The factor of inertia (FI) must also be given for the operation modes S4, S5, S7 & S8.

Below some indicative examples of operation modes are presented according to IEC with the corresponding symbols:

S1	
S2	60min
S3	25%
S4	25% 10 starts per hour with FI=2
S5	25% 30 starts per hour with FI=4
S6	40%
S7	30 cycles per hour with FI=5
S8	25KW, 740rpm, 40%, FI=10, and 60KW, 1450rpm, 60%, FI=10

In case no reference is made on the name plate to the operation mode of the motor, S1 will be considered the specified operation mode.

Finally, the operation modes can be classified into the following three basic categories:
1. Continuous operation at full load with full efficiency over the entire operation period.
2. Short duration operation according to which the motor operates for a short interval, every time starting in the cold condition.
3. Cyclic operation according to which the motor performs loading cycles with starts affecting its final temperature.

OPERATION CONDITIONS

Standard motors are suitable to operate under the following conditions, according to IEC 34-2, paragraphs 11 & 12. Upon special request, of course, it is possible to manufacture motors suitable for different conditions.

1. Altitude

This should not exceed 1,000m above the sea level.

2. Ambient temperature

The ambient temperature and, especially, the temperature of the cooling medium should not exceed 40°C.
In case a motor should be installed at an altitude higher than 1,000m, the ambient temperature must be relatively lower than 40°C.
Depending on the insulation class, the following higher limits of the ambient temperature are specified according to IEC 34-1, paragraph 16 for altitudes higher than 1,000m.

Altitude	Ambient Temperature (°C)				
	Insulation Class				
	A	E	B	F	H
1000m	40	40	40	40	40
2000m	34	33	32	30	28
3000m	28	26	24	20	15
4000m	22	19	16	10	5

3. Electrical conditions (network power supply)

According to IEC 34-1, the specified electric motors are suitable to operate connected in three-phase power supply networks of 50Hz or 60Hz with practically sinusoid voltage supply, constituting a symmetric system. In these specifications, explaining the above terms, the following are defined:

a) A voltage that is applied to a motor at its rated load is practically considered sinusoidal, when the difference between its instantaneous value and the corresponding instantaneous value of its main component (i.e. the basic harmonic) does not exceed 5% of the possible span of the latter.

b) A multiphase voltage system is considered to be symmetric, if the voltage of the negative sequence component deviates up to 1% from the value of the main component for a long time (or up to 1,5% for a short period) and the voltage of the zero sequence component does not exceed 1% of the voltage of the positive sequence component.

In case these two limits are simultaneously exceeded at full load, the allowable temperature limits are increased by 10°C.

Voltage fluctuation during operation

According to IEC 34-1, paragraph 12.3, the allowable voltage fluctuation should not exceed ±5% of the rated value. All motors must be able to deliver full power at a voltage within 105% and 95% of the rated value but, in any case, at rated frequency.
In case of continuous operation at the above limits at full load, the allowable temperature limits are increased by 10°C.

PROTECTION DEGREE (IP)

The protection degree of rotating electrical machines is specified according to IEC 34-5, where the following are defined:

1. Human protection against contact with voltage carrying or moving components
2. Machine protection against penetration of solid foreign materials
3. Machine protection against water inflow
4. Encoded characterization of various protection degrees, and, finally
5. Tests for protection degree certification

These specifications does not define protection degrees against mechanical damages, moisture (e.g. due to condensation), oxidizing vapors, mold, or insects. They do not refer to protection of machines operating in explosive environments.
External screens mounted for human protection are not taken into account in the definition of the protection degree.

Symbols
The symbol that is used to express the protection degree is IP accompanied by three characteristic numbers. The first one represents human protection as well as protection of the machine against penetration of solid foreign materials. The second characteristic number represents the protection of the machine against water inflow. The third characteristic number represents the mechanical protection of the machine.

Protection degree coding example:

IP 4 4 1

Characteristic letters
1st characteristic number
2nd characteristic number
3rd characteristic number

The three characteristic numbers mentioned above are defined in the following table:

1st characteristic number

0	No protection
1	Protection against solid foreign objects up to 50mm in diameter
2	Protection against solid foreign objects up to 12mm in diameter
3	Protection against solid foreign objects up to 2.5mm in diameter
4	Protection against solid foreign objects up to 1mm in diameter
5	Protection against dust

3rd characteristic number

0	No protection
1	Protection from impacts up to 0.225J (150gr/15cm)
2	Protection from impacts up to 0.375J (250gr/15cm)
3	Protection from impacts up to 0.500J (250gr/20cm)
5	Protection from impacts up to 2J (500gr/40cm)
7	Protection from impacts up to 6J (1.5Kgr/40cm)
9	Protection from impacts up to 20J (5Kgr/40cm)

2nd characteristic number

0	No protection
1	Protection against vertical water precipitation in the form of drops
2	Protection against vertical water precipitation in the form of drops with the motor inclined up to 15^0
3	Protection against water spraying at an angle of 60^0 from the vertical direction
4	Protection against water spraying from any direction
5	Protection against water jet from any directions
6	Protections against falling of sea waves or strong water jets
7	Protection against submersion into the water under certain pressure for a certain period
8	Protection against permanent submersion into the water under conditions specified by the manufacturer. The machine is considered totally enclosed. However, in some cases water may get in but in a way that cannot harm the machine.

The most common protection degrees of electric motors are the following:

1) IP 23: The motor is internally ventilated.
It is protected against contact with fingers and solid foreign materials over 12mm in diameter.
It is protected against water spraying at an angle of 60^0 from the vertical.
2) IP 44: The motor is externally ventilated.
It is protected against contact with tools, wires or similar objects as well as against solid foreign objects over 1mm in diameter.
It is protected against water spray from any direction.
3) IP 54: The motor is externally ventilated.
It is totally protected against any contact and dust, as well.
The protection against water is the same with IP 44.
4) IP 55: The motor is externally ventilated.

The protection degree is the same with that of IP 54 against contact and foreign materials.
It is protected against water jet from any direction.

In case we want to define only the protection degree against water or only against direct contact, only one characteristic number is needed to define the corresponding protection degree. The second one must be replaced with X, e.g. IPX5 or IP2X.

Complementary letters
Additional information on protection, apart from that provided above, are represented with a complementary letter following the 2nd characteristic number.
In special applications, (such as machines installed on ship decks, equipped with an open cooling circuit and air inlet/outlet vanes, which remain closed when the machine is stopped), the characteristic numbers may be accompanied by an additional letter defining whether the protection against harmful water inflow is sufficient or has been tested. The letter S indicates that the specific test has been performed with the machine stopped (out of operation), while the letter M indicates that the test has been performed with the machine in operation. In these cases the resulting protection degree is IP55S and IP20M, correspondingly.
Lack of the letters S or M in the protection code indicates that the specific protection degree refers to normal operation conditions.
Regarding air-cooled, open-type machines, suitable for extreme weather conditions and provided with additional protection means, their protection degree must be identified with the letter W.

Condensate drainage orifices
Externally ventilated motors are usually provided with two orifices at the bottom of their housing to remove condensing vapors. Depending on the motor design, these orifices are permanently open or they remain open during operation and are closed when the motor stops.
In case a motor is provided with IP3X or IP4X protection the drain orifices must meet the requirements of IP2X protection. The drain orifices of motors provided with IP5X protection must meet the requirements of IP4X protection.

External fans
Fans mounted outside the motor housing must be protected against direct contact with a proper screen, so as objects larger than 50mm in diameter could not get through the openings for motors of IP1X protection. For motors provided with higher protection degrees (IP2X up to IP5X) the screen should not be penetrated by a human finger.

COOLING METHODS

The cooling methods of rotating electrical machines are specified in IEC 34-6, where the following are defined:

1. Cooling circuit arrangement (1st identification number)
2. Type of the primary coolant (1st identification letter)
3. Circulation method of the primary coolant (2nd identification number)
4. Type of the secondary coolant (2nd identification letter)
5. Circulation method of the secondary coolant (3rd identification number)

Symbols

The code representing the cooling method consists of the letters IC accompanied by three identification numbers and two additional letters.

Example of identification code:

IC 4 A 1 A 1

Characteristic letters
Cooling circuit arrangement
Type of primary coolant
Circulation method of the primary coolant
Type of secondary coolant
Circulation method of the secondary coolant

In the above example, the letter A indicates that air is the primary coolant. This can be omitted, thus the identification code is IC411.

Motors of K, KM & KΔ Series are provided with IC411 cooling type.

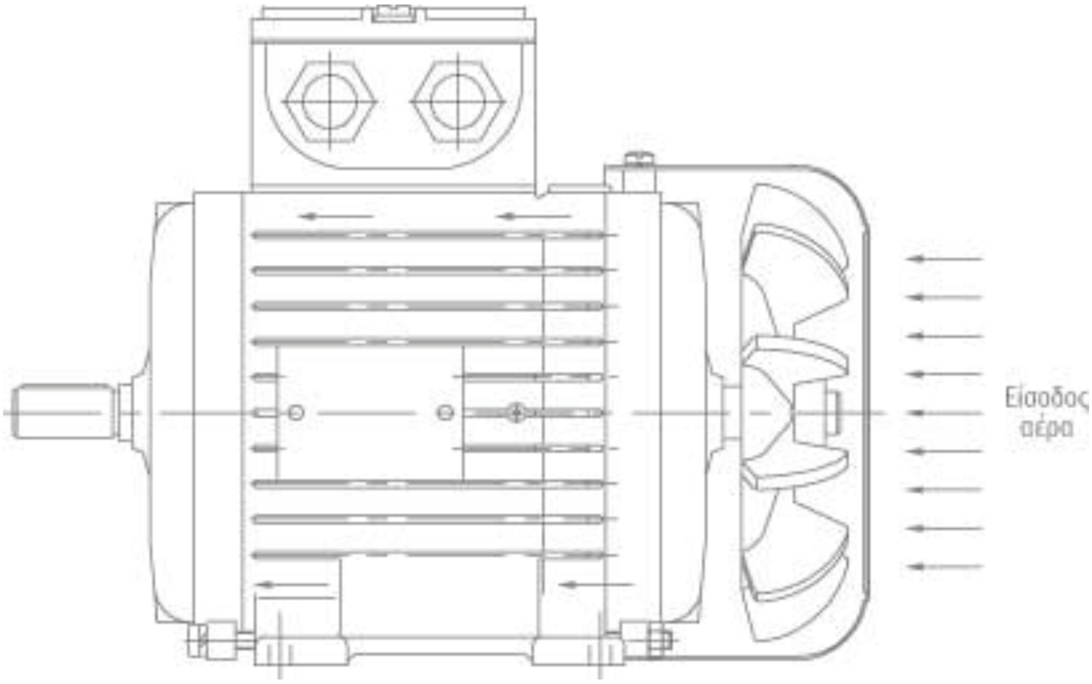
Cooling Circuit Arrangement		
Characteristic number	Brief description	Definition
0	Free circulation	The cooling medium comes from the machine's environment and inflows/outflows freely.
1	Machine with a suction system of the cooling medium	The cooling medium does not come from the machine's environment. It is forwarded into the machine through a suction system and outflows freely to the same environment.
2	Machine with a compression system of the cooling medium	The cooling medium is freely sucked from the environment and outflows through a compression system, being forwarded to a different environment.
3	Machine with both suction & compression system	The cooling medium is sucked from a different environment than that of the machine, it is forwarded into the machine and outflows to a different environment through a compression system.
4	Cooling medium coming in contact with the surface of the machine	The primary cooling medium circulates in a closed circuit, transferring heat to the secondary cooling medium, which surrounds the machine, coming in contact with its surface. The specific surface of the machine may be smooth or provided with cooling fins.
5	Embedded heat exchanger (using the medium surrounding the machine)	The primary cooling medium circulates along a closed circuit, transferring heat to the secondary cooling medium, which surrounds the machine. Heat transfer takes place in a heat exchanger embedded in the machine, forming a single body.
6	Heat exchanger mounted on the machine (using the medium surrounding the machine)	The primary cooling medium circulates along a closed circuit, transferring heat to the secondary cooling medium, which surrounds the machine. Heat transfer takes place in a separate heat exchanger mounted on the machine.
7	Embedded heat exchanger (not using the medium surrounding the machine)	The primary cooling medium circulates along a closed circuit, transferring heat to the secondary cooling medium that does not surround the machine. Heat transfer takes place in a heat exchanger embedded in the machine, forming a single body.
8	Heat exchanger mounted on the machine (not using the medium surrounding the machine)	The primary cooling medium circulates along a closed circuit, transferring heat to the secondary cooling medium that does not surround the machine. Heat transfer takes place in a separate heat exchanger mounted on the machine.
9	Separate heat exchanger (using or not the medium surrounding the machine)	The primary cooling medium circulates along a closed circuit, transferring heat to the secondary cooling medium in a separate heat exchanger installed outside the machine.

