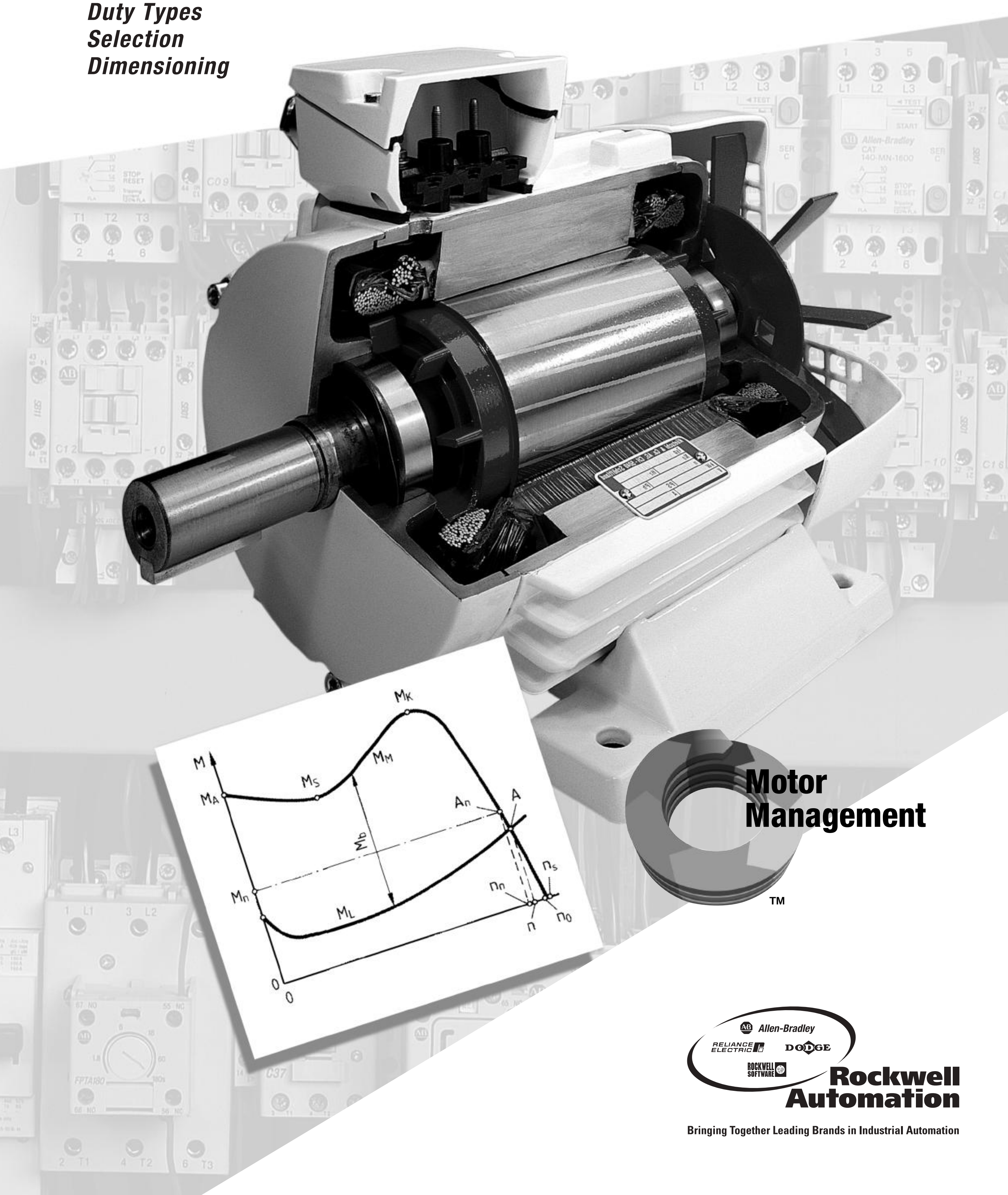
Application basics of operation of three-phase induction motors

Design
Duty Types
Selection
Dimensioning



Motor Management™

Foreword

This technical manual for Three-Phase Induction Motors is the first publication of a series on the topic of "Motor Management".

With these published fundamentals the user will have a growing reference work on the performance and operational data required for design and application. The following topics will be covered:
- Starting and operating motors
- Protection of motors and drives
- Selection and operation of controls
- Communications

Electric motors can be found in almost every production process today. Getting the most out of your application is becoming more and more important in order to ensure cost-effective operations. "Motor Management" from Rockwell Automation will help you
- to optimize the use of your systems
- to reduce maintenance costs
- to increase dependability

We are pleased that our publications may help you find economical and efficient solutions for your applications.

Table of Contents

1 Three-Phase Induction Motors

The three-phase induction motor, also called an asynchronous motor, is the most commonly used type of motor in industrial applications. In particular, the squirrel-cage design is the most widely used electric motor in industrial applications.

1.1 Principles of Operation

The electrical section of the *three-phase induction motor* as shown in **Figure** 1.2.2 consists of the fixed stator or frame, a three-phase winding supplied from the *three-phase mains* and a turning *rotor.* There is no electrical connection between the stator and the rotor. The currents in the rotor are induced via the air gap from the stator side. Stator and rotor are made of highly magnetizable core sheet providing low eddy current and hysteresis losses.

1.1.1 Stator

The *stator winding* consists of three individual windings which overlap one another and are offset by an electrical angle of 120°. When it is connected to the power supply, the incoming current will first magnetize the stator. This *magnetizing current* generates a *rotary field* which turns with *synchronous speed* n_s.

For the smallest pole number of 2p = 2 in a 50 Hz circuit the highest synchro-

Synchronous speed $\mathbf{n_s = 60 \frac{f}{p}}$	n_s = synchronous speed/minute f = frequency s^{-1} (per second) p = pole pair number (pole number/2)

nous speed is $n_s = 3000/\text{min}^{-1}$. Synchronous speeds in a 50 Hz circuit are shown in **Table** 1.2.1:

1.1.2 Rotor

The *rotor* in induction machines with squirrel-cage rotors consists of a slotted cylindrical rotor core sheet package with aluminum bars which are joined at the front by rings to form a closed cage.
The *rotor* of three-phase induction motors sometimes is also referred to as an *anchor*. The reason for this name is the anchor shape of the rotors used in very early electrical devices. In electrical equipment the anchor's winding would be induced by the magnetic field, whereas the rotor takes this role in three-phase induction motors.

Pole Number 2p	2	4	6	8	10	12	16	24	32	48
n_s in rpm	3000	1500	1000	750	600	500	375	250	188	125

Table 1.2.1 Typical synchronous speeds in a 50 Hz circuit

Synchronous speeds are 20% higher in a 60 Hz circuit

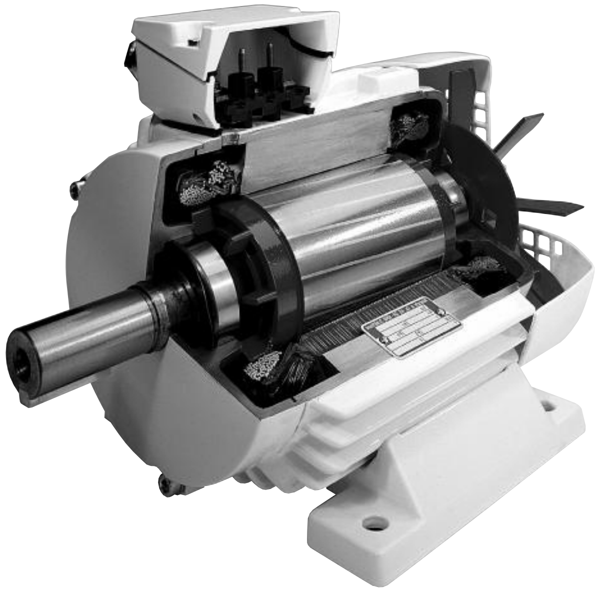
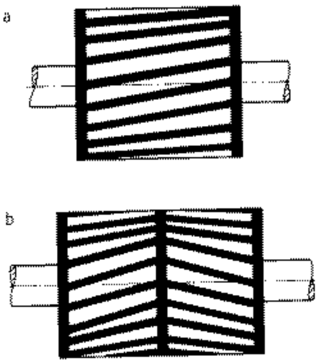


Figure 1.2.2 State-of-the-art closed squirrel-cage three-phase motor

The *stopped* induction motor acts like a transformer shorted on the secondary side. The *stator winding* thus corresponds to the *primary winding,* the *rotor winding* (cage winding) to the *secondary winding*. Because it is shorted, its internal rotor current is dependent on the induced voltage and its resistance. The interaction between the *magnetic flux* and the *current conductors in the rotor* generates a *torque* that corresponds to the rotation of the rotary field. The cage bars are arranged in an offset pattern to the axis of rotation in order to prevent torque fluctuations (see **Figure** 1.3.1). This is called "skew".

At *idle* the rotor almost reaches the synchronous speed of the rotary field, since only a small counter-torque (no-load losses) is present. If it were to turn exactly synchronously, voltage would no longer be induced, current would cease to flow, and there would no longer be any torque.

During *operation* the speed of the rotor drops to the *load speed* n. The difference between the synchronous speed and the load speed is called *slip s*. Based on this load-dependent slip s, the voltage induced in the rotor winding changes, which in turn changes the rotor current and also the torque M. As slip s increases, the rotor current and the torque rise. Because the three-phase induction motor acts like a transformer, the rotor current is transformed to the stator side (secondary side) and the stator supply current changes essentially to the same degree. The *electrical output* of the stator generated by the power supply is converted via the *air gap into mechanical power* in the rotor. The stator current therefore consists of two components, the *magnetization current* and the actual *load current*.



a single offset cage bars

b double transposed cage bars

Figure 1.3.1 Forms of squirrel-cage rotor windings

1.1.3 Slip

The difference between the synchronous speed n_s and the speed n in rated operation is called *slip s* and is generally expressed in percent. Depending on the size of the machine, in rated operation it is roughly 10 to 3%. Slip is one of the most important characteristics of an induction machine.

Slip $s = \dfrac{n_s - n}{n_s}$	s = slip n_s = synchronous speed n = rotor speed

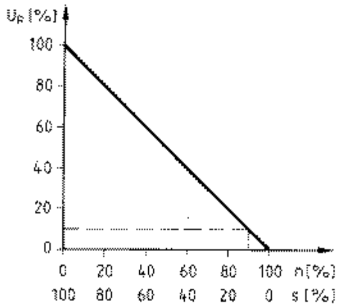


Figure 1.4.1 The rotor voltage U_R is a proportional function of slip s. A rotor voltage of 10% corresponds to a slip of 10%

The induced rotor voltage U_R as shown in **Figure** 1.4.1 is proportional to the slip s. In the stopped position, it peaks at n = 1 and s = 1, which also results in the strongest current flow. This fact is confirmed in real-life applications by the high starting current (starting current inrush). The torque also peaks during the stop period at a certain rotor resistance. This behavior can be modified by design variation. However the rotor resistance is not usually used for this purpose. The following formula applies to the rotor speed:

Rotor speed $n = n_s \cdot (1 - s)$	n = rotor speed n_s = synchronous speed s = slip

1.1.4 Dissipation

Since the rotor speed n is less than the synchronous speed n_s of the rotary field by the amount of slip s, the mechanical rotor power P_2 is also less than the electrically transmitted rotating field power P_D. The difference P_{VR} is lost in the rotor as heat. These winding losses are thus directly dependent on the slip s. Beginning with the first instant of the starting process all the power induced in the rotor is converted into heat.

Dissipation in the rotor $P_{VR} = P_D \cdot s$ = ohmic loss P_{CuR} in W

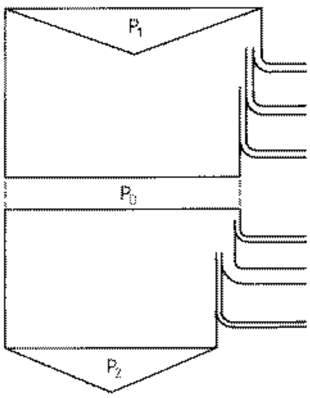
The equation shows that the thermal danger is greatest for a stationary rotor at s = 1, since all the electric power input is converted to heat dissipation in the motor. Due to the increased starting current of induction motors the heat dissipation is a multiple of the rated motor power. In addition, conventional self-ventilated motors do not provide adequate cooling when stopped.

If we examine all power losses P_v in a motor, as shown in **Figure** 1.5.1, we find the following *individual losses:*

• P_{Fe}	*Core loss in the stator*	⇒ roughly constant in operation
• P_{CuS}	*Ohmic loss in the stator*	⇒ square function of current
• P_{CuR}	*Ohmic loss in the rotor*	⇒ square function of current
• P_{Lu}	*Windage loss*	⇒ roughly constant in operation
• P_{La}	*Bearing friction losses*	⇒ roughly constant in operation
• P_{zus}	*Stray losses*	⇒ roughly constant in operation

The *core loss* P_{Fe} in the stator is caused by hysteresis and eddy current losses which are dependent on the voltage and frequency. Therefore during operation they are roughly constant. In the rotor, the losses are insignificant because of the low frequency of the rotor current during operation. *Ohmic losses* occur in the stator P_{CuS} and in the rotor P_{CuR}. Both are a square function of load. *Windage losses* P_{Lu} and *bearing friction losses* P_{La} are likewise constant due to the essentially constant speed in operation. *Stray losses* P_{zus} are caused mainly by eddy currents in the metal components of the machine.

Legend:



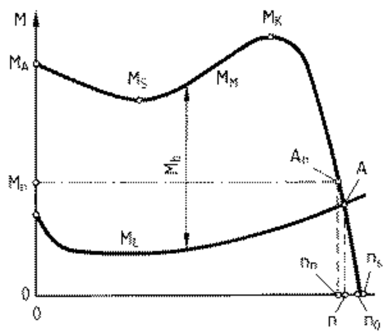
P_1 = electric power input
P_{Fe} = core loss in the stator
P_{CuS} = ohmic loss in the stator
P_{zus} = stray loss
P_D = rotor field power (air gap power)
P_{CuR} = ohmic loss in the rotor
P_{Lu} = windage and ventilation loss
P_{La} = bearing friction losses
P_2 = mechanical power output

Figure 1.5.1 Output and losses in a three-phase induction motor

1.2 Torque Characteristic

1.2.1 Principal Characteristic

Figure 1.6 shows the typical torque characteristics of induction motors with squirrel-cage rotors which are identified by the following parameters. The *acceleration torque* is defined as the entire range of the torque characteristic from stop to full speed.



M_n = rated torque
M_L = load torque
M_K = pull-out torque
M_M = motor torque
n_S = synchronous speed
A_n = nominal working point
M_A = breakaway torque
M_B = acceleration torque
M_S = pull-up torque
n_n = rated speed ($0.94..0.99 \cdot n_S$)
n = operating speed
A = working point
n_0 = no-load speed ($0.98..0.997 \cdot n_S$)

Figure 1.6.1 Induction motor torque characteristic over speed

M_A *Locked-rotor torque* at stop, also called the *breakaway torque.* The values provided by the motor manufacturers should have tolerances from -15% to +25%.

M_n *Rated torque* during rated operation at *rated power* P_n and at rated speed n_n. At no-load the torque is very low and covers internal friction. When the motor is loaded, its speed drops slightly by the amount of slip s and the torque increases. A standard motor must be able to deliver the rated torque in continuous operation without exceeding its temperature limit.
In certain operating modes (S2, S3 and S6) the rated torque may also be exceeded to a certain degree, if the temperature limit is not exceeded, across the full operating range.

M_K *Pull-out torque.* This is the *maximum torque* which the motor can deliver. If the power is increased above the rated load P_n, slip s continues to increase, speed n decreases, and the motor delivers a higher torque. This can be increased up to a maximum value M_K (pull-out torque) where the motor becomes *unstable,* i.e., its speed suddenly decreases at this slip value (breakdown slip) and the motor speed goes to 0.

According to standards, the pull-out torque must be $M_K \geq 1.6\ M_n$ and it must be possible to overload the motor for at least 15 seconds with this value at the rated voltage and rated frequency. The catalog data may have up to -10% tolerance. In most motors the pull-out torque is significantly greater and usually reaches values of $M_K = 2...3.5\ M_n$. Therefore induction motors are especially well suited for intermittent loads, provided the additional heat can be dissipated.

M_S *Pull-up torque,* also called the *pull-through torque,* is the smallest torque during acceleration. In any case it must be greater than the simultaneously effective load torque M_L since otherwise the motor cannot be accelerated. Minimum values for the pull-up torque are specified in the standards for rated voltage operations.

M_L *Load torque,* the *counter-torque* which represents the load during acceleration.

M_M *Motor torque,* also called the *acceleration torque.*

M_B *Acceleration torque* as the difference of the motor torque M_M minus the load torque M_L

In continuous duty with operating mode S1 and rated load P_n a properly sized motor rotates with rated speed n_n and delivers the rated torque M_n:

Rated torque	$\mathbf{M_n = 9555 \cdot \frac{P_n}{n_n}}$	M_n = rated torque in Nm P_n = rated power in kW n_n = rated speed/minute

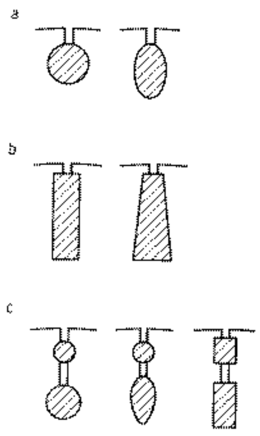
Torque M can however also be computed using the electrical data of the motor:

Rated torque	$\mathbf{M_n = \frac{\sqrt{3} \cdot U \cdot I \cdot \cos\varphi \cdot \eta \cdot 9.55}{n}}$	U = voltage in V I = current in A cosφ = power factor η = efficiency n = speed

During starting, the breakaway torque M_A must be greater than the breakaway torque of the load and during the entire acceleration phase the motor torque M_M must remain above the load torque M_L, as shown in **Figure** 1.6.1..
At the intersection of the two torque lines (operating point A) the motor operates with constant speed n. In case of overload the working point A rises above the nominal working point A_n. This is allowable only for a short time to avoid overheating the motor.
Working point A however should not be too low either, i.e., an oversized motor should not be chosen. Below 50% of the rated load the efficiency η and the power factor cosφ fall dramatically and motors no longer run economically. A larger motor also has a larger starting current I_A since starting current is independent of the load torque. Only the acceleration time would be shortened by a larger motor.