Circulation Method		
Characteristic number	Brief description	Definition
0	Free flow	Circulation is effected only due to temperature difference between inlet and outlet points. The ventilation provided through the rotor is negligible.
1	Self-driven circulation	The circulation of the cooling medium depends on the rotation speed of the machine. It is driven either only by the rotor or by an arrangement mounted on the rotor
2,3,4		Not specified yet
5	Independent arrangement	Circulation of the cooling medium is achieved with a totally independent arrangement, the power of which is not affected by the speed of the machine.
6	Separate arrangement mounted on the machine	Circulation of the cooling medium is achieved with an independent arrangement mounted on the machine. The power of this arrangement is not affected by the speed of the machine.
7	Separate & independent arrangement or forced circulation of the cooling medium (under pressure)	Circulation of the cooling medium is achieved with a separate electrical or mechanical arrangement that is not assembled on the machine or through forced circulation of the cooling medium (under pressure)
8	Relative circulation	Circulation of the cooling medium is achieved through relative motion between machine and cooling medium (the cooling medium flows around the machine or the machine moves against the cooling medium)
9	Other methods	Circulation of the cooling medium is achieved with other methods, apart from those mentioned above. These must be analytically described.

Cooling Medium	
Characteristic letter	Coolant Type
A	Air
F	Freon
H	Hydrogen
N	Nitrogen
C	Carbon Dioxide

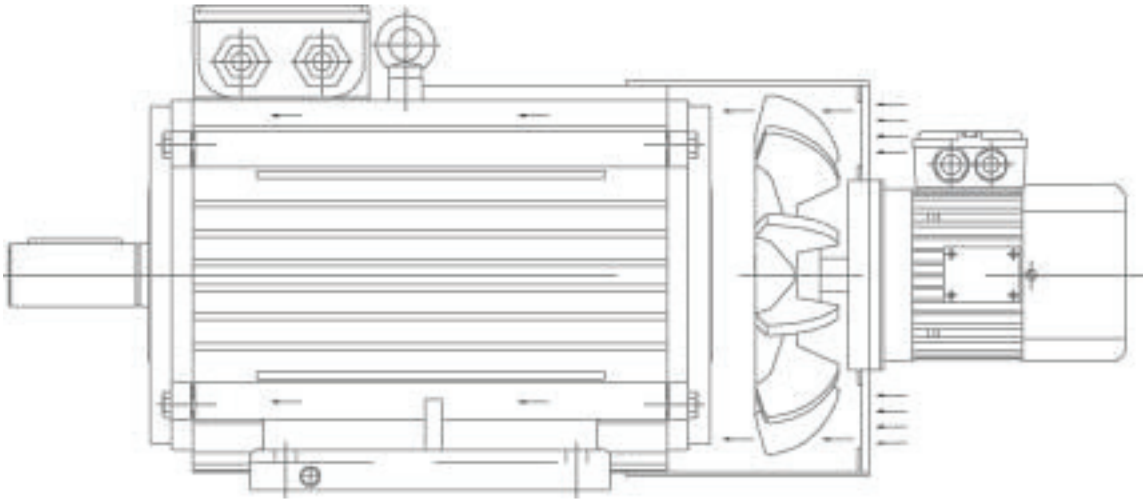
W	Water
U	Oil
S	Any other liquid (must be specially defined)
Y	The cooling medium has not been selected yet (has been temporarily used)

Three characteristic cooling methods are described below:

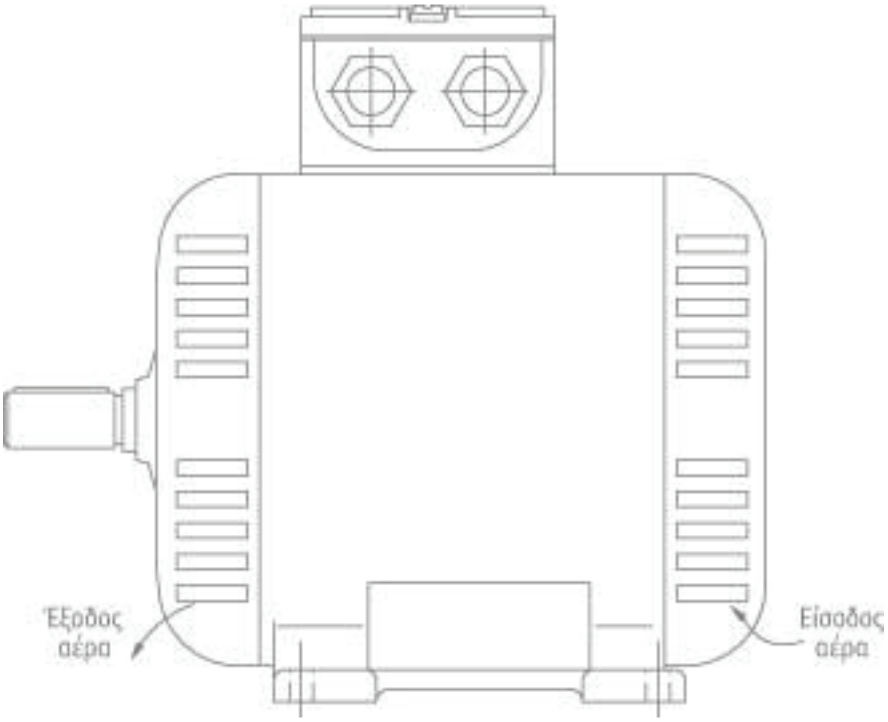


Είσοδος αέρα = air inflow

IC 411
Totally enclosed motor
Finned housing
External fan mounted on the shaft



IC 416
Totally enclosed motor
Finned housing
External fan mounted on the motor



Έξοδος αέρα = air outflow | Είσοδος αέρα = air inflow

IC 01
Motor provided with IP23 protection
Internal fan

INSULATION CLASSES

Allowable temperature limits
According to IEC 34-1, paragraph 16, the following allowable highest temperature limits are specified for each insulation class:

Insulation Class	Maximum allowable temperature rise (°C)	Final temperature in an ambient of 40°C
A	60	100
E	70	110
B	80	120
F	100	140
H	125	165

According to IEC 34-1, table I (see Chapter: "Tests"), the measurement of temperature rise is carried out with the method of Ohmic Resistance Measurement.

If a motor operates at ambient temperatures lower than 30°C, the allowable temperature rise is increased by 10°C (IEC 34-1, paragraph 16.3.1).

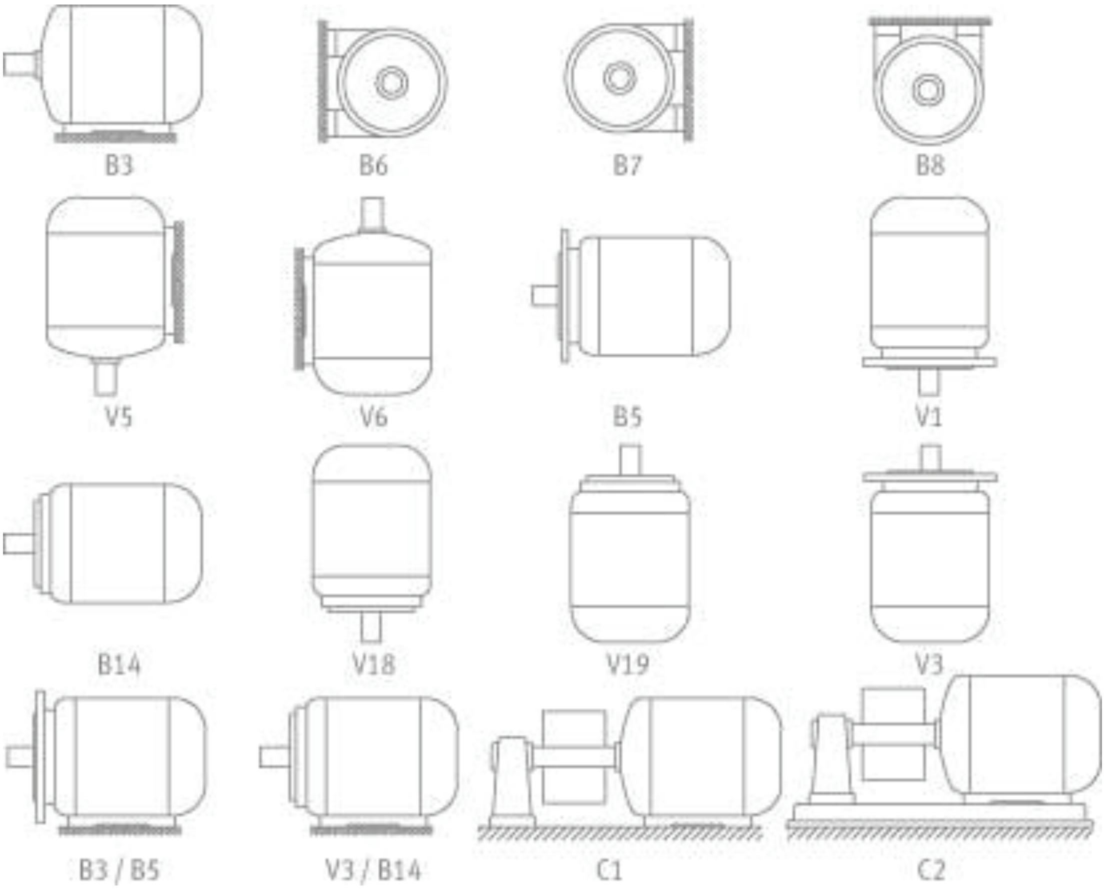
If a motor operates at ambient temperatures between 30°C and 40°C, the allowable temperature rise inside the motor is added to the ambient temperature (IEC 34-1, paragraph 16.3.2).

If a motor operates at ambient temperatures between 40°C and 60°C, the allowable temperature rise inside the motor is decreased by the ambient temperature (IEC 34-1, paragraph 16.3.3).

For ambient temperatures above 60°C there is no specification for maximum limits of temperature rise inside the motor according to IEC. Such a limit has to be agreed between manufacturer and customer (IEC 34-1, paragraph 16.3.4).

ELECTRIC MOTOR MOUNTING

The main mounting types of electric motors are presented in fig.7, below. The corresponding symbols comply with DIN 42950/1965.



The correspondence of the symbols provided in the previous page with the ones specified in IEC is shown in the following table:

DIN	IEC	IEC	DIN	IEC	IEC
42950	**Code II**	**Code I**	**42950**	**Code II**	**Code I**
B3	IM 1001	IM B3	V3	IM3031	IM V3
V5	IM 1011	IM V5	B14	IM3601	IM B14
V6	IM 1031	IM V6	V18	IM3611	IM V18
B6	IM 1051	IM B6	V19	IM3631	IM V19
B7	IM 1061	IM B7	B10	IM4001	IM B10
B8	IM 1071	IM B8	V10	IM4011	IM V10
B15	IM1201	IM B15	V14	IM4031	IM V14
B3/B5	IM 2001	IM B35	V18	IM4131	IM V18
B3/B14	IM 2101	IM B34	B9	IM9101	IM B9
B17	IM 2202		V8	IM9111	IMV8
B5	IM3001	IMB5	V9	IM9131	IMV9
V1	IM3011	IMV1			

TOLERANCES

According to IEC 34-1, paragraph 26, the following allowable tolerances are specified for the technical characteristics of electric motors:

	Characteristic size	**Tolerance**	
1	Efficiency factor		
	a. Motors with rating ≤ 50kW	-15% of (1-n)	
	b. Motors with rating > 50kW	-10% of (1-n)	
2	Power factor (cosϕ)	-(1/6) x (1-cosϕ)	Min 0.02 Max 0.07
3	Slip	±20%	
4	Starting current	+20%	
5	Starting torque	-15% to +25%	
6	Minimum starting torque (breakaway torque)	-15%	
7	Breakdown torque	-10%	
8	Moment of Inertia	±10%	

MOTOR SELECTION

Power, torque and speed of a motor operating at rated conditions must be defined as accurately as possible.
The main formulas for some common operation modes are stated below, from which the specific parameters are derived.