1.2.2 Motor Design

The torque characteristics can be largely adapted to the application in three-phase induction motors. Important properties here are a *low starting current* I_A and *high starting torque* M_A. The torque characteristic and also the size of the starting current are determined mainly by the *type of rotor cage* and the *shape of the rotor slot* as shown in **Figure** 1.8.1
A high breakaway torque M_A and a small starting current I_A can be achieved by a relatively high ohmic rotor resistance in the starting torque. Basically a more or less large "current displacement effect" (skin effect) takes place during starting; this applies to all types of rotor designs. The following designs are distinguished:



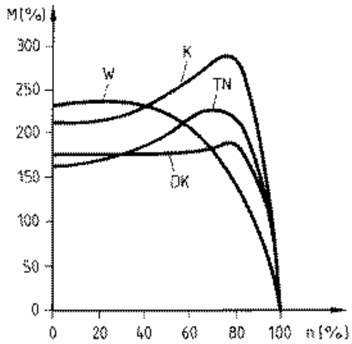
a single cage rotor for diecast version

b deep slot version

c double cage rotor

Figure 1.8.1 Slot shapes for squirrel-cage rotors

- *Normal squirrel-cage rotors with single slot* and round, rectangular or trapezoidal conductors usually made of aluminum with a relatively high starting torque of 1.8...2.5 x M_n and a high starting current of 5...10 x I_n.
- *Current displacement rotors,* also called *deep-bar rotors.* If the cage bars are made tall and narrow, during power-up *current displacement* takes effect, since then the rotor frequency is high. The current flows on the outside or "skin" of the rotor. This effect causes a reduction of the effective conductor cross section and therefore an increase of the ohmic resistance. The result is good starting torque M_A and a favorable low starting current I_A. During operation current displacement no longer has any effect, since the rotor frequency is then very low and the motor has normal currents and torques.
- *Double squirrel-cage rotors* have the bar divided into two individual bars which are usually electrically isolated from one another. The *outside cage* is made with *high,* the *inside cage* with *low ohmic resistance.* This is done by using an appropriate material (Cu, Al, Ms) and proper dimensioning of the conductor cross sections. The effect is even more pronounced than in a current displacement rotor. During start-up, current flows essentially only in the outside cage; this reduces the starting current I_A and causes a relative increase of the starting torque M_A. During operation the current is then distributed between the two cages according to their ohmic resistances.
- *High-resistance squirrel-cage rotors,* also called slip rotors, have a slot shape as in a normal squirrel-cage rotor, but use brass conductors or high resistance aluminum alloy instead of Al or Cu conductors. This causes the ohmic resistance to increase. In contrast to the current displacement rotor, it remains constant over the entire speed range and during operation leads to high slip with a *flexible* speed characteristic and without a pronounced pull-out torque. The starting torque M_A is high according to the rotor resistance and the starting current I_A is reduced. Since the high ohmic resistance is maintained during operation, relatively large losses occur, resulting in uneconomical operation. Therefore, these rotors are not widely used today, especially since the desired characteristics can also be achieved with low-loss electronic devices, such as drives and soft starters.



K = normal cage (Al)
TN = deep-bar rotor (Al or Cu)
DK = double cage rotor (Al or Cu or Al outside and Ms inside)
W = high resistance squirrel-cage rotor M_S
M = torque
n = speed

Figure 1.10.1 Fundamental torque characteristic of various types of cages

1.3 Operating characteristics

Operating characteristics are a graphical presentation of the behavior of:

- speed
- power factor
- efficiency
- current
- power
- slip

as a function of load.

Figure 1.10.2 shows the operating characteristics of a typical induction motor.

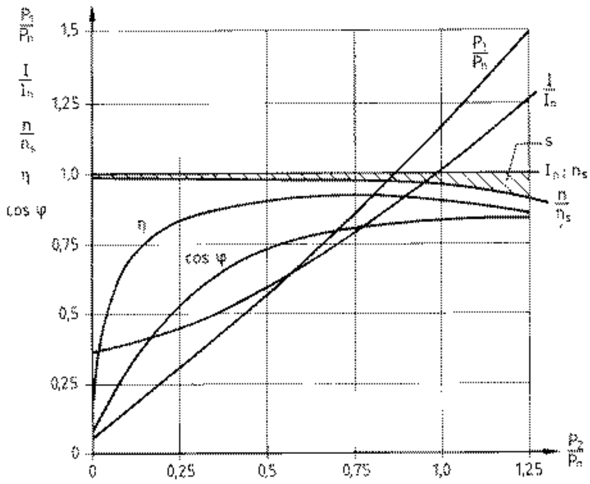


Figure 1.10.2 Operating characteristics of an induction motor as a function of load

n = speed
P_1 = power input
η = efficiency
I = current input
s = slip
n_S = synchronous speed
P_2 = power output
cosφ = power factor
I_n = rated current
P_n = rated power

n The *speed* n decreases only slightly as load increases. Standard squirrel-cage motors thus have *"stiff" speed characteristics.*

s *Slip s* increases roughly proportionally as load increases.

cosφ The *power factor* cosφ depends *largely on load* and it peaks typically during overload. In the partial load range it is relatively unfavorable, since even under partial loads magnetization is essentially constant.

η *Efficiency* η exhibits a *relatively flat* characteristic and is almost constant above half-load. It generally peaks below the rated power P_n.

I *Current* I increases *proportionally* beginning roughly at half-load. Below half-load it decreases only slowly until it becomes the no-load current I_O. (Constant magnetization)

P The *power* P_1 increases roughly in proportion to load starting from the no-load power. In the overload range it increases slightly faster since losses also increase faster.

Since the efficiency η and power factor cosφ can have a major effect on the economic efficiency of a motor, knowledge of the partial load values is very important. Both values determine the economic efficiency during operation. In the partial load range they both drop. In addition, in low-speed motors the power factor cosφ is smaller than in high-speed motors. Therefore closely sized, high-speed motors are not only less expensive purchase, but they also cost less to operate.

2 Duty Types of Electric Motors

Normally, continuous duty three-phase induction motors are designed for the rated power. Actuators are an exception. Most motors however are operated with a duty type which is not continuous. Some motors are turned on only briefly, others run all day, but are only briefly loaded, and numerous motors must accelerate a large flywheel or are run in a switched mode and electrically braked.
In all these different duty types a motor heats up differently than in continuous duty. To prevent damaging the motor winding and rotor due to overheating, these special heating processes must be taken into account.

2.1 Primary duty types S1... S9

For design purposes information on the *duty type* must be as accurate as possible, since the power yield can diverge greatly from continuous output. The number of possible duty types is thus theoretically unlimited. For the sake of agreement between manufacturers and operators, nine main duty types S1 through S9 were detailed in IEC 34. Almost all cases which occur in practice can be assigned to one of these duty types:

- S1: Continuous duty
- S2: Temporary duty
- S3: Intermittent periodic duty-type without starting
- S4: Intermittent periodic duty with starting
- S5: Intermittent periodic duty with starting and electrical braking
- S6: Continuous-operation duty type
- S7: Continuous-operation duty with starting and electrical braking
- S8: Continuous-operation periodic duty with related load/speed changes
- S9: Duty with non-periodic load and speed variations

Motor manufacturers must assign the load capacity of the motor in one of these defined duty types and where necessary provide the values for operating time, load period, or relative duty cycle.

In the descriptions and diagrams for duty types S1 through S9 the following symbols are used:

P	= power in kW	t_{Br}	= braking time in s, min
P_v	= losses in kW	t_L	= idle time s, min, or h
n	= speed/min	t_r	= relative duty cycle (%)
ϑ	= temperature in °C	t_S	= cycle duration in seconds
ϑ_{max}	= maximum temp. in °C	t_{St}	= stop period in s, min, or h
t	= time in s, min, or h	T	= thermal time constant in minutes
t_B	= load period	t_A	= starting time in s, min
J_M	= moment of inertia of the motor in kgm^2		
J_{ext}	= moment of inertia of the load referenced to the motor shaft in kgm^2		

The speed n is usually specified in revolutions per minute. Generally the rating plate gives the rated speed n_n at full load, but in catalogs also the synchronous or rated speed is specified.

Duty types S1 through S9 cover many of the applications which occur in the field. If the type of load cannot be assigned to any of the defined duty types, the exact cycle description should be indicated to the manufacturer or a duty type should be selected which conforms to least as heavy a load as the actual application.

2.1.1 S1: Continuous duty

Operation with a constant load state as shown in **Figure** 2.2.1 with a duration sufficient to reach thermal equilibrium. The load period t_B is much greater than the thermal time constant T

Identification S1: Specification of power in kW, if necessary with abbreviation S1.

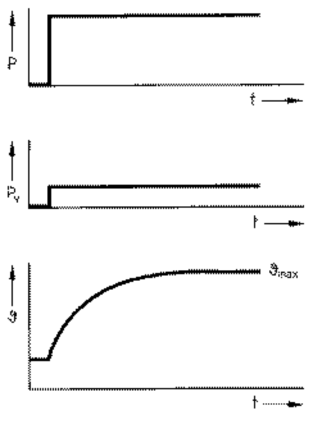


Figure 2.2.1 Duty type S1: Continuous duty

2.1.2 S2: Temporary duty

Operation with a constant load state as shown in **Figure** 2.3.1 which however does not last long enough to reach thermal equilibrium, and with a subsequent interval which lasts until the machine temperature differs by not more than 2 K from the temperature of the coolant.