Rotating motion

In this case the value of power is derived from the following formula:

$$P = \frac{M \times n}{9.55 \times 1{,}000}$$

Where:

P : Motor output power (kW)
M : Required torque (Nm)
n : Speed of the driven load (rpm)

And, correspondingly:

$$M = \frac{9.55 \times P \times 1{,}000}{n}$$

In case when transmission belts or speed reducers are used, the torque must refer to the motor speed.

$$M_1 = M_2 \frac{n_2}{n_1}$$

Where:

M1 : Torque at the motor shaft (Nm)
M : Torque at the shaft of the driven load (Nm)
n1 : Motor Speed (rpm)
n2 : Speed rate of the driven load (rpm)

Vertical motion

When an object of mass (m) moves vertically upwards with a speed (v), the required power is:

$$P = \frac{m \times g \times v}{1{,}000}$$

Where:

P : Power (kW)
m : Mass (Kg)
g : Gravity (9.81 m/s2)
v : Vertical Speed (m/s)

Linear motion

The equivalent torque is derived from the following formula:

$$M = \frac{9.55 \times F \times v}{n}$$

Where:

M : Equivalent Torque (Nm)
F : Exerted Force (N)
v : Speed (m/s)
n : Rotation Rate (rpm)

Pumps

The required motor power is:

$$P = \frac{Q \times H \times \gamma}{270}$$

Where:

P : Power (HP)
Q : Capacity (m3/h)
H : Gauge Pressure (m)
γ : Specific Weight of the pumped liquid (kg/dm3)

Fans

The required motor power is:

$$P = \frac{V \times p}{102}$$

Where:

P : Power (kW)
p : Outlet Pressure (kgfm3)
H : Fan Capacity (m3/s)

Note: In all formulas mentioned above, the results must be divided by the efficiency factor of the corresponding machine, e.g. the required power for a pump with a 10m^3/h capacity, 50m pressure gauge and 61% efficiency is:

$$P = \frac{10 \times 50}{270 \times 0.61} = 3HP$$

Load Torque

Apart from the power, the determination of the corresponding torque (in relation to the speed) during starting is also very important. In general, loads are classified in the following four categories according to the variation of power and torque in relation to the speed:

1. The torque remains practically constant, while the power is increasing proportionally to the speed. This holds for hoisting machinery, reciprocating pumps, constant-pressure compressors, blowers, belt conveyors, etc.
2. The torque is increasing proportionally to the speed, while the power is proportional to the square of the speed ratio.
3. The torque is increasing proportionally to the square of the speed ratio, while the power is proportional to the cubic of the speed ratio. This holds for centrifugal pumps, fans, etc. Thus, e.g. in a fan rotating at 1,000rpm, equipped with a 2HP motor, in order to increase the speed rate to 1,300rpm (i.e. to increase its air capacity) the required power is: $P = 2 \times \frac{1300^3}{1000^3} = 4.4HP$
4. The torque is inversely proportional to the speed, while the corresponding power remains constant. This holds for winding machines, etc.

Moment of Inertia

In order to determine the conditions of motor starting/braking, the moment of inertia of the driven load and the characteristics of coupling or pulley must also be known.

In case of complex assemblies forming a single body subject to torsion, the moment of inertia is usually determined with a deceleration test.
In simple cases, the moment of inertia is determined through the weight G (or with calculation by measuring the corresponding dimensions and taking into account the specific weight) and the equivalent diameter (D), which is derived from the geometric one (d).

For a shaft of diameter (d), the equivalent diameter is derived from the following formula:

$$D = \frac{d}{\sqrt{2}}$$

In this case, the resulting moment of inertia is:

$$J = \frac{m \times d^2}{8}$$

Where:

J : Moment of Inertia (kgm2)
d : Geometric Diameter (m)
m : Mass (kg)

For a cyclic ring with inner diameter d_1 and outer diameter d_2, the equivalent diameter is derived from the following formula:

$$D = \frac{\sqrt{d_1^2 + d_2^2}}{2}$$

In this case, the resulting moment of inertia is:

$$J = m\frac{d_1^2 + d_2^2}{8}$$

Where:

J : Moment of Inertia (kgm2)
d1,d2 : Geometric Diameters (m)
m : Mass (kg)

In the same way with torque, the moment of inertia is reduced to the motor speed. Thus we take:

$$J_{\varphi\kappa} = J_{\varphi}\frac{n_{\varphi}^2}{n_{\kappa}^2}$$

Where:

Jϕκ : Moment of Inertia of the driven load reduced to the motor speed
Jϕ : Moment of Inertia of the drivel load
nϕ : Speed Rate of the driven load
nκ : Motor Speed Rate

Thus, the total moment of inertia reduced to the motor shaft is:

ΣJ = Jm + Jϕκ

Where:

Jm : Motor Moment of Inertia

Finally, in case of linearly moving masses, the equivalent moment of inertia reduced to the motor shaft is derived from the following formula:

$$J = \frac{m}{39.48} \times \frac{(60 \times v)^2}{n^2}$$

Where:

J : Moment of Inertia of the driven load reduced to the motor shaft (kgm2)
m : Mass (kg)
v : Speed of the moving mass (m/s)
n : Motor speed rate (rpm)

MOTOR CLASSIFICATION DEPENDING ON THE STARTING TORQUE

According to IEC 34-12, low voltage (up to 690V), three-phase, single-speed, squirrel-cage motors, suitable for continuous operation (S1 mode), are classified in the following classes regarding their starting torque:

1. N class
This refers to standard dipole, 4-pole, 6-pole or 8-pole, 0.4-630kW, 50Hz or 60Hz motors, designed for direct starting.

2. NY class
This refers to similar motors as above, but designed for star-delta starting. During the star connection, the minimum values of starting & breakaway torque must equal to 25% of the values mentioned in table I.

3. H class
This refers to 4-pole, 6-pole or 8-pole, high-torque, 0.4-160kW, 60Hz motors, designed for direct starting.

4. HY class
This refers to motors similar to those of H class above, but designed for star-delta starting. During star starting, the minimum values of starting & breakaway torque must be equal to 25% of the values mentioned in table IV.

The classes mentioned above are not compulsory for the motor manufacturers; the selection of any class is a matter of agreement between manufacturer and customer.
For special requirements, motors of different specifications may be necessary.
The values of torque and apparent power mentioned in the tables below represent the limits specified according to IEC 34-12 without any tolerance. In the contrary, the values mentioned in the catalogues of various manufacturers meet the tolerances specified in IEC 34-1, as these are presented in chapter “Tolerances”.

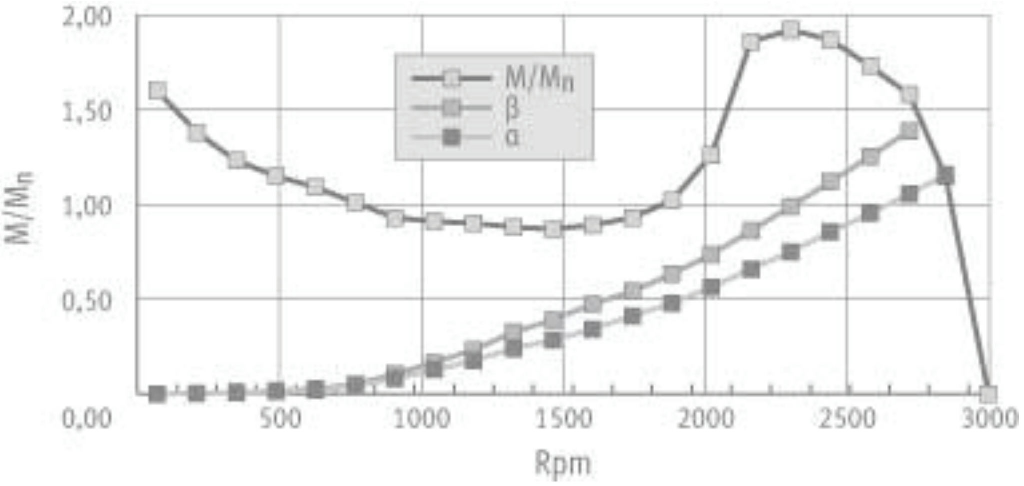
The minimum allowable values of the starting torque for motors belonging to the classes mentioned above are specified in IEC 34-12, and, especially, the following:

Ma : starting torque
Ms : minimum torque (breakaway torque)
Mk : breakdown torque

In particular, the following are specified:

1. **For N class**, the minimum allowable values at rated voltage & frequency are mentioned in the table I, below.

The specific values include no tolerances.
Of course, higher values are allowable.
In addition, it is specified that the torque at any speed between zero and the value corresponding to the breakdown torque must be at least 1.3 times the torque derived from a torque-speed curve that is directly proportional to the square of speed and becomes equal to the rated torque at rated speed.
The above term is cleared with the following example:
The torque-speed curve of a 250kW, 3,000rpm motor manufactured in our factory and the corresponding (a) & (b) curves are presented in the following diagram.



The curve (a) begins at 0 and ends to 1 at the rated speed, varying directly proportionally to the square of speed.
The values of curve (b) result by multiplying those of curve (a) by 1.3.
The above multiplication factor (1.3) has been chosen with respect to the fact that during the acceleration of the motor a voltage drop of approx. 10% is caused.
Thus, according to this specification, during the entire starting period the curve of starting torque must be located higher than curve (b) in the diagram.

The maximum apparent power at starting is also specified in IEC 34-12, i.e. with locked rotor. The ratio of the absorbed apparent power at starting (expressed in KVA) to the rated power that is expressed in kW is presented with S1 and it should not exceed the values mentioned in the table II, below.
The values of this table hold for all motors irrespective of the pole number.

Finally, according to IEC 34-12, paragraph 6, N-class motors must be able to perform two consecutive starts from the cold condition (i.e. with a pause between those two starts) and another one from the hot condition after a certain operation period at rated conditions.
The motor must meet the above requirements under the following conditions:

a) The resistance torque of the driven load is proportional to the square of speed.

b) The resistance torque of the driven load is equal to the rated torque of the motor at rated speed.
c) The moment of inertia of the driven load is equal to the values mentioned in the table III, below.

In any case, an additional starting is allowable only if the temperature inside the motor does not exceed the value of thermal balance when the motor operates at rated conditions. According to IEC 34-12 it is recommended to keep the starting rate as low as possible because it affects the life of the motor.

2. **For NY class**, the corresponding torque values have already been mentioned. Of course, the resistance torque of the driven load must be lower than the corresponding torque of the motor in star connection, in order to accelerate the system to the desired speed.
3. **For H class**, the minimum allowable values at rated voltage and frequency are mentioned in the table IV, below.

The specific values include no tolerances.
Of course, higher values are allowable.
The ratio of the absorbed apparent power during starting (expressed in KVA) to the rated one that is expressed in kW is presented with S1 and it should not exceed the values mentioned in the table II, below.
The values of this table hold for all motors irrespective of the pole number.
Finally, according to IEC 34-12 paragraph 10, H-class motors must be able to perform two consecutive starts from the cold condition (i.e. with a pause between those two starts) and another one from the hot condition after an operation period at rated conditions.
The motor must meet the above requirements on the following conditions:

a) The resistance torque of the driven load is constant, independent of the speed rate and equal to the rated one.
b) The moment of inertia of the specific load is equal to 50% of the values mentioned in the table III, below.

In any case, an additional starting is allowable only if the temperature inside the motor does not exceed the value of thermal balance when the motor operates under rated conditions. According to IEC 34-12 it is recommended to keep the starting rate as low as possible because it affects the life of the motor.

4. **For HY class**, the corresponding torque values have already been mentioned. Of course, the resistance torque of the driven load must be lower than the corresponding torque of the motor in star connection, in order to accelerate the system to the desired speed.

TABLE I
Minimum Values of Torque for N-class Motors

Power (kW)	Number of pole pairs											
	2			4			6			8		
	Ma	Ms	Mk	Ma	Ms	Mk	Ma	Ms	Mk	Ma	Ms	Mk
>0.4≤0.63	1.9	1.3	2.0	2.0	1.4	2.0	1.7	1.2	1.7	1.5	1.1	1.6
>0.63≤1.0	1.8	1.2	2.0	1.9	1.3	2.0	1.7	1.2	1.8	1.5	1.1	1.7
>1.0≤1.6	1.8	1.2	2.0	1.9	1.3	2.0	1.6	1.1	1.9	1.4	1.0	1.8
>1.6≤2.5	1.7	1.1	2.0	1.8	1.2	2.0	1.6	1.1	1.9	1.4	1.0	1.8
>2.5≤4.0	1.6	1.1	2.0	1.7	1.2	2.0	1.5	1.1	1.9	1.3	1.0	1.8
>4.0≤6.3	1.5	1.0	2.0	1.6	1.1	2.0	1.5	1.1	1.9	1.3	1.0	1.8
>6.3≤10	1.5	1.0	2.0	1.6	1.1	2.0	1.5	1.1	1.8	1.3	1.0	1.7
>10≤16	1.4	1.0	2.0	1.5	1.1	2.0	1.4	1.0	1.8	1.2	0.9	1.7
>16≤25	1.3	0.9	1.9	1.4	1.0	1.9	1.4	1.0	1.8	1.2	0.9	1.7
>25≤40	1.2	0.9	1.9	1.3	1.0	1.9	1.3	1.0	1.8	1.2	0.9	1.7
>40≤63	1.1	0.8	1.8	1.2	0.9	1.8	1.2	0.9	1.7	1.1	0.8	1.7
>63≤100	1.0	0.7	1.8	1.1	0.8	1.8	1.1	0.8	1.7	1.0	0.7	1.6
>100≤160	0.9	0.7	1.7	1.0	0.8	1.7	1.0	0.8	1.7	0.9	0.7	1.6
>160≤250	0.8	0.6	1.7	0.9	0.7	1.7	0.9	0.7	1.6	0.9	0.7	1.6
>250≤400	0.75	0.6	1.6	0.75	0.6	1.6	0.75	0.6	1.6	0.75	0.6	1.6
>400≤630	0.65	0.5	1.6	0.65	0.5	1.6	0.65	0.5	1.6	0.65	0.5	1.6

The relative torque values (in relation to the rated torque), i.e. Starting Torque (Ma), Minimum Torque (Ms) and Breakdown Torque (Mk), are mentioned in the above table.