It is temporary duty when the load period $t_B \leq 3$ T (thermal time constant). Compared to continuous duty the motor can deliver more power during the load period. Consult the manufacturer for details.

Identification S2: by specification of the load period t_B and power P in kW

- Example: S2: 10 min, 11 kW.
- For the operating time t_B periods of 10, 30, 60 and 90 min are recommended.

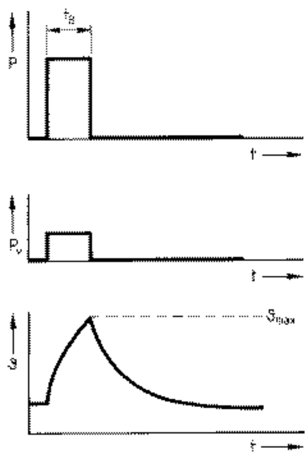


Figure 2.3.1 Duty type S2: Temporary duty

2.1.3 S3: Intermittent periodic duty-type without starting

Operation as shown in **Figure** 2.4.1 which is composed of a sequence of similar duty cycles with cycle duration t_S at constant load and an interval which is generally so short that thermal equilibrium is not reached and the starting current does not noticeably affect heating. This is the case when $t_B \leq 3$ T. The power during this time should be higher than the continuous output of the motor. Consult the manufacturer for details.

Relative duty cycle $$\mathbf{t_r = \frac{t_B}{t_B + t_S} \cdot 100}$$

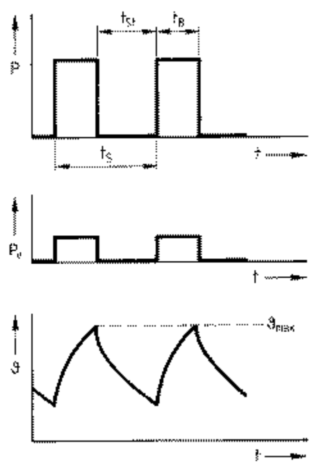
t_B load period in s, min

t_s = cycle duration in s, min

t_r = relative duty cycle in %

Identification: by specification of the load period t_B, cycle duration t_S and power P, but also by the relative duty cycle t_r in % and by the cycle duration.

- Example: S3: 15 min / 60 min. 11 kW
- Example: S3: 25%, 60 min. 11 kW



relative duty cycle

$$t_r = \frac{t_B}{t_B + t_S} \cdot 100$$

Figure 2.4.1 Duty type S3: Intermittent periodic duty-type without starting

If no cycle duration is specified, t_S = 10 min applies.
Recommended values for the relative duty cycle t_r are 15%, 25%, 40%, and 60%.

2.1.4 S4: Intermittent periodic duty with starting

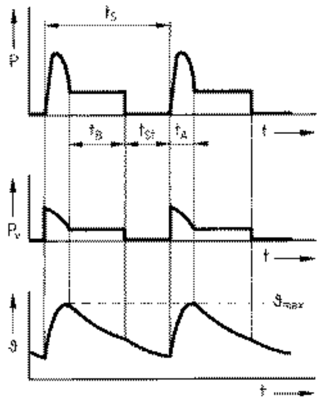
Operation as shown in **Figure** 2.5.1 which consists of a sequence of identical duty cycles with cycle duration t_S, whereby each cycle encompasses a distinct starting time t_A, time t_B with constant load, and interval t_{St}.

Relative duty cycle $\mathbf{t_r} = \dfrac{\mathbf{(t_A + t_B) \cdot 100}}{\mathbf{t_A + t_B + t_{St}}} = \dfrac{\mathbf{t_A + t_B}}{\mathbf{t_S}} \cdot \mathbf{100}$

t_A = starting time s, min
t_r = relative duty cycle in %
t_{St} = stop period in s, min
t_s = cycle duration in s, min
t_B = load period in s, min

Identification: by the relative duty cycle t_r in %, number Z_L of starts per hour and power P

- Example: S4: 25%, 500 starts per hour, 11 kW
- plus information on the moment of inertia of the motor and load J_M and J_{ext} during starting.



relative duty cycle

$$t_r = \frac{t_A + t_B}{t_A + t_B + t_{St}} \cdot 100$$

Figure 2.5.1 Duty type S3: Intermittent periodic duty with starting

Here it should be noted whether the motor stops under the effect of the load at the end of the cycle, or whether it is being stopped by a mechanical brake. If the motor continues to run after it is shut off so that the windings cool down significantly, this should be indicated. If not indicated it is assumed that it will stop within a very short time.
In this duty type the maximum no-load shifts Z_0 are used as a basis from which the maximum frequency of operation shifts is computed according to the load torque, possible additional mass and a possible flywheel effect. Compared to continuous duty S1 a power reduction can be noted.

2.1.5 S5: Intermittent periodic duty with starting and electrical braking

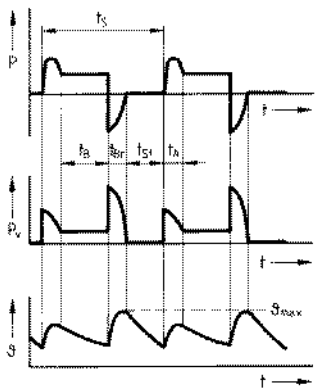
Operation as shown in **Figure** 2.6.1 which is composed of a sequence of similar duty cycles with cycle duration t_S, whereby each cycle encompasses a distinct starting time t_A, time t_B with constant load and time t_B of high-speed electrical braking. There is no interval.

Relative duty cycle $$\mathbf{t_r = \frac{(t_A + t_B + t_{Br}) \cdot 100}{t_A + t_B + t_{Br} + t_{St}} = \frac{t_A + t_B + t_{Br}}{t_S} \cdot 100}$$

t_A	= starting time s, min	t_{St}	= stop period in s, min
t_B	= load period in s, min	t_r	= relative duty cycle in %
t_s	= cycle duration in s, min	t_{Br}	= braking time in s, min

Identification: similar to S4, but also identified with specification of the type of braking (plug braking, regenerative braking, etc.)

- In case of doubt and when the starting and braking times are long relative to the rated operating time, all three time intervals should be indicated separately.
- Example: S4: 25%, 500 starts per hour, plug braking, 11 kW
- Additional information on the moment of inertia of the motor and load J_M and J_{ext} during starting and braking.



relative duty cycle

$$t_r = \frac{t_A + t_B + t_{Br}}{t_A + t_B + t_{Br} + t_{St}} \cdot 100$$

Figure 2.6.1 Duty type S5: Intermittent periodic duty with starting and electrical braking.

Compared to continuous duty S1 a power reduction is necessary in this mode. Consult the manufacturer for details.

2.1.6 S6: Continuous-operation periodic duty

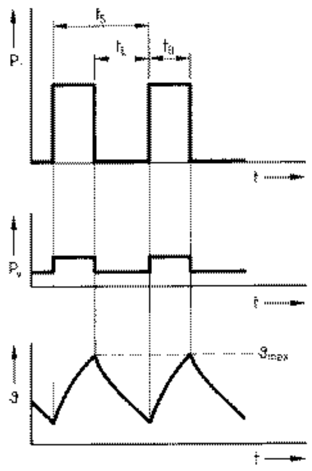
Operation as shown in **Figure** 2.7.1 which is composed of a sequence of similar duty cycles with cycle duration t_S, whereby each cycle encompasses a time t_B with constant load and an idle time t_L, with no interval. After operating time t_B the motor continues to turn at no-load and due to the no-load current does not cool down to the coolant temperature, but is ventilated during the idle time t_L. This is the operating state when $t_B \leq T$.

Relative duty cycle $$t_r = \frac{t_B}{t_B + t_L} \cdot 100 = \frac{t_B}{t_S} \cdot 100$$

t_B = load period in s, min
t_L = idle time in s, min
t_s = cycle duration in s, min
t_r = relative duty cycle in %

Identification: as in S3, by the duty cycle t_B, cycle duration t_S, and power P

- Example: S6: 25%, 40 min, 11 kW
- If no indication is given for the cycle duration, t_S = 10 min applies.



relative duty cycle

$$t_r = \frac{t_B}{t_B + t_L} \cdot 100$$

Figure 2.7.1 Duty type S6: Continuous-operation intermittent duty

Compared to continuous duty S1, the power may be selected to be greater during operating time t_B. Consult the manufacturer for details.

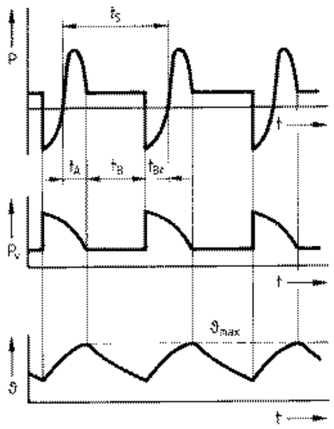
2.1.7 S7: Continuous-operation duty with starting and electrical braking

Operation as shown in **Figure** 2.8.1 which is composed of a sequence of similar duty cycles with cycle duration t_S, whereby each cycle encompasses a distinct starting time t_A, time t_B with constant load P and time t_{Br} with high-speed electrical braking. There is no interval.

Relative duty cycle t_r = 1

Identification: like S4, identified without indication of relative duty cycle t_r, but with indication of the type of braking (plugging, regenerative braking, etc).

- In case of doubt and when the starting and braking times are long enough in relation to the rated operating time, all three time intervals should be indicated separately.
- Example: S7: 500 duty cycles per hour, braking by plugging, 11 kW.
- Additional information on the moment of inertia of the motor and load J_M and J_{ext} during starting and braking.



relative duty cycle t_r = 1

Figure 2.8.1 S7: Continuous operation-duty with starting and electrical braking

Compared to continuous duty S1 a power reduction is necessary in this mode. Consult the manufacturer for details.

2.1.8 S8: Continuous-operation periodic duty with related load/speed changes

Operation as shown in **Figure** 2.10.1 which is composed of a sequence of similar duty cycles with cycle duration t_S; each of these cycles comprises a time with a constant load and a certain speed; then one or more times with different loads which correspond to different speeds, for example, by pole reversal. There is no interval or idle time.

This mode cannot be recorded with one simple formula. A suitable continuous load must be used as the reference dimension for the load cycle:

Relative duty cycle
$$t_{r1} = \frac{(t_A + t_{B1}) \cdot 100}{t_A + t_{B1} + t_{Br1} + t_{B2} + t_{Br2} + t_{B3}} = \frac{t_A + t_{B1}}{t_S} \cdot 100$$

Relative duty cycle
$$t_{r2} = \frac{(t_{Br1} + t_{B2}) \cdot 100}{t_A + t_{B1} + t_{Br1} + t_{B2} + t_{Br2} + t_{B3}} = \frac{t_{Br1} + t_{B2}}{t_S} \cdot 100$$

Relative duty cycle
$$t_{r3} = \frac{(t_{Br2} + t_{B3}) \cdot 100}{t_A + t_{B1} + t_{Br1} + t_{B2} + t_{Br2} + t_{B3}} = \frac{t_{Br2} + t_{B3}}{t_S} \cdot 100$$

t_A = starting time s, min
t_B = load period in s, min
t_{Br} = braking time in s, min
t_s = cycle duration in s, min
t_r = relative duty cycle in %

Identification: like S5, except that for each speed the time must be specified during which these speeds occur within every cycle period.

- Example: S8: 30%, 3000/m, 10 min, 1500/m 20 min. 2 cycles per hour. 11 kW
- Additional information on the moment of inertia of the motor and load J_M and J_{ext} during starting and braking.

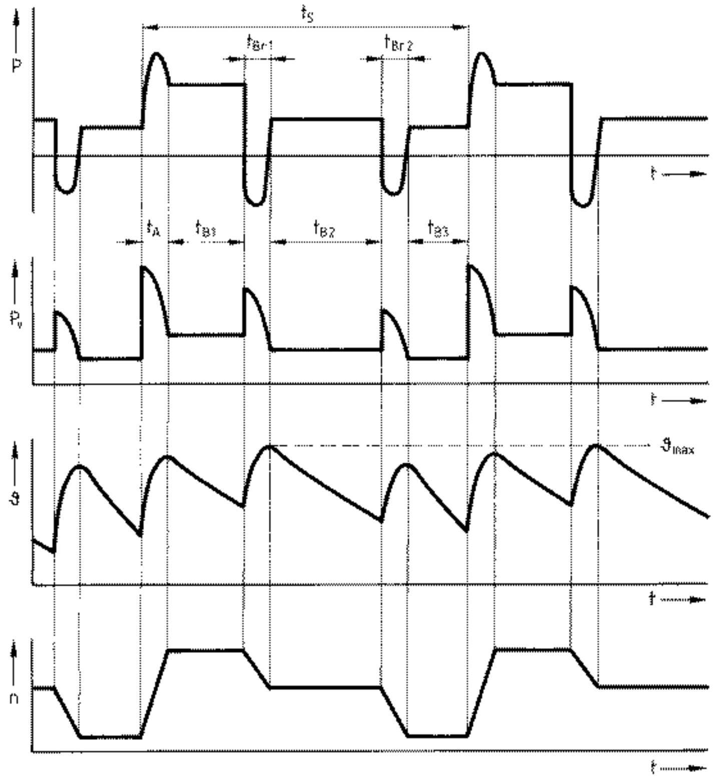


Figure 2.10.1 *Duty type S8: Continuous-operation periodic duty with related load/speed changes*

$$\text{Relative duty cycle } t_{r1} = \frac{t_A + t_{B1}}{t_A + t_{B1} + t_{Br1} + t_{B2} + t_{Br2} + t_{B3}} \; 100$$

$$\text{Relative duty cycle } t_{r2} = \frac{t_{Br1} + t_{B2}}{t_A + t_{B1} + t_{Br1} + t_{B2} + t_{Br2} + t_{B3}} \; 100$$

$$\text{Relative duty cycle } t_{r3} = \frac{t_{Br2} + t_{B3}}{t_A + t_{B1} + t_{Br1} + t_{B2} + t_{Br2} + t_{B3}} \; 100$$

Compared to continuous duty S1 a power reduction is necessary in this duty type. Exact computation is very complex and is possible only with detailed information from the manufacturer.

2.1.9 S9: Duty with nonperiodic load and speed variations

In this mode of operation as shown in **Figure** 2.11.1 the load and the speed change nonperiodically within the maximum operating range. Load peaks which can be far above the rated power may occur frequently. The overload can be taken into account by selective oversizing.
The duty type cannot be recorded with one simple formula. A suitable continuous load must be used as the reference dimension for the load cycle:

Identification: Manufacturers and users generally agree on an equivalent ("equ") continuous output instead of the varying load for different speeds and irregular operation including overload.

Example: S9, 11 kW equ 740/min; 22 kW equ 1460/min

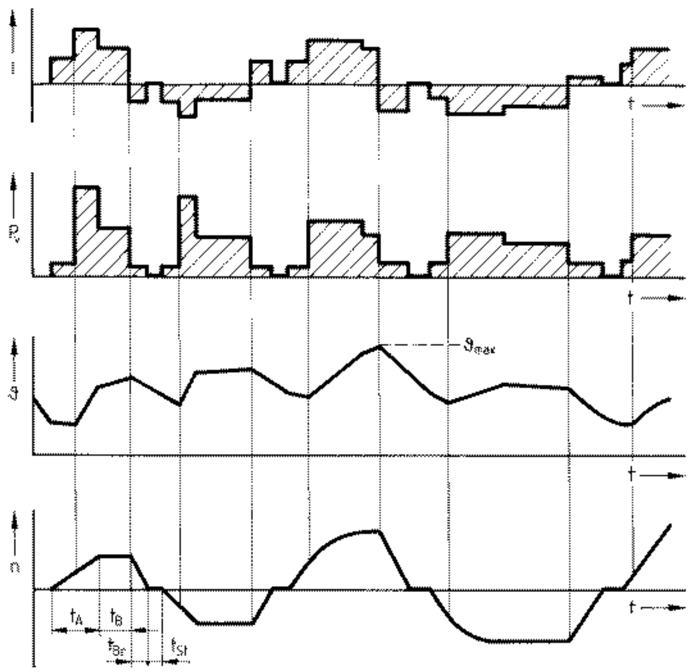


Figure 2.11.1 Duty type S9: Duty with nonperiodic load and speed variations

Compared to continuous duty S1 the equivalent continuous output of duty type S9 can be lower, the same, or even higher, depending on the load characteristic and the length of the intervals.

2.2. Mean values of power, torque and current

In many cases the actual use of a motor diverges from duty types S1 through S9 because the required power P or torque M_L and thus current I are not constant. Since losses P_v change with the square of the load, the individual values (powers, torques, currents) can be replaced by a mean power P_{mi}.

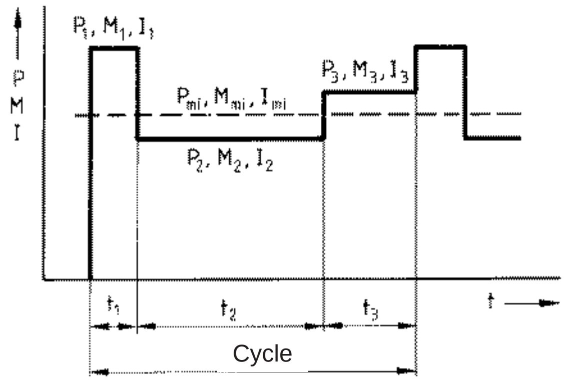


Figure 1.12.1 Determining mean power P_{mi}, mean torque M_{mi} and mean current I_{mi} (I_{eff}).

$$\text{Mean power } P_{mi} = \sqrt{\frac{P_1^2 \cdot t_1 + P_2^2 \cdot t_2 + P_3^2 \cdot t_3}{t_1 + t_2 + t_3}}$$

These values are determined by a quadratic conversion, as shown in **Figure** 2.12.1, using the individual outputs and the associated effective times. The maximum torque which occurs here should not exceed 80% of the pull-out torque for a three-phase induction motor. However, this type of averaging is not possible in S2.