TABLE II
Maximum Value of Apparent Starting Power

Power (kW)	**S1**
>0.4≤6.3	13
>6.3≤25	12
>25≤100	11
>100≤630	10

S1 is the ratio of the Apparent Starting Power (kVA) to the rated power (kW).

TABLE III
Moment of Inertia of the Driven Load

Power (kW)	2	4	6	8
	(kgm^2)	(kgm^2)	(kgm^2)	(kgm^2)
0.4	0.018	0.099	0.273	0.561
0.63	0.026	0.149	0.411	0.845
1.0	0.040	0.226	0.624	1.28
1.6	0.061	0.345	0.952	1.95

2.5	0.091	0.516	1.42	2.92
4.0	0.139	0.788	2.17	4.46
6.3	0.210	1.19	3.27	6.71
10	0.318	1.80	4.95	10.2
16	0.485	2.74	7.56	15.5
25	0.725	4.10	11.3	23.2
40	1.11	6.26	17.2	35.4
63	1.67	9.42	26.0	53.3
100	2.52	14.3	39.3	80.8
160	3.85	21.8	60.1	123
250	5.76	32.6	89.7	184
400	8.79	49.7	137	281
630	13.2	74.8	206	423

The values of the moment of inertia inn the above table are derived from the formula mr^2 or $md^2/4$, where:

m : **Mass (kg)**
r : **Equivalent Radius**
d : **Equivalent Diameter** (see chapter Motor selection, Moment of inertia)

For intermediate power values (i.e. ratings found between consecutive values in the above table), the moment of inertia of the driven load is derived from the following formula, which also has been applied for the values of the table above:

$$J = 0.04 \times P^{0.9} \times p^{2.5} \ (kgm^2)$$

Where:
m : **Mass (kg)**
P : **Rated Power (kW)**
p : **Number of Pole Pairs**

TABLE IV
Minimum Values of Torque for H-class Motors

Power (kW)	Number of pole pair								
	4			6			8		
	Ma	Ms	Mk	Ma	Ms	Mk	Ma	Ms	Mk
>0.4≤0.63	3.0	2.1	2.1	2.55	1.8	1.9	2.25	1.65	1.9
>0.63≤1.0	2.85	1.95	2.0	2.5	1.8	1.9	2.25	1.65	1.9
>1.0≤1.6	2.85	1.95	2.0	2.4	1.65	1.9	2.1	1.5	1.9
>1.6≤2.5	2.7	1.8	2.0	2.4	1.65	1.9	2.1	1.5	1.9
>2.5≤4.0	2.55	1.8	2.0	2.25	1.65	1.9	2.0	1.5	1.9
>4.0≤6.3	2.4	1.65	2.0	2.25	1.65	1.9	2.0	1.5	1.9

>6.3≤10	2.4	1.65	2.0	2.25	1.65	1.9	2.0	1.5	1.9
>10≤16	2.25	1.65	2.0	2.1	1.5	1.9	2.0	1.4	1.9
>16≤25	2.1	1.5	1.9	2.1	1.5	1.9	2.0	1.4	1.9
>25≤40	2.0	1.5	1.9	2.0	1.5	1.9	2.0	1.4	1.9
>40≤63	2.0	1.4	1.9	2.0	1.4	1.9	2.0	1.4	1.9
>63≤100	2.0	1.4	1.9	2.0	1.4	1.9	2.0	1.4	1.9
>100≤160	2.0	1.4	1.9	2.0	1.4	1.9	2.0	1.4	1.9

The values mentioned in the above table, i.e. Starting Torque (Ma), Minimum Torque (Ms) and Breakdown Torque (Mk), are the relative ones (in relation to the rated torque). According to IEC 34-12, H-class motors must meet the following:

a) The relative value of the starting torque (Ma) must be 1.5 times higher than the corresponding one of N-class motors, but, in any case, not lower than 2.
b) The relative value of the minimum torque (Ms) must be 1.5 times higher than the corresponding one of N-class motors, but, in any case, not lower than 1.4.
c) The relative value of the breakdown torque (Mk) must be equal to the corresponding one of N-class motors, but, in any case, not lower than 1.9 or the minimum (breakaway) torque.

STARTING METHODS OF THREE-PHASE MOTORS

There are various starting methods of asynchronous, squirrel-cage motors. The most important of them are the following:

a) Direct starting
b) Star-Delta starting
c) Starting by means of ohmic resistors in series connected with the stator
d) Starting by means of choke coils connected in series with the stator
e) Starting by means of an autotransformer
f) Starting by means of a soft starter

It must be noted, that both the torque and current of the motor remain constant, irrespective of the starting method.
The most common starting methods for small or medium size motors are the direct or star-delta starting.
If it is possible, direct starting is preferable for asynchronous, squirrel-cage motors. In case that for any reason the absorbed current must be kept low, star-delta starting is recommended. In this way, the starting current is 25-30% of the corresponding value during direct starting. Therefore, this method is applied in case of low requirements on starting torque. During the starting process, with the motor in star connection, the delivered torque must be greater than that of the driven load. The change from star to delta connection must take place just after the motor has been accelerated to the rated speed.

In order to decide about the most indicated starting method, the following must be taken into account:

1) Power and speed of the driven load
2) Required motor speed
3) Torque of the driven load as a function of speed
4) Total moment of inertia
5) Number of starts per unit of time
6) Operation factor

For two-speed motors the above information must be taken into account for both speed rates.

The soft starter is an electronic device that is used to control the starting process of the motor. Depending on the torque of the driven load we can adjust the voltage in order to achieve a perfect starting of the motor, in respect of both the torque and current. Another also important advantage of the soft starter is the avoidance of high currents, as it happens during start-delta starting and, especially, during the switching from star to delta connection.

In any case, during this process a peak current is caused that sometimes activates the overcurrent magnetic element of the switch, resulting to a motor stop. During starting with a soft starter these current peaks do not exist, since the motor directly starts at a reduced voltage that is gradually increasing.

STARTING TIME

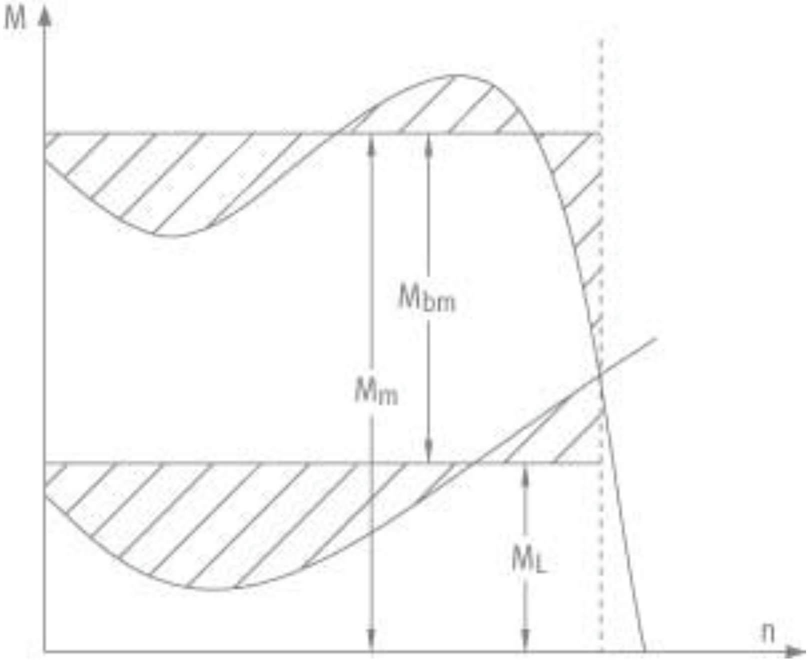
The starting time of a motor is derived from the following formula:

$$t_a = \frac{n \times \Sigma J}{9.55 \times Mb_m}$$

Where:

ta : **Starting Period (sec)**
ΣJ : **Total Moment of Inertia of the rotating masses (kgm^2)**
n : **Speed (rpm)**
Mbm : **Average Acceleration Torque (Nm)**

The average acceleration torque can be derived by a high degree of approximation as shown in fig.8, below.
The total moment of inertia of the rotating masses comprises the moment of inertia of the rotor, the driven load and the coupling or pulley, respectively.
In case of a starting period longer than 10sec, we have to examine if it is allowable, with respect to the temperature inside the motor. Special calculation and design is required for motors with high starting rates occurring within short time intervals.



In case when due to the moment of inertia of the driven load or its torque a motor cannot start properly, a larger motor must be selected even if it would not fully deliver its rated power. Alternatively, another motor type (e.g. slip-ring motor) or a centrifugal coupling may be installed.

It is indicatively noted that the starting period of 4-pole motors at no-load takes from 0.03 to 1.5sec, depending on the motor size. However, this time (i.e. the no-load starting period) does not constitute any criterion of thermal loading of the motor during its starting at any particular load.

Heat losses during starting

With the exception of the no-load starting, the heat losses of a motor are higher during star-delta starting (Y/Δ). This happens because during Y/Δ starting the starting torque delivered by the motor is lower, resulting to a longer starting period.

During no-load starting, the rotor losses are practically equal to the acceleration work. This is equal to the kinetic energy of the rotor at full speed, which is derived from the following formula:

$$W = J \times \frac{\omega^2}{2} = J \times \frac{1}{2} \times \left(\frac{2 \times \pi \times n}{60} \right)^2$$

Where:

W : **Kinetic Energy (J)**
J : **Moment of Inertia (kgm^2)**
ω : **Angular Speed (rad/sec)**
n : **Motor Speed (rpm)**

From the above formula it is concluded that at no-load starting the rotor losses depend on the rotor moment of inertia and the square of its synchronous speed. These are independent from the starting mode, acceleration torque or rotor design (e.g. single or double squirrel cage).

In the contrary, during starting at a certain load the starting torque plays a significant role. Subsequently, this is substantially affected by the rotor type.

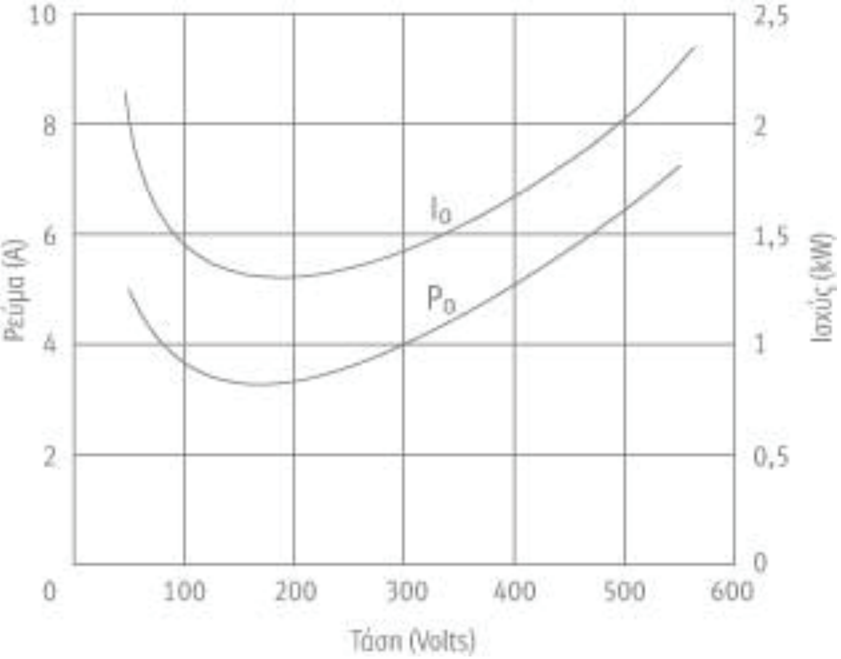
ELECTRIC MOTOR TESTS

1. No-load test

One of the most indicated tests is the no-load one with the following results:

- Iron losses
- Mechanical losses (friction & fan losses)
- No-load current
- No-load cosφ

In addition, any possible mechanical defects, noise, false connection or other improper conditions should be detected during this test.
The test is performed connecting the motor to a grid at rated frequency and adjustable voltage. Voltage, current and power measurement instruments also are connected to the circuit.



Ρεύμα = Current, Ισχύς = Power, Τάση = Voltage

The motor is left to operate for a long time in order to check for possible strain or fatigue on the bearings. Then, we increase the voltage by 15-20% above the rated value and we measure the absorbed current and power.

We start taking the specific measurements from the high values of voltage.
The characteristic curves of the no-load motor testing are presented in fig. 9.

At rated voltage, the corresponding no-load current (I_o/I_n) is strongly variable depending on motor size and rpm. Below you may find a table with the corresponding no-load current of various types of 3-phase motors. The values in the table are indicative.