Mean power

$$P_{mi} = \sqrt{\frac{P_1^2 \cdot t_1 + P_2^2 \cdot t_2 + P_3^2 \cdot t_3 + \ldots}{t_1 + t_2 + t_3 + \ldots}}$$

Mean torque

$$M_{mi} = \sqrt{\frac{M^2 \cdot t_1 + M_2^2 \cdot t_2 + M_3^2 \cdot t_3 + \ldots}{t_1 + t_2 + t_3 + \ldots}}$$

Mean current

$$(I_{eff}) = \sqrt{\frac{I_1^2 \cdot t_1 + I_2^2 \cdot t_2 + I_3^2 \cdot t_3 + \ldots}{t_1 + t_2 + t_3 + \ldots}}$$

When the powers differ by more than a factor of 2, this averaging is too inaccurate, and the calculations must be done with the mean current taken from the motor characteristics.

Example: In an automatic industrial handling machine the following load cycles are determined for a cycle duration of 10 minutes:

6 kW for 3 minutes, 3 kW for 2 minutes, 7 kW for 2 minutes, 2 kW for 3 minutes:

What is the mean load?

$$P_{mi} = \sqrt{\frac{P_1^2 \cdot t_1 + P_2^2 \cdot t_2 + P_3^2 \cdot t_3 + \ldots}{t_1 + t_2 + t_3 + \ldots}} = \sqrt{\frac{6^2 \cdot 3 + 3^2 \cdot 2 + 7^2 \cdot 2 + 2^2 \cdot 3}{3 + 2 + 2 + 3}} = 4.85 \text{ kW}$$

2.3 Motor power and duty types

Duty types S1 through S9 can be divided into two groups, whereby an increase or decrease of the rated power over S1 is possible or necessary:

Power increase compared to S1:	⇒ for S2, S3 and S6
Power reduction compared to S1:	⇒ for S4, S5, S7 and S8

2.3.1 Power increase compared to S1

Since in duty types S2, S3 and S6 the machine is not being operated continuously at full load, but only in blocks, it can cool down again during the stop time t_{St}, and therefore it can overloaded mechanically and thermally during the load period t_B. In determining the maximum increase the following variables play an important part:

P_n	Rated power of the motor in kW
P_{mech}	Mechanical limit rating of the motor in kW
P_{th}	Thermal limit rating of the motor in kW
M_n	Rated torque in Nm
M_K	Pull-out torque in Nm
T	Thermal time constant in minutes **(Table** 2.18.1)
k_0	Ratio of equivalent no-load/load losses **(Table** 2.18.2)
t_r	Relative duty cycle in %
h	Ratio of ventilated/unventilated heat dissipation **(Table** 2.19.1)
z_0	No-load reversing frequency per hour **(Table** 2.19.2)

To some extent the calculation is not simple. Therefore, many manufacturers of three-phase induction motors also offer computer programs for motor calculation. The proper motor can be found quickly and reliably with their aid.

2.3.2 Mechanical limit rating

When the power is increased in duty types S2, S3, and S6 the mechanical limit rating P_{mech} must be noted. Standards state: "It must be possible to overload multiphase induction motors regardless of their duty type and design for 15 seconds at the rated voltage and input frequency up to 1.6 times the rated torque." Catalog data however are subject to tolerances up to -10% so that the pull-out torque M_K should be higher by a factor of ≤ 1.76 with respect to the new increased torque M_{max}. Therefore the mechanical limit rating can be defined as follows with regard to catalog data:

Mechanical limit rating $$P_{mech} \leq \frac{M_K}{M_n} \cdot \frac{P_n}{1.76}$$

P_n = rated power in W
M_n = rated torque in Nm
M_k = pull-out torque in Nm

2.3.3 Power reduction compared to S1

In duty types S4, S5, S7, S8 and S9 the motor power must be reduced, since in all these cases starting losses or braking losses play a major part.

The computational method is based on the maximum no-load change-over frequency z_0 as shown in **Table** 2.19.2. This is the maximum allowable hourly number of reversals without the motor becoming too hot. The maximum allowable change-over frequency z for a certain load conditions can then be determined using reduction factors such as the factor of inertia, counter-torque factor, and load factor.

The factor of inertia *FI* takes into account the external moments of inertia such as the moment of inertia of the motor J_{Mot} and load moment of inertia J_{zus}:

Factor of inertia $$FI = \frac{J_{Mot} + J_{zus}}{J_{Mot}}$$

J_{Mot} = moment of inertia of the motor in kgm^2
J_{zus} = load moment of inertia in kgm^2

If the speeds of the driven machine and the motor are not the same, all moments of inertia must be converted to the motor speed n_{Mot}:

$$\textbf{Converted load moment of inertia } J_{zus} = \frac{J_1 \cdot n_1^2 + J_2 \cdot n_2^2 + ...}{n_{Mot}^2}$$

J = moment of inertia in kgm²
n = speed/min

The *counter-torque factor kg* takes into account a mean load torque M_L which is present during acceleration and which must be overcome by the mean motor torque M_{Mot}:

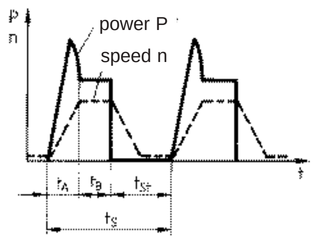
$$\textbf{Counter-torque factor } k_g = 1 - \frac{M_L}{M_{Mot}}$$

M_L = load torque M_{Mot} = motor torque

When gears with gear efficiency h_G are used and thus speeds are different, the load torques of the driven machine must be converted to the motor speed nn:

$$\textbf{Converted load torques } M_L = \frac{M_{L1} \cdot n_1}{\eta_{G1} \cdot n_n} + \frac{M_{L2} \cdot n_2}{\eta_{G2} \cdot n_n} + ...$$

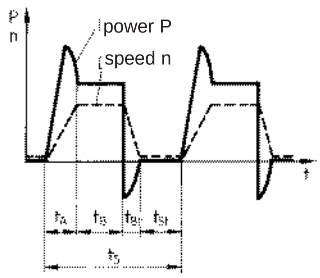
M = torque in Nm n = speed/min
η = gear efficiency



Due to the effect of the starting process with respect to heating, the rated power P_n of the motor should be chosen to be larger than is required by the actual power demand P.

t_A = starting time, t_B = load time,
t_{St} = stop period, t_S = cycle duration

Figure 2.17.1 Duty type S4 for periodic duty of an automatic machining center



Due to the effect of the starting and braking process with respect to heating, the rated power P_n of the motor should be chosen to be larger than is required by the actual power demand P.

t_A = starting time, t_B = load time,
t_{Br} = braking time, t_{St} = stop period,
t_S = cycle duration

Figure 2.17.2 Duty type S5 for periodic duty of a circular saw

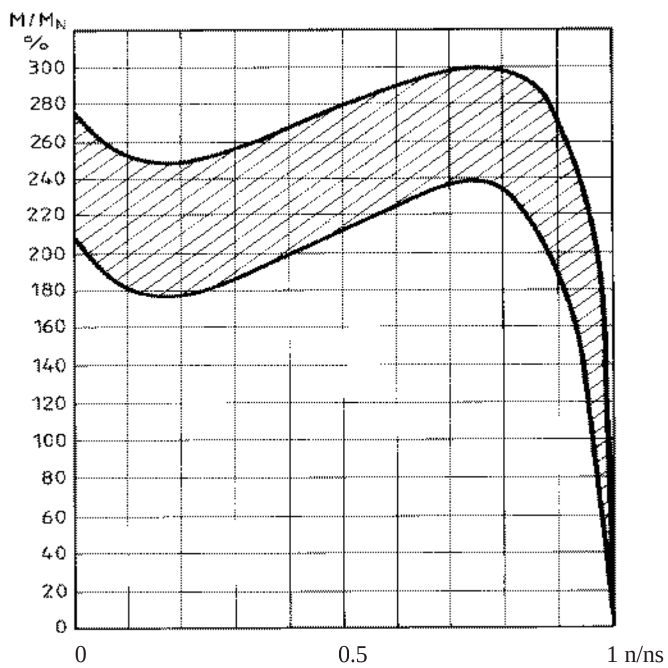


Figure 2.17.3 Typical range of variation of the torque characteristic for three-phase induction motors

The *load factor* k_L with which the load is taken into account during operation. In cases in which the load characteristic is not exactly known the following applies:

$$\textbf{Load factor } k_L = 1 - (P / P_n)^2 \cdot \frac{(1 - k_o)t_r}{(1 - k_o)t_r + (1 - t_r)h}$$

k_L = Load factor
P = Required power in kW
P_n = Rated power of the motor
k_0 = Ratio of equivalent no-load/load losses **(Table** 2.18.2
h = Ratio of ventilated /unventilated heat dissipation **(Table** 2.19.1)
t_r = Relative duty cycle (see duty types S1...S9)

P_n rated power kW	2 pole min	4 pole min	6 pole min	8 pole min
0.09 … 1.1	7 … 10	11 … 10	12	—
1.5 … 3.0	5 … 8	9 … 12	12	12 … 16
4.0	14	11	13	12
5.5 … 18.5	11 … 15	10 … 19	13 … 20	10 … 14
22 … 45	25 … 35	30 … 40	40 … 50	45 … 55
55 … 90	40	45 … 50	50 … 55	55 … 65
110 … 132	45 … 50	55	60	75

Table 2.18.1 Typical heating time constant T in minutes for induction motors

P_n rated power kW	2 pole	4 pole	6 pole	8 pole
0.09...1.5	0.35	0.45	0.5	0.5
2.2...18.5	0.25	0.25	0.3	0.3
22				
30...55	0.25	0.3	0.3	0.3
75...160	0.35	0.35	0.3	0.3

Table2.18.2 Typical ratio of equivalent losses K_O at no load to those in operation

Equivalent losses are the sum of the percentages of individual losses which contribute to heating of the winding, such as load, core and rotor losses.