Corresponding no-load current

Power KW	Number of poles			
	2	4	6	8
0.1-1	75-60	85-65	80-75	75-70
1-10	50-35	65-45	75-60	65-55
10-100	35-20	40-25	50-25	50-30

The numbers represent the specific percentage (%) of the rated current.
During the no-load operation, the power factor (cosφ) remains too low. This is explained by the fact that both current components, I_{or} (the reactive component for magnetization) and I_{oa} (the active component for the losses), significantly differ from each other in magnitude. Normally, I_{or} is 5-10 times larger than I_{oa}, since I_{oa} covers only the iron and mechanical losses.
The decrease of voltage results to a corresponding decrease of the absorbed power and current due to simultaneous decrease of the magnetic flux, which is proportional to the voltage.
For voltage values near the rated one, the power vs. voltage curve is approximately parabolic, since the iron losses are proportional to the square of the magnetic flux, and, consequently, to the voltage.
The decrease of voltage results to an increase of the power factor (cosφ), since the reactive component (I_{or}) increases faster than I_{oa}. Really, this is possible to increase in order to cover the mechanical losses, which practically remain constant and require a larger current component to compensate them in lower voltages.
If we decrease the voltage e.g. to the 25% of the rated value, both the no-load current and the iron loss are low. At the same time, the motor speed (rpm) has slightly fallen but both friction and ventilation still remain at the same level, requiring a significant I_{oa} current to compensate the corresponding rotor current that initially is low but keeps increasing over time and takes effect with the already decreased magnetic flux maintaining the motor in rotation. In this way, the increase of cosφ is explained when we supply the motor with decreased voltage.
Some no-load measurements performed on a motor of 315KW, 1500rpm, B3, and IP54 that was manufactured in our factory are stated below.
Initially, we measure the ohmic resistance at ambient temperature (19°C) and we find it equal to Ro = 0,00776Ω.
Then, we supply the motor with various voltages and we take the following readings:

U_o	$I1_0$	$I2_0$	$I3_0$	I_o	P_o	Pcu_o	P_o-Pcu_o
V	A	A	A	A	W	W	W
399	239.3	240.5	239.3	239.7	9375	446.7	8.928
380	208	209	208	208.3	8475	339	8.136

361.5	171.7	172.3	171.7	171.9	7650	230.6	7.419
330.9	141.8	143.5	141.8	142.4	7200	158.2	7.042
301.5	115.6	116	115.6	115.7	6300	104.9	6.195
271.5	100.1	100.4	100.1	100.2	6000	78.6	5.921
241	85.9	86	85.9	85.9	5450	57.7	5.392
211.2	74.5	74.6	74.5	74.5	5138	43.4	5.095
189.7	66.6	66.8	66.6	66.7	4950	34.7	4.915
170.5	60	60.3	60	60.1	4750	28.2	4.722
148.6	53.2	53.4	53.2	53.3	4550	22.2	4.528
127	47.4	47.2	47.4	47.3	4375	17.5	4.358

Where:

U_o = supplied voltage

$I1_o$, $I2_o$, $I3_o$ = absorbed current per phase

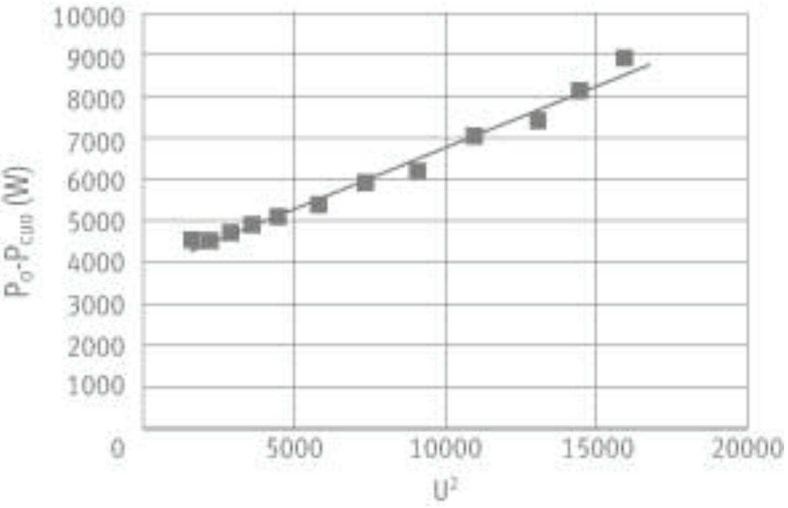
I_o = no-load absorbed current, i.e. the mean average of $I1_o$, $I2_o$, $I3_o$

P_o = absorbed power, i.e. the total losses

Pcu_o = ohmic losses, i.e. $3RI_\phi^2$ and, due to Δ configuration, $I_\phi = \sqrt{3}\, I_o$, thus $Pcu_o = RI^2$.

$P_o - Pcu_o$ = this gives the iron and mechanical losses

By marking various points corresponding to the values of P_o–Pcu_o and U^2 a curve is derived, which resembles a straight line and is presented in fig.10 below.



By extending this line in the diagram up to the point this intersects the $P_o - Pcu_o$ axis (i.e. for $U_o = 0$), we find the mechanical losses, since for $U_o = 0$ there are no iron losses. In this test we take P_{m+v} = 3,838W.

At the rated voltage the total losses are 8,475W and the ohmic ones are 339W. Consequently, the iron losses at the rated voltage become: $P_{fe} = P_o - (Pcu_o + P_{m+v})$ = 8,475 – (339 + 3,838) = 4,298W.

2. Short-circuit test

This test is performed by supplying voltage to the stator that is increasing under rated frequency, while keeping the stator immobilized and measuring both the absorbed current and power.

Possible mechanical defects cannot be noticed during this test, since its main purpose is to identify the following characteristics:

- Starting current
- Short-circuit losses
- Current balance control

The position where the rotor has been immobilized may affect the current. Therefore, we have to change this position in order to take an average value of the absorbed current.
The applied voltage is kept low to avoid high currents.
The absorbed power at short circuit depends exclusively on the ohmic losses I^2 R (or Joule losses). This is explained by the fact that the magnetic flux during the short circuit is decreasing, resulting to a corresponding decrease in the iron losses, while at the same time there are no mechanical losses. Consequently, the power vs. voltage curve becomes parabolic.

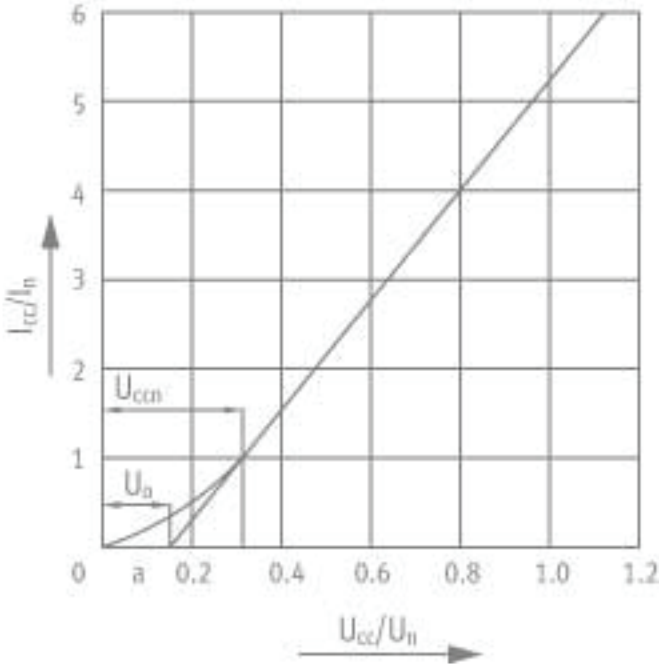
Determination of the starting current

If we consider the short-circuit parameters of an asynchronous motor constant during the starting process, the short-circuit current vs. voltage curve will become a straight line. In this case, the following can be derived with sufficient proximity:

$I_{ccn} = I_{cc} \times U_n / U_{cc}$

and $P_{ccn} = P_{cc} U_n^2 / U_{cc}^2$

Where:
I_{ccn} = short-circuit (starting) current at rated voltage
I_{cc} = short-circuit current at test voltage
U_n = rated voltage
U_{cc} = test voltage
P_{ccn} = short-circuit power at rated voltage
P_{cc} = short-circuit power at test voltage



But in practice, the short-circuit current vs. voltage curve is not a straight line. The deviation is evident when $I_{cc} < I_n$ but at higher voltage values, where $I_{cc} > I_n$, virtually, the specific curve becomes a straight line. Therefore, the most accurate method to determine the corresponding current is stated below:
The motor is tested at short-circuit voltages resulting to values of short-circuit current (I_{cc}) between I_n and 2.5 x I_n. Within this section, the curve can be considered a straight line. By extending this line up to the point where $U_{cc} = U_n$, we find the value of I_{ccn}.

The same result can also be derived with a calculation, by extending the straight section of the curve up to the point it intersects with the U-axis at the point (a). The corresponding voltage is (U_o).Thus, we take:

$$I_{ccn} = I_{cc} \times \frac{U_n - U_0}{U_{cc} - U_0}$$

and

$$P_{ccn} = P_{cc} \times \frac{(U_n - U_0)^2}{(U_{cc} - U_0)^2}$$

where:
U_{cc} = Short-circuit voltage at a point where the specific curve is considered a straight line, i.e. where $I_{cc} > 2 \times I_n$.

Regarding current balance, a variation of ≤5% is acceptable.
Knowing the values of both short-circuit current and the corresponding power, it is easy to calculate the corresponding cosφ.

3. Determination of the Motor Efficiency

The calculation of the motor efficiency is based on the determination of the total losses. The motor is coupled with a brake and is supplied with rated voltage & frequency. During the test, we measure the voltage, current, absorbed power and speed (rpm) of the motor.
First, the ohmic resistance and the no-load characteristics must be measured.
According to IEC 34-2, paragraph 5, during the determination of the motor efficiency, the ohmic resistance of the motor winding must be measured at 75°C for motors of A, E or B insulation class and at 115°C for motors of F or H insulation class. Thus, if the ohmic resistance of an F-class motor in the cold condition (e.g. at 19°C) is 0.007338Ω, a winding temperature of 115°C must be taken into account, i.e. R=0.010112Ω.
The measurements to determine the efficiency of the 315KW, 1500rpm motor mentioned above that was manufactured in our factory are stated below:

U	V	380	380	380	380	380
I_1	A	830	705	594	460	320
I_2	A	832	707	594	460	321
I_3	A	833	706	595	461	321
I	A	832	706	594	460	321
Pα	W	467400	396000	332700	249300	153000
PJst	W	6994.1	5040.1	3571.8	2142.8	1038.7
Pfe	W	4298	4298	4298	4298	4298
Total Pst	W	11292	9338	7870	6441	5337
Pem	W	456108	386662	324830	242859	147663
s	%	2.2	1.871	1.471	1.2	0.73
PJrot	W	10035.4	7234.1	4776.9	2913.7	1077.8
Ps	W	2337	1980	1663.5	1246.5	765
Pm+v	W	3838.1	3838.1	3838.1	3838.1	3838.1
Total P	W	27503	22390	18148	14439	11018
Pm	W	439898	373610	314552	234861	141983
n	%	94.12%	94.35%	94.55%	94.21%	92.80%
cosϕ		0.85	0.85	0.85	0.82	0.73
M	Nm	2869.6	2423.9	2032.4	1513.4	910.6

Where:
U = supplied voltage (in case of acceptance test, this must be the rated one)
I_1, I_2, I_3 = absorbed current in each phase
I = absorbed current, i.e. the mean average of I_1, I_2, I_3
Pa = absorbed power
PJst = Joule losses of the stator, i.e. R I^2
Pfe = iron losses (already determined during the no-load test)
Total Pst = total losses of the stator (i.e. PJst + Pfe)
Pem = power transferred to the rotor (i.e. Pa – Tot.Pst)
s = motor slip
PJrot = Joule losses of the rotor (i.e. Pem x s)
Ps = additional losses (i.e. 0.005 Pa)
Pm+v = friction & ventilation losses (already determined during the no-load test)

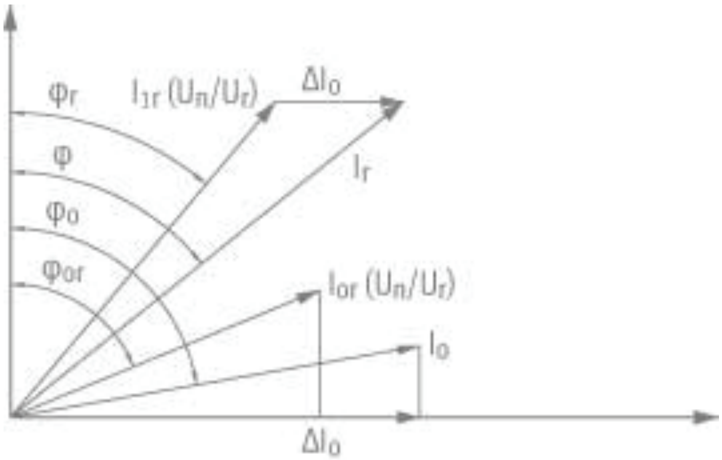
Tot.P = total losses (i.e. PJst + Pfe + PJrot + Ps + Pm+v)
Pm = rotor output power (i.e. Pa – Tot.P)
n = motor efficiency, i.e. Pm / Pa)
cosϕ = power factor, i.e. Pa / ($\sqrt{3}$ UI)
M = torque (i.e. 9.55 Pm / v), where v is the rotor speed in rpm

Determination of efficiency with a test at reduced voltage

According to IEC 34-2, paragraph 9.1.2.3, we can determine the motor efficiency by testing it at a reduced voltage.