P_n rated power kW	2 pole	4 pole	6 pole	8 pole
0.09...18.5	0.4	0.45	0.5	0.5
22...500	0.2	0.3	0.3	0.3

Table 2.19.1 Typical ratio h of heat dissipation between unventilated and ventilated motors

Size	2-pole	4-pole	6-pole	8-pole
56	2 300	5 000	8 000	-
63	3 000	8 600	8 000	-
71	4 000	6900	6 000	7 000
80	1 700	5 000	5 500	8 000
90S	2 000	3 000	7 900	11 000
90L	2 000	2 500	6 200	11 000
100L	1 000	4 000	5 100	10 000
112M	720	1700	3 200	2 500
132S	450	850	2 200	2 800
132M	-	1000	1 700	3 000
160M	400	900	1 700	2 300
160L	400	900	1 600	2 300
180M	200	600	-	-
180L	-	550	800	1 200
200L	150	400	620	900
225S	-	280	-	700
225M	90	270	450	670
250M	60	200	320	500
280S	41	130	260	400
280M	39	120	240	370
315S	34	100	180	300
315M	32	90	170	269

Table 2.19.2 Typical no-load change-over frequency z_0 per hour

3 Characteristic Load Torques

Motors are correctly sized when they are operated on the average with the rated torque M_n at the rated speed n_n. Then they will deliver the rated output P_n and consume the rated current I_n. The torque characteristic of most driven machines can be assigned to typical and thus characteristic curves; this greatly facilitates motor design.

Loads or *driven machines* are mechanical devices which are used to machine or shape materials, such as *machine tools, presses, calenders, centrifuge, etc.,* but also *conveyor systems such as cranes, conveyor belts, and traversing mechanisms.* Furthermore, *pumps and fans* can be combined into one group. In very large and complex machinery such as *rolling mills or paper-making machines,* the system is divided into parts and the individual motors are examined separately. The detailed structure of the driven machine is generally not considered for the motor design. Usually it can be described accurately enough by the *torque characteristic* $M_L = f(n)$ or $M_L = f(t)$, speed as a *function of time* $n = f(t)$, by the maximum *allowable acceleration/deceleration* and the entire moment of inertia, relative to the drive shaft.

The characteristics generally differ greatly between no-load and full load. The moment of inertia can also vary, depending on whether there is more or less process material in the machine.

For *motor dimensioning* and for verification of starting and braking cycles, knowledge of the behavior of the *load torque* M_L as a function of speed is extremely important.

Any driven machine applies a certain torque against the motor which is generally dependent on speed. It is also called the *steady-state torque* and is dictated essentially by the technological process. In general it acts against the direction of motion, except in lifting mechanisms during the lowering motion, where it acts in the direction of motion. In addition there are *acceleration and deceleration torques* when the speed changes; they are determined by the moment of inertia.

The load torque characteristic in a motor is often typical and can therefore be described with certain features. This is called the *classification of driven machines.*

In order to gain an overview of the many different driven machine designs, they are categorized by their typical load characteristics or output curves as shown in **Figure** 3.2.1 and **Figure** 3.4.1. Here it should be observed that for example fans and compressors exhibit different characteristics, depending on whether they are run under full load or no load. It is better to start them unloaded.

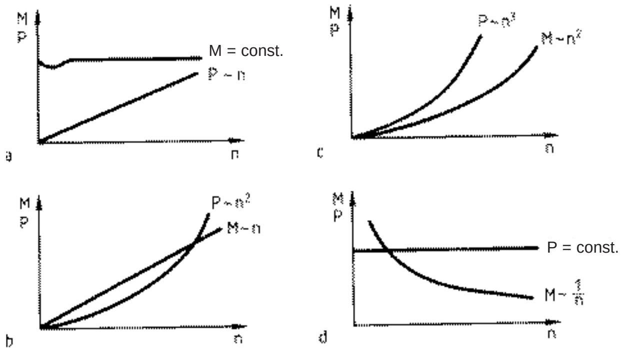


Figure 3.2.1 Torque or output characteristic for typical loads as a function of speed

a	M ≈ const.	⇒ P proportional to n
b	M ≈ proportional to n,	⇒ P proportional to n^2
c	M ≈ proportional to n^2	⇒ P proportional to n^3
d	M ≈ proportional to 1/n	⇒ P ≈ const.

In many cases the mean load torque M_{Lm} is important. For a known torque characteristic it can be determined according to the torque M_n after completed acceleration.

3.1 Load torques as a function of speed

The physical principles of motor engineering teach that the mechanical power P of a motor is a function of the torque M and speed n or angular velocity ω:

3.1.1 Torque remains constant

The torque of a driven machine results essentially from mechanical friction which remains constant in a wide range of speeds, as shown in **Figure** 3.2.1 a. During starting increased static friction must often be overcome.

$P = M \cdot 2\pi \cdot n = M \cdot \omega$

At a constant torque M the power P is proportionally a function of the speed n

$P \sim n$

Examples of mechanical loads with constant torque are:
- lifting mechanisms, elevators, winches
- machine tools with a constant cutting force
- conveyor belts, feed motors
- grinders without fan action
- piston pumps and compressors at constant pressure
- roller mills
- in part also shears and punches
- planers
- bearings, gearing

The mean load torque M_{Lm} in these applications corresponds roughly to the rated torque M_N of the load. Thus, in these applications the power P can be proportionally reduced by reducing the speed n. *Cutting the speed in half cuts the power in half.*

3.1.2 Torque increases in proportion to speed

This relationship arises as shown in **Figure** 3.2.1 for example in speed-proportional friction (viscous friction) during rolling and processing of paper, textiles or rubber tiles.

When the torque M increase proportionally, power P increases with the square of the speed n:

$P \sim n^2$

Examples are:
- calenders, extruders
- paper and textile glazing
- eddy-current brakes

The mean load torque M_{Lm} in these applications is roughly half the rated torque $M_n / 2$. When the speed n is reduced the power P decreases by its square. *When speed n is cut in half the power P is only one fourth.*

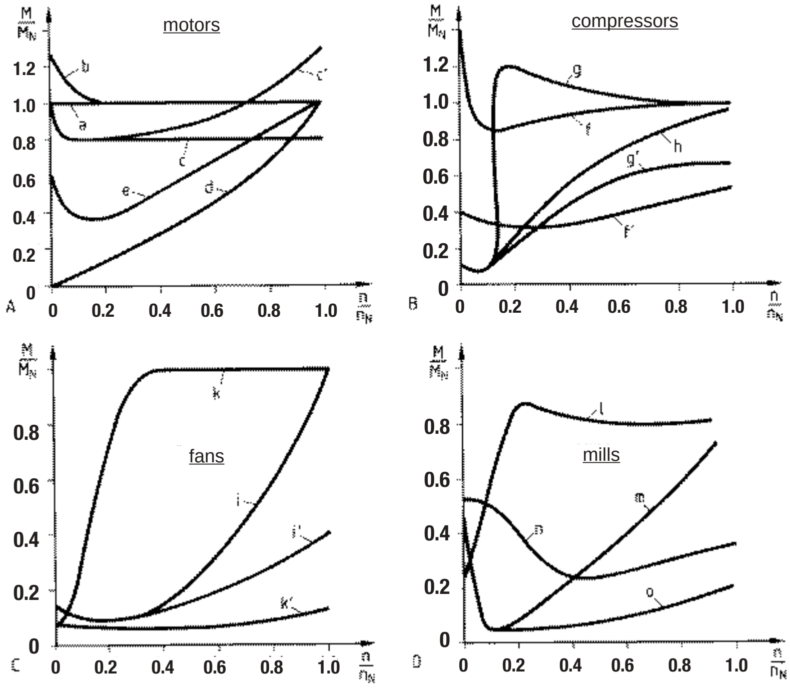


Figure 3.4.1 Typical load-torque characteristic of driven machines with start-up

A Various applications
a elevators, lifts, feed motors
b metal-cutting machine tools
c slow-speed vehicles, c' high-speed vehicles
d extruders
e calenders

B Compressors
f back-pressure piston compressors, f' unloaded
g back pressure rotary compressors, g' unloaded
h turbocompressors

C Fans
i back-pressure fans or centrifugal pumps, i' fans unloaded
k rotary piston blowers, k' unloaded

D Mills
l ball mills
m centrifugal mills
n hammer mills
o impact mills

3.1.3 Torque increases with the square of speed

This relationship arises as shown in **Figure** 3.2.1 primarily when there is gas or liquid friction.