When we reduce the supplied voltage, keeping at the same time the speed constant, the absorbed current is decreasing almost proportionally to the voltage, while the absorbed power is decreasing almost proportionally to the square of the voltage. Thus, when the voltage is reduced to the half of its rated value, the corresponding current will be approx. the half of its rated value and the power will be approx. equal to ¼ of its rated value, respectively.

Initially, we perform a no-load test of the motor at rated voltage to obtain the value of Io. Then, we test the motor at a reduced voltage Ur and we find the no-load current Ior.



Then, we supply the motor with this reduced voltage (Ur) and we measure the absorbed power (P_{1r}), the absorbed current (I_{1r}) and the slip (s).

The vector of current I_1 at a certain load and rated voltage is derived from fig.12 in the following way:

We add the vector ΔI_0 (derived from the following formula) to the product of I_{1r} multiplied by (Un/Ur).

$$\Delta I_0 = I_0 \times \sin\varphi - I_{0r} \times \frac{U_n}{U_r} \times \sin\varphi_{0r}$$

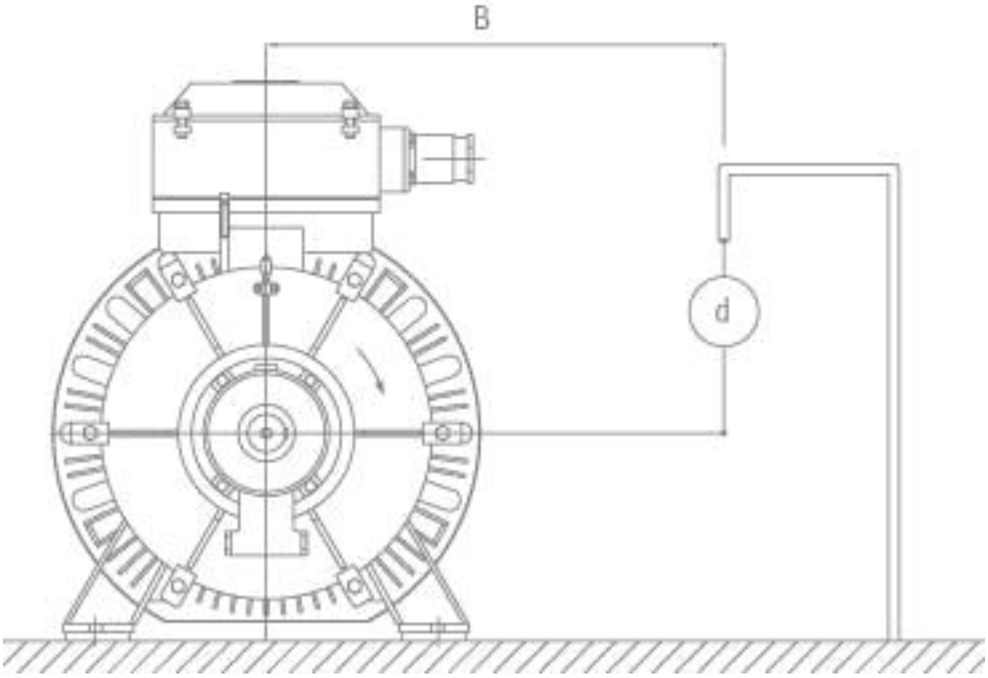
The resulting vector represents the absorbed current at rated voltage (Un), when the absorbed power is:

$$P_1 = P_{1r} \times \left(\frac{U_n}{U_r} \right)^2$$

Thus, by knowing the absorbed current (I_1), the absorbed power (P_1) and the slip (s) that is measured at a reduced voltage Ur, we can calculate the losses and efficiency.

4. Starting torque test

This test is performed using an arm, the one end of which is fixed on the motor shaft and at the other end a dynamometer is mounted as shown in fig.13, below.



We supply the motor with a reduced voltage Ur and we take a reading T on the dynamometer. The starting torque is equal to:

$$\mathrm{M}_{\alpha} = \mathrm{B} \times \mathrm{T} \times \frac{U_n^2}{U_r^2}$$

Where:

Ma = **Starting Torque (kgm^2)**
Un = **Rated Voltage**
Ur = **Test Voltage**
B = **Lever length (m)**
T = **Dynamometer Indication (kg)**

The starting torque can also be calculated through the short-circuit test. In fact, the absorbed power & current are determined in this test and the ohmic resistance of the stator is measured. Since it is known that:

$$\frac{P_{tot}}{P_{jrot}} = \frac{1-s}{s}$$

And:

$$M_{tot} = \frac{P_{tot} \times p}{2 \times \pi \times f \times (1-s)}$$

It is concluded that:

$$M_{tot} = \frac{P_{Jrot} \times p}{2 \times \pi \times f \times s}$$

During the starting process s=1, thus:

$$M_{a} = \frac{P_{Jrot} \times p}{2 \times \pi \times f}$$

Where:

Ma = Starting Torque (kgm^2)
p = Number of Pole Pairs
P_{Jrot} = Ohmic Losses of the rotor at starting
f = Current Frequency (Hz)

During starting, since there are no mechanical losses and the iron losses are negligible the whole absorbed power is converted to omhic losses in both the stator and rotor. Thus, the short-circuit power is equal to:

$$P_{ccn} = P_{st} + P_{Jrot}$$

Where:

P_{ccn} = Short-circuit Power
P_{st} = Ohmic Losses of the stator at starting
P_{Jrot} = Ohmic Losses of the rotor at starting

Since we know the starting current and the ohmic resistance, it is easy to calculate the ohmic losses of the stator at starting.

It is noted that the short-circuit test must be performed very quickly to avoid extended motor overloading. In addition, when the motor is connected in delta configuration, upon completion of the short-circuit test we measure the ohmic resistance between two terminals. The resulting value is:

Rcc ≈ Rϕ / 1.5

The results of the short-circuit test for a 4-pole, 150HP, 50Hz, 380V, motor manufactured in our factory are stated below. During the specific test the motor was connected in delta configuration.

U_{cc}	$I1_{cc}$	$I2_{cc}$	$I3_{cc}$	I_{cc}	P_{cc}
273.0	824.0	838.0	829.2	830.5	112.500
262.8	773.8	784.4	780.0	779.4	102.500
256.4	743.1	750.6	748.1	747.3	93.500
250.8	713.1	725.0	718.8	719.2	88.750
232.4	637.5	643.8	640.0	640.4	68.750
216.0	571.9	581.3	580.0	577.7	56.250
208.4	528.1	537.5	537.5	534.4	49.500
131.4	236.9	243.8	241.2	240.6	10.250
126.3	218.8	225.0	223.4	222.4	9.087
120.8	200.0	206.3	204.7	203.6	7.500
116.3	184.4	190.0	187.5	187.5	6.750

Where:

Ucc = Short-circuit test voltage (V)
I_{1cc}, I_{2cc}, I_{3cc} = Short-circuit (starting) current per phase at test voltage (A)
Icc = Short-circuit (starting) current per phase at test voltage (A), i.e. the mean average of I_{1cc}, I_{2cc}, I_{3cc}
Pcc = Short-circuit power at test voltage (W)

The resistance is measured equal to Rcc = 0.03620 Ω.

Drawing the I_{cc}-U_{cc} curve, we find that:

Uo = 107.48V

Thus:

$$I_{ccn} = 830.5 \times \frac{380 - 107.48}{273 - 107.48} = 1367\text{A}$$

And the corresponding starting current is:

$$\frac{I_{ccn}}{I_n} = \frac{1367}{205} = 6.6$$

The short-circuit power is:

$$P_{ccn} = 112500 \times \frac{(380-107.48)^2}{(273-107.48)^2} = 305164W$$

And the power factor at short-circuit (starting) is:

$$\cos\phi_{ccn} = \frac{305164}{\sqrt{3}\times 380 \times 1367} = 0.33$$

Stator ohmic losses at starting:

$$P_{st} = 1.5 \times 0.03620 \times 1367^2 = 101470W$$

The ohmic losses of the rotor during starting will be equal to:

$$P_{Jrot} = 305164 - 101470 = 203694W$$

Thus, the starting torque of the motor is:

$$Ma = \frac{2\times 203694}{314} = 1297\,Nm$$

And the corresponding starting torque is:

$$\frac{Ma}{Mn} = \frac{1297}{707} = 1.9$$

5. Torque test

This test is used to draw the torque-speed curve and, particularly, from the starting point up to the synchronous speed (the starting torque is determined through the test described in paragraph 4, above).

The test is performed by overloading the motor through a proper brake, in such a way that it can rotate at various speed rates from 0rpm up to the rated one.

The motor is usually supplied with a reduced voltage (to avoid high currents) at rated frequency.

The power that is available at the rotor shaft, the supplied voltage and the absorbed current (I) are measured at each speed rate.

The torque test results to the following characteristics:

- Torque-speed curve
- Maximum torque (breakdown torque) and
- Minimum (breakaway) torque

In the common case when the test is performed at a reduced voltage, the torque at rated voltage is derived by a satisfactory degree of approximation from the following formula:

$$M_1 = M_2 \times \left(\frac{U_1}{U_2} \right)^2$$

Where:

M_1 = Torque at rated voltage
U_1 = Rated voltage
M_2 = Torque at the test voltage
U_2 = Test voltage

However, the above formula does not hold for very low speed rates (<200rpm). It is proved that the best approximate value is derived from the following formula:

$$M_1 = M_2 \times \left(\frac{I_1}{I_2} \right)^2$$

Where:

M_1 = Torque at rated voltage
I_1 = Motor starting current at rated voltage
M_2 = Torque at the test voltage
I_2 = Absorbed current at the test voltage

Motor testing arrangement

This is a system suitable for testing ac motors, designed and developed by our company, which is consisted of the following main components:

1. Electric panel for the motors to be tested
2. DC machine for motor braking
3. Electric panel for power supply & control of the dc machine
4. Three-phase power analyzer to measure various electrical parameters
5. Computer for braking control and collection/processing of measurement readings
6. Special bench for mounting the motors to be tested

Electric panel for motor starting/testing

The panel is equipped with a 400-kVA autotransformer with multiple tappings. Thus, the motor can be supplied with 80V up to 430V, gradually increasing in steps, by means of power relays. The no-load test is also performed with this panel.

Direct current machine

A dc machine has been chosen as a brake (loading system), supplying the proper current at the required power. The dc machine that is coupled to the motor to be tested through an elastic coupling is equipped with an independent excitation arrangement for more accurate and simpler control, and a separate cooling arrangement to allow rated operation at very low speed rates for a long time. When we load an alternating current motor, the dc machine acts as a generator, thus, the generated electrical energy is converted to mechanical (load on motor), and returns to the power supply network as electrical through a four quadrant DC converter.

Electric panel of the direct current machine

This is equipped with a high-tech electronic power controller. The power return from the machine to the network is controlled with this controller, every time achieving the desired braking ratio of the motor under testing.
The controller is also equipped with an embedded, closed speed loop. In this way, it is possible to record the behavior of the tested motor at various speed rates. This is necessary in order to determine the torque-speed curve of the motor.
Finally, the controller provides information about the torque at the shaft of the dc machine. This is calculated by the microprocessor controller after we input the technical characteristics of the machine we use. This is very important, because otherwise we should need torque sensors to measure the torque, which are sensitive and too expensive.

Three-phase power analyzer

All data of the tested motor (voltage, current, absorbed power and power factor) are recorded in this unit. The power analyzer is provided with an LC display where the results are presented and a printer as well. Finally, it is provided with an RS232 port for connection with a computer to store the specific data for further processing. The three-phase power analyzer is installed in the electric panel of the motor to be tested.

Computer

With the computer we have access to the dc machine to set the motor speed. The computer is necessary because it performs a quick scanning of the entire motor speed range from zero to the rated speed, in order to draw the torque-speed curve. Most of the points on this curve constitute not allowable motor operation points. In case of extended operation at these points the motor would be damaged. Therefore, the torque test must be performed as fast as possible.
Finally, the computer is used to process the measurement data, to draw the necessary graphs and to store the corresponding results.

Motor mounting bench

We have developed a special mounting bench where the motor to be tested can be easily mounted irrespective of its size. This is achieved by means of upward/downward adjustment of the bench in order to align the motor shaft with that of the dc machine for any motor size. The motor is fixed on the bench with proper clamps.

With this system we can test motors at full load, determining their efficiency.

Moreover, by locking the rotor we can measure the starting torque as well.

A general layout of the ac motor testing arrangement with all the components described above is presented below.

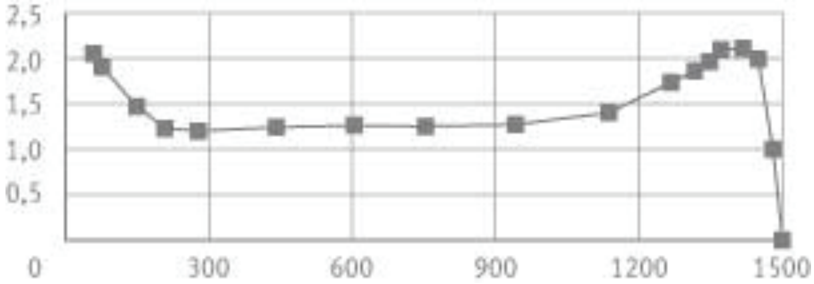
ΔΙΚΤΥΟ	*Power Network*
Μετατροπέας AC/DC	*AC/DC Converter*
Ηλεκτρική μηχανή ΣΡ	*DC Machine*
Μηχανικός Σύνδεσμος (σταυρός)	*Mechanical Coupling (cross coupler)*
Μετρούμενη Ηλ. Μηχανή	*Tested Electric Motor*
Μετατροπέας AC/AC	*AC/AC Converter*
ΔΙΚΤΥΟ	*Power Network*
Διάταξη Ελέγχου & Μετρήσεων	*Control/Measurement Arrangement*

The readings of the torque test and the resulting torque-speed curve of a 132KW, 1,500rpm, 380V motor manufactured in our factory are presented in the next table.

The specific test has been performed at 222V. This value has been reduced to the rated one of 380V using the formulas mentioned above.

I	n	M222V	M380V	M/Mn
-	0	-	-	1.91
772	59	350	1469	1.72
769	115	320	1354	1.59
763	150	281	1208	1.41
756	208	350	1025	1.20
751	278	365	1069	1.25
725	441	361	1058	1.24
706	604	367	1075	1.26
684	753	364	1067	1.25
656	942	369	1081	1.27
628	1137	409	1198	1.40
602	1234	504	1477	1.73
544	1316	543	1591	1.86

503	1359	600	1758	2.06
494	1371	609	1784	2.09
459	1387	616	1805	2.11
400	1417	580	1699	1.99
350	1450	437	1280	1.50
-	1480	-	-	1.00
-	1500	-	-	0.00



Torque-speed curve of a 132kW, 1500rpm motor

6. Megger Test

During this test the resistance between phases and between each particular phase and the earth is measured. The specific test is performed with a Megger instrument. 380/440V motors can be checked with a Megger instrument of 500V, while for 6KV motors an instrument of 1000V or 2500V is recommended.
In case of a motor provided with 6 terminals, the measurement is performed between phases and between each particular phase and the earth.
In case of a motor provided with 3 terminals (internal star of delta connection), the measurement is performed between the three connected phases and the earth.
Megger tests for motor acceptance are performed prior and directly after the tests of dielectric strength.
A measured value is accepted if

$$R = \frac{20 \times U}{1000 \pm 2P}$$

Where:

R = Resistance (MΩ)
P = Rated Power (KW)
U = Rated Voltage (V)

Megger test must undergo each new motor prior to be put in operation and, especially, motors not being used for a long time.

7. Measurement of the ohmic resistance

A Wheatstone bridge or a low-voltage dc power source may be used to measure the ohmic resistance by measuring the current. The resulting resistance is R=V/I. In case of a motor provided with 6 terminals (i.e. a motor suitable for Y/Δ starting) we measure the resistance of each particular phase. In case of a motor provided with 3 terminals (internal star connection) the resistance of 2 phases is measured. The readings should not differ more than 3% from each other.
The ohmic resistance is measured in the cold condition. The motor efficiency must be calculated with respect to the ohmic resistance and the maximum allowable operation temperature at full load.

Knowing the ohmic resistance in the cold condition, we can calculate the corresponding one in the hot condition from the following formula:

$$\frac{t_2 + 235}{t_1 + 235} = \frac{R_2}{R_1}$$

Where:

t_1 = measurement temperature in the cold condition (°C)
t_1 = maximum allowable temperature (°C)
R_1 = ohmic resistance in the cold condition
R_2 = ohmic resistance in the hot condition

With the above formula we can calculate the temperature increase in the winding.
Thus, we obtain:

$$\Delta_t = \frac{R_2 - R_1}{R_1} \times \left(235 + t_1\right) + (t_1 - t_a)$$

Where:

Δt = temperature increase
Ta = ambient temperature at the end of the test

8. Deceleration test

With this test, which is practically performed only on large motors, we measure the moment of inertia. In order to proceed to this test we have to know the mechanical losses of the motor, i.e. a no-load test should be preceded.

According to IEC 34-2 paragraph 15, the moment of inertia is equal to:

$$J = \frac{45600 \times Pt}{\delta \times n^2}$$

Where:

J = Moment of inertia (kgm^2)
P = Mechanical losses (KW)
n = Rated speed (rpm)
t = Deceleration time (sec) from a speed rate of [n x (1+δ)] to [n x (1-δ)]

9. Overspeed test

According to IEC 34-2 paragraph 21, this test is not necessary but can be performed on agreement between customer and seller when ordering a motor. According to IEC 34-1, table IX, a speed value of 1.2 times the synchronous one for two minutes is specified for the overspeed test of asynchronous induction motors.
The test is considered successful, if after its completion, there is no deformation or other anomalies observed that may obstruct the normal operation of the motor.

10. Vibration test

During this test, with the motor operating at rated voltage and frequency, the vibrations at 5 preset points along the XYZ axes are measured.
According to ISO 2954 and DIN 45 666 the resulting vibrations within a frequency range of 10 to 1000Hz must be measured with the installed instrument.
According to ISO 2372 and VDI 2056, the machines are classified into 6 categories depending on the importance of the vibration size for each one.
According to ISO 2372 and DIN 45 666, the following vibration limits are specified depending on the corresponding size:

Category	Speed (rpm)	Vibration limits (10-1000Hz) expressed in mm/s		
		Motor size		
		80÷132	160÷225	250÷315
N (normal)	600÷1800	1.8	2.8	4.5
	1800÷3600			
R (improved)	600÷1800	0.71	1.12	1.8
	1800÷3600	1.12	1.8	2.8
S (special)	600÷1800	0.45	0.71	1.12
	1800÷3600	0.71	1.12	1.8

11. Dielectric test

With the dielectric test or high-voltage test, the strength of the insulating material that separates the motor winding from the earth is determined. For motors provided with 6

terminals, the specific test is performed for each phase separately, while for motors with 3 terminals this is performed once for all phases together (in this case, the specific terminals are bridged only for the purposes of the measurement).
According to IEC 34-1 (chapter 6) the test voltage is derived from the following formula: Utest=1000Volt + 2Un, where: Un is the rated voltage of the motor that is applied for one minute.
The dielectric test is performed only once in the factory of manufacture and is not repeated. Upon customers' request this can be carried out by applying a voltage equal to 80% of the total test voltage (2Un+1000Volt) for one (1) minute.
In case of partial replacement of the motor winding, the voltage that is applied for the dielectric test should not exceed 75% of the total test voltage (2Un+1000Volt) for one (1) minute, after having undergone an oven treatment to achieve absolute drying of the entire winding.
The test voltage for motors undergoing an acceptance test after their maintenance is 1.5Un, with a minimum value of 1000Volt. The duration of the test remains 1min.

Measurement procedure

A. In case of a motor provided with 6 terminals, we disconnect the bridges of the star or delta configuration, if existing.
    - We mark both terminals of the phase to be measured.
    - The remaining 4 terminals and the body of the motor are connected with the grounding conductor of the power supply network.
    - We permanently ground the thermocouples Pt100 or Ptc (thermistors) during the corresponding tests.
    - We connect the one pole of the apparatus to a terminal of the phase to be tested and the other one on the motor body. The other terminal of the phase to be tested remains free.
    - We put the apparatus in operation increasing the applied voltage step by step. The initially applied voltage should not exceed 50% of the test voltage. We increase the voltage supply to the apparatus step by step up to the final value within a period not less than 10sec.
    - The test voltage must be applied for 1 min.
    - After 1 min we reduce the voltage step by step up to zero and, then, we switch off the apparatus.
    - We discharge the circuit (from possibly remaining static electricity) and we repeat the test for the other two phases, in succession, each time following the same procedure.

B. In case of a motor provided with 3 terminals (internal star or delta connection), we bridge those three terminals, then, we connect one pole of the apparatus to the bridge and the other one to the body of the motor and, finally, we follow the same procedure only once.

12. Test of temperature increase

The motor is coupled with a brake and operates at full load, rated voltage & frequency. After a long time (approximately 3-4 hours) we measure the ohmic resistance of each phase. Through the increase of its value we calculate the temperature increase of the winding with the following formula:

$$\Delta t = \frac{R_2 - R_1}{R_1} \times (235 + t_1) + (t_1 - t_a)$$

Where:

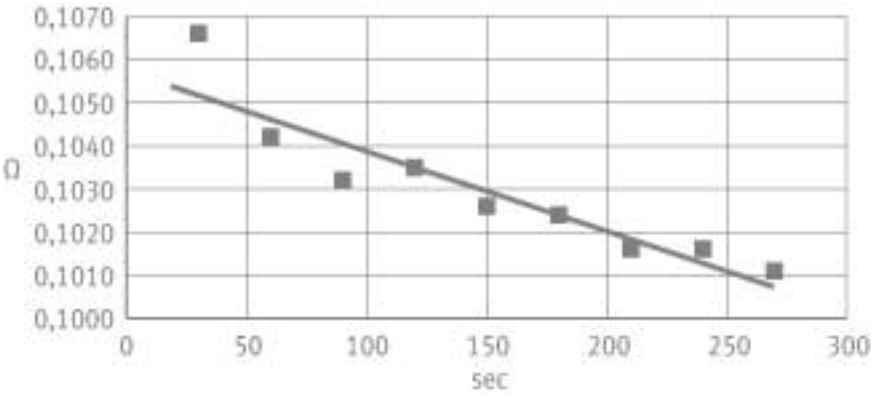
t_1 = Temperature in the cold condition (C)
R_1 = Ohmic Resistance in the cold condition
R_2 = Ohmic Resistance in the hot condition
Δt = Temperature Increase
ta = Ambient Temperature at the end of the test

More accurate results can be derived with the following method: Upon the end of the test we measure the ohmic resistance at regular time intervals (e.g. every 30 sec) and we draw the curve of its variation in relation to the time. Extending this curve up to t=0, we find the ohmic resistance just at the moment of pausing.

The results of the ohmic resistance measurement of a 55KW (=75HP), 1500rpm motor provided with F-class insulation are presented in the next table:

Time (sec)	Ohmic Resistance (Ω)
30	0.1066
60	0.1042
90	0.1032
120	0.1035
150	0.1026
180	0.1024
210	0.1016
240	0.1016
270	0.1011

Drawing the R-t curve and extending it up to t=0 we find R=0.1058Ω.



We already know that the ohmic resistance in the cold condition is 0.082Ω at an ambient temperature of 12°C and the ambient temperature at the end of the test is 14°C. Inserting these values at the formula mentioned above, we obtain:

$$\Delta t = \frac{0.1058-0.082}{0.082}\times\left(235+12\right)+\left(12-14\right)$$

And, finally:

Δt = 70°C

During this test, we measure the temperature at the bearings, finding a temperature increase of $\Delta\theta_\rho$.
We also measure the temperature of the housing at regular time intervals (e.g. every hour) at the worse point regarding ventilation, and we find a temperature increase of the motor housing equal to $\Delta\theta_\kappa$. With the results of this measurement we can calculate the Heating Time Constant (T) of the motor.
Considering the motor as a uniform body, the temperature increase at the motor housing is derived from the following formula:

$$\Delta\theta = \Delta\vartheta_{\max}\times\left(1-e^{-t/T}\right)+\Delta\theta_0\times e^{-t/T}$$

Where:

Δθ = Temperature Increase in the motor housing after an operation for a time period (t)
$\Delta\theta_{max}$ = Maximum Temperature Increase in the motor housing
t = Operation Time

$\Delta\theta_0$ = Temperature Increase in the motor housing prior to the beginning of the specific measurement
T = Heating Time Constant (=mc/Aλ)
m = Motor Mass
c = Average Specific Heat of the motor, considered as a uniform body
A = Cooled Surface
λ = Heat Transfer Coefficient

In case the temperature increase $\Delta\theta_0$ in the above formula becomes 0, i.e. if the motor starts from the cold condition, then we obtain:

$$\Delta\vartheta = \Delta\vartheta_{\max} \times \left(1 - e^{-t/T}\right)$$

According to the above formula, for a time period t = T, the temperature increase at the housing becomes $\Delta\theta = 0.633 \times \Delta\theta_{max}$, while for t = 3T this becomes $\Delta\theta = 0.95 \times \Delta\theta_{max}$.
The constant T mentioned above is calculated by measuring Δθ during two time intervals, e.g. within an hour from the beginning of the test and within two hours, respectively. After one hour and two hours of operation, the temperature increase ($\Delta\theta_\kappa$) at the housing of the above 55KW (= 75HP), 1500rpm motor was found 20°C and 26°C, respectively. Applying these values to the above formula, we obtain:

$$20 = \Delta\theta_{max} \times (1 - e^{-1/T}),$$

and:

$$26 = \Delta\theta_{max} \times (1 - e^{-2/T})$$

Thus:

$$\frac{26}{20} = \frac{\Delta\vartheta_{\max} \times \left(1 - e^{-2T}\right)}{\Delta\theta_{\max} \times \left(1 - e^{-1T}\right)}$$

And:

$$\frac{26}{20} = \frac{\left(1 + e^{-1/T}\right) \times \left(1 - e^{-1/T}\right)}{1 - e^{-1/T}}$$

And:

$$1.3 = 1 + e^{-1/T}$$

And

$$e^{-1/T} = 1.3 - 1 = 0.3$$

And

$$e^{1/T} = 1 / 0.3 = 3.33$$

And

$$\frac{1}{T} = 2.3 \times \log 3.33 = 2.3 \times 0.52 = 1.2$$

Thus:

T = 0.83 hours

or

T = 50 min

13. Noise Level Measurement

According to IEC 34-9, this test must be performed under the following conditions:

1. No-load motor operation at rated voltage & frequency
2. Horizontal motor mounting for B3 and vertical for V1 mode, respectively.
3. The voltage supply must meet the requirements of IEC 34-1 paragraph 12 (see: power supply from a power network). It is noted that any increase in the voltage (or current), any possible deformation of the waveform or asymmetry of the power network increase both the noise level and vibrations.

The acoustic parameters are determined through the following factors:

1. Acoustic Power
2. Acoustic Pressure

The maximum limits of the noise acoustic power are specified in IEC 34-9 depending on the power, speed rate and protection degree of the motor. The maximum limits of acoustic power for 1-500kW motors provided with protection degree within IP44 & IP55 are presented in the following table.

Rated Speed	n≤960	960<n≤1320	1320<n≤1900	1900<n≤2360	2360<n≤3150	3150<n≤3750
Rated Power Pn (kW)	Maximum acoustic power Lw, expressed in dB(A)					
1≤Pn≤1.1	73	76	78	81	84	88
1.1<Pn≤2.2	74	78	82	85	88	91
2.2<Pn≤5.5	78	82	86	90	93	95
5.5<Pn≤11	82	85	90	93	97	98
11<Pn≤22	86	88	94	97	100	100
22<Pn≤37	90	91	98	100	102	102
37<Pn≤55	93	94	100	102	104	104
55<Pn≤110	96	98	103	104	106	106
110<Pn≤220	99	102	106	107	109	110
220<Pn≤550	102	105	108	109	111	113

The values mentioned in the above table are expressed in dB(A) units, where dB is the standard unit of acoustic power that is specified as the following ratio:

$$10 \times \log_{10}\left(\frac{P}{P_0}\right)$$

Where:

P = Acoustic Power of the motor (W)
P_0 = Reference Acoustic Power, that is equal to 10^{-12} W

Thus, if the noise level of a motor is 50dB, the delivered acoustic power is:

$$50 = 10 \times \log_{10}\left(\frac{P}{10^{-12}}\right)$$

or:

P = 0.001W

The index (A) that is included in the dB(A) unit refers to the sensitivity of the human ear to any sound intensity. Various sounds are classified according to curves of "equal subjective intensity" depending on the difference between the sound level sensed by a human and the actual (absolute) one. There are various such A, B, C, D, or E decibel curves. The curve, that has prevailed and is commonly used to calculate the sound level is the A curve. Therefore, dB(A) is mentioned as the unit of measurement.

The maximum allowable limits of acoustic power are specified in the IEC standards, since this determines the emitted energy irrespective of the measured surface and the ambient conditions. In practice, however, we measure the sound pressure p, which also is expressed in dB(A) units. The unit of sound pressure is specified as the following ratio:

$$20 \times \log_{10}\left(\frac{p}{p_0}\right)$$

Where:

p = Sound Pressure (N/m^2)
p_0 = Reference Sound Pressure, that is equal to 2×10^{-5} N/mm^2

The method of sound pressure measurement is not specified in IEC. According to VDE 0530, this is measured at a distance of 1m from the motor. If we calculate the theoretical surface that surrounds the motor at a distance of 1m, we can calculate the sound pressure that corresponds to the acoustic power, which is specified in IEC.

The maximum limits of sound pressure are presented in the following table, expressed in dB(A), as these have been calculated according to the recommended limits in IEC at a distance of 1m from the motor.

Rated Speed	n≤960	960<n≤1320	1320<n≤1900	1900<n≤2360	2360<n≤3150	3150<n≤3750
Rated Power Pn (kW)	Maximum acoustic power Lw, expressed in dB(A)					
1≤Pn≤1.1	62	65	67	70	73	77
1.1<Pn≤2.2	63	67	71	74	77	80
2.2<Pn≤5.5	67	71	75	79	82	84
5.5<Pn≤11	71	74	79	82	86	87
11<Pn≤22	75	77	83	86	89	89
22<Pn≤37	79	80	87	89	91	91
37<Pn≤55	82	83	89	91	93	93
55<Pn≤110	85	87	92	93	95	95
110<Pn≤220	88	91	95	96	98	99
220<Pn≤550	91	94	97	98	100	102

TESTS OF MEDIUM-VOLTAGE ELECTRIC MOTORS

Apart from the previous tests, the following measurements are taken for medium-voltage motors:

1. Polarization Index measurement

With this measurement we can check the dryness condition of the stator winding.
A Megger instrument of 1000 or 2500V with uninterrupted power supply is used for this measurement, during which voltage is applied between the winding and the body of the motor for 10min.
We take records of the specific measurements in MΩ at the 30th sec, and, then, every minute from the 1st to the 10th one. The polarization index (or winding dryness factor) is equal to the ratio of the resistance (MΩ) measured at the 10th minute to the corresponding value taken at the 1st minute.
The ratio of the resistance (MΩ) at the 1st minute to the value taken at the 30th sec is called dielectric absorption ratio. This is also useful information about the insulation condition of the motor winding.
During these tests we observe that the insulation resistance is increasing with the time. This is explained due to the fact that ions inside the insulating material, which are dipoles, prior to dc voltage supply through the Megger instrument, are randomly directed. With the time, the dipoles start to align with the applied voltage (i.e. they are polarized). The ohmic resistance of the insulating material increases due to the polarization of the ion dipoles. The presence of moisture inside the insulating material inhibits dipole alignment, resulting to a negligible or zero increase of the ohmic resistance and a low value of the polarization index.

The time-resistance values of a 430KW, 1,000rpm, 6,000V motor that was rewound in our factory are presented in the next table.

Time (min)	Resistance (MΩ)
0.5	3500
1	6000
2	10300
3	13500
4	16000
5	18000
6	20000
7	21500
8	23000
9	24000
10	25000

According to this table, the polarization index is equal to:

$$25{,}000 / 6{,}000 = 4.1$$

and the resulting dielectric absorption factor is:

$$6{,}000 / 3{,}500 = 1.7$$

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These two indexes provide information about the insulation quality and condition. The values of these indexes with the corresponding conclusions are presented in the following table. It is noted that the specific values have been obtained by experience as these are accepted by the Greek Public Power Company (ΔΕΗ) – see “Tests and Measurements of Electric Insulations”, by Evdokimos Mousloglou).

Insulation Condition	**Dielectric Absorption Coefficient**	**Polarization Index**
Dangerous	**<1**	**<1**
Poor	**<1.1**	**<1.5**
Problematic	**1.1-1.25**	**1.5-2**
Medium	**1.25-1.4**	**2-3**
Good	**1.4-1.6**	**3-4**
Excellent	**>1.6**	**>4**

2. Measurement of dielectric losses (tanδ)

With this measurement we check the insulation condition and whether there are air voids (babbles) inside the insulating material that surrounds the winding. Electric discharges are caused due to the existence of such air voids, resulting to the progressive destruction of the insulating material and the winding as well.

The meaning of tanδ

When an insulating material is subjected to in an alternating electric field, electric current flows inside it, causing dielectric losses. Moreover, if a solid insulating material is not absolutely uniform, containing small babbles of air or any other gas (a very common fact), electric discharges occur inside these babbles resulting to the emission of energy. These losses contribute to temperature increase and, if they are too high, they may cause local destruction or chemical corrosion of the insulation.

Regarding its electrical behavior, an insulating material separating two conductive materials, on which a sinusoid alternating voltage is applied, is equivalent to a perfect capacitor (i.e. without losses) in parallel connected with an ohmic resistance.
The current that flows through the insulation system shows a phase deviation angle in relation to the voltage (the angle ϕ in fig.14, below).
The complementary of this angle (i.e. angle δ) is called loss angle. The larger is the angle δ the larger are the losses.
The tangent of this angle, tanδ, is called dielectric loss coefficient and is derived from the following formula:

$$\tan\delta = \frac{ActiveCurrent}{\mathrm{Re}\,activeCurrent} = \frac{ActivePower}{\mathrm{Re}\,activePower}$$

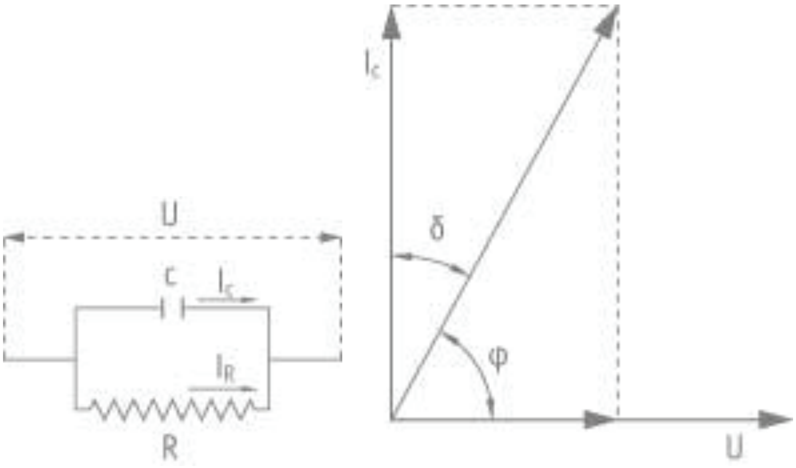

Fig.14

Tanδ is usually measured with a Schering bridge. Its value does not depend on the shape and dimensions of the object to be tested. Tanδ is a characteristic value of a simple insulating material, a combination of various insulating materials, a turn of motor winding or even an entire machine.
The value of tanδ for a certain insulating material or a motor is affected by the following factors:

- Frequency
- Temperature
- Humidity
- Field Intensity

The measurements of tanδ according to VDE0530 are performed on ac motors larger than 5,000KW. However, the specific measurement is required by the Public Power Company of Greece even for much smaller motors as well as for the maintenance of motors with low horsepower.

As already mentioned above, the specific measurements are performed with a Schering bridge, supplying an adjustable voltage between motor winding & body and recording the resulting values of tanδ. We begin the measurements with a voltage equal to 0.2 times the rated one and we carry on increasing it in successive steps of 0.1 times the rated voltage. The maximum allowable values of tanδ according to VDE0530 are presented in the next table:

$\tan\delta_{0.2}$	½ x ($\tan\delta_{0.6}$-$\tan\delta_{0.2}$)		Δtanδ at 0.2Un steps	
	95% of the probes	The remaining 5% of the probes	95% of the probes	The remaining 5% of the probes
40×10^{-3}	2.5×10^{-3}	3×10^{-3}	5×10^{-3}	6×10^{-3}

The measurements of tanδ for a 460kW, 1,000rpm, 6,000V motor that was rewound in our factory are presented below:

No	U/Un	Voltage (V)	tanδ
1	0.2	1,200	0.0081
2	0.4	2,400	0.0083
3	0.6	3,600	0.0086
4	0.8	4,800	0.0125
5	1.0	6,000	0.0156

From these measurements the following are concluded:

1. $\mathrm{Tan}\delta_{0.2} = 0.0081 = 8.1 \times 10^{-3} < 40 \times 10^{-3}$
2. ½ x ($\tan\delta_{0.6} - \tan\delta_{0.2}$) = ½ x (0.0086 – 0.0081) = ½ x 0.0005 = 0.00025 = $0.25 \times 10^{-3} < 2.5 \times 10^{-3}$
3. Max Δtanδ (i.e. max tanδ difference between successive steps of 0.2xUn) = $\tan\delta_{0.8} - \tan\delta_{0.6} = 0.0125 - 0.0086 = 3.9 \times 10^{-3} < 5 \times 10^{-3}$

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