When the torque M increases quadratically, the power P increases with the cube of the speed n.
$P \sim n^3$

Examples are:

- blowers and fans of all types
- propellers
- piston engines with delivery into an open pipe circuit
- centrifugal pumps
- stirring apparatus, centrifuges
- vehicles

The mean load torque M_{Lm} is roughly one third of the rated torque: $M_n/3$.
Because the torque M increases quadratically as the speed n increases, the power P is a function of the cube of the speed. *Cutting the speed in half requires only one eighth of the power.*
This relationship is important, for example, in pump and fan motors for heating and ventilation motors. Instead of reducing the amount of delivery with a slide valve or throttle valve, it is better to adjust the speed of the drive motor.

3.1.4 Torque decreases in inverse proportion to speed

If the torque M decreases in inverse proportion to the speed n, the power P remains constant.
$P \approx$ const.

As the speed increases, as shown in **Figure** 3.2.1, the torque drops. Examples are:

- facing lathes
- rotary peeling machines
- winding machines
- coilers

The mean load torque M_L can only be determined on a graph.

3.2 Load torques as a function of angle

These characteristics appear in machinery with *reciprocating motion*, for example, in table motors. They are also present in piston machinery (compressors in heat pumps) due to intermittent loading. The electric input current of the drive motor follows this motion cycle and can generate a rhythmically fluctuating voltage drop in the line. Generally a so-called *torque force diagram* is plotted in the planning of these applications.

3.3 Load torques as a function of path

They are typical, for example, in vehicles, or in table motors, cableways and conveyor belts.

3.4 Load torques as a function of time

These motors are loaded intermittently or periodically. Examples are:

- punches
- hoists
- conveyor systems
- rock crushers
- ball mills

3.5 Breakaway torque

Another important concept is the so-called *breakaway or static torque* which is caused by static friction. In order for a motor to start reliably, this value should be known as accurately as possible and the starting torque M_A of the motor should exceed the load torque. In large machines with slide bearings it may significantly exceed the rated torque M_n.
Figure 3.4.1 shows certain torque characteristics of common driven machines. Comparison with **Figure** 3.2.1 shows that most of them have a typical characteristic and thus classification is possible.

Example: The speed of an induction motor operated with a load controller can be infinitely adjusted between 50% and 100%. How does this affect the delivery rate of a piston or centrifugal pump?

- *Piston pump:* The torque demand is almost independent of speed as shown in **Figure** 3.2.1 a, and the torque remains almost constant. The delivery output is therefore proportional to the speed. At half speed it also falls accordingly to $P' = P \cdot 0.50 = 50\%$

- *Centrifugal pump:* In centrifugal pumps, as shown in **Figure** 3.2.1 c, there is a quadratic relationship between torque demand and speed. Therefore the power changes in the cube. At half-speed the power is thus $P' = P \cdot 0.5^3 = 0.125 = 12.5\%$. The delivery rate can therefore be reduced to one eighth of the original value.

The example shows how automatic speed control greatly influences the power of a driven machine.

4 Choosing and Dimensioning Electric Motors

Electric motors are energy converters for *kinematic processes* as they occur in the technology of most driven machines. Examples are:

- *Motor applications:*
  - machine tools
  - cranes, elevators, vehicles
  - pumps, fans, compressors
  - presses, bending machines, rolling mills, calenders, etc.
- *Actuator processes:*
  -slides and valves
  - feed devices, robot applications
  - kinematic processes in control linkages

All kinematic processes involve the quantities *force* - *torque* - *power* - *energy and time.* Solids, liquids, or gases change their location as a function of time. But other concepts such as *velocity, acceleration, efficiency,* etc., also play a part. Electric motors draw energy from a utility supply and convert it into mechanical energy. Auxiliary devices such as clutches, transmissions, gears, brakes and driven machines can be located between the motor and the actual load, i.e., the moving solid, liquid, or gas. To choose and dimension a motor the relevant parameters of all element in the chain of energy flow, starting with the actual load, must be determined with relative accuracy. Proper selection is therefore important. For proper selection of a motor it is necessary to find an ideal motor for the kinematic task at hand. Even more important than the appropriate motor type with accessories such as gears, brakes, clutches, etc., is the proper sizing of the motor.
An undersized motor will fail in continuous duty. An oversized motor causes unnecessary expenses, runs uneconomically (greater procurement costs, poorer operating efficiency and higher losses, requires more reactive power) and may load the machine with an excessively high acceleration torque.

In any case, the basic application conditions will have to be defined, whereby the following factors are significant:

- *power transmission:* As a single drive the motor can be coupled to the load directly or via a transmission, or it can be used as a central motor connected to intermediate shafts, belt and chain drives, etc.
- *operating conditions* such as overload capacity, frequency of starting, operating mode, peak torques, ambient temperature, etc., affect not only the motor size requirement, but also the selection of motor accessories.
- *space conditions* and the layout possibilities of the entire system affect mainly the choice of motor accessories.

4.1 Motor Capacity

The *three-phase induction motor* is most widely used in drive technologies because of its simple mechanical and electrical structure and due to its high reliability. Its application is limited only by its torque and speed characteristics.

In the *stator winding* as well as in the *rotor* the current passage generates heat; this heat may not exceed the temperatures specified for insulation materials *IP class.* The temperatures which develop depend on the level of the motor load, its variation over time, and cooling conditions. Motors should be sized such that at constant load with rated power and rated cooling conditions they do not exceed maximum temperatures.

- The *torque required for accelerating* the centrifugal mass increases motor acceleration time. The *starting current* flowing during this time heats up the winding dramatically.
- The maximum *change-over frequency*, i.e., the number of consecutive starts, is limited. During frequent starting processes the motor reaches its allowable temperature limit even without load torque and without an additional centrifugal mass.
- The *duty cycle* is another important factor for selection. The cooling time at switching intervals must be long enough to ensure that the temperature limit is not exceeded during subsequent starting. If the duty cycle is short, the motor can accept a higher load since it cannot heat up to the temperature limit during this short time and cools down again during the intervals.
- Undersized motors can be thermally overloaded because of an overly long starting time, whereas oversized motors would overload the transmission and the driven machine during the starting process.

4.1.1 Catalog data and application parameters

For most application requirements a so-called "standard motor", usually an induction motor, is used. The following information applies to this type of motor unless indicated otherwise. Induction motors can be used in a wide range of applications. In order to select a suitable motor in accordance with manufacturer specifications minimum requirements must be established. The objective is to establish requirements regarding

- *power supply*
- *electrical and mechanical characteristics of the motor*
- *operating conditions*
- *investment, operating and maintenance costs*
- *service life*
- *environmental protection and accident protection measures.*

Based on these requirements, a suitable motor and appropriate auxiliary devices can be selected.

Selection factor		**Motor feature**
Torque	⇒	*Power*
Moment of inertia	⇒	*Starting time*
Typical load torques	⇒	*Motor torque*
Design analysis by	⇒	*Optimization*
- load torque		- motor torque
- acceleration torque		- starting time
- acceleration time		- acceleration capacity
- reversing frequency		- motor heating
Operating modes	⇒	*Motor heating*
Starting conditions	⇒	*Torque characteristic*
Braking and reversing	⇒	*Brake heat*
Thermal processes	⇒	*Capacity*

Table 4.3.1 Selection factors for motor type and rated power

4.1.2 Determination of unit rating

The unit rating of a motor can be determined according to various aspects, since every application requirement is different. The outline in **Table** 4.3.1 indicates which selection factors are important:

4.1.3 Catalog data

The degree to which an individual motor meets requirements can be determined by comparison of the motor to the manufacturer's catalog data. **Table** 4.5.1 lists the most important parameters to be observed, depending on the application. Some of these parameters have been standardized, others are specific to the manufacturer or can be selected by the customer, generally from several alternatives. Therefore the design engineer often has a certain freedom of choice in defining the details of a motor. Many manufacturers offer modular motor designs. The following specifications can usually be defined when ordering

- *rotor design* and thus the torque characteristic
- *cooling system*
- *insulation* class of the windings
- *style*
- *type of installation*
- *degree of protection* and protective devices as well as other data.

4.1.4 Operating conditions

For design purposes the operating conditions and the parameters of the driven load are as important as the motor data.
Table 4.6.1 shows the most important data to be observed for design. In critical cases the proper drive motor for the given motor task should be selected in cooperation with the motor supplier.

4.1.5 Procedure for selecting motors

Most motors are operated in continuous duty S1. The first selection consideration is the output in continuous duty. Since the service life of electrical machinery depends largely on the continuous operating temperature, the choice must be made carefully. As a second step, the suitability of the motor for the starting conditions should be examined with respect to starting time or starting torque. In motors with complex operating modes (S2 ... S9) basically the same considerations apply, whereas consultations with the suppliers are usually necessary due to the changing load conditions and the fluctuating winding temperatures.

Data to be defined		Remarks
Electrical requirements		
Type of current		Operating voltage, for multi-
Three-phase current,		voltage motors indicate all
single phase current	V	values and possible tolerances
Frequency	Hz	
Catalog Data		
Type designation		Manufacturer specifications
Rating		For motors with several speeds, rating per speed
Speed		For motors with several poles, speed per output
Rated current	A	Manufacturer specifications
Breakaway starting/rated current		Manufacturer specifications
Torque	Nm	For special applications
Breakaway/rated torque		Manufacturer specifications
Pull-up/rated torque		Manufacturer specifications
Pull-out/rated torque		Manufacturer specifications
Moment of inertia	kgm^2	Manufacturer specifications
Efficiency η	%	Manufacturer specifications
Max. blocking time	s	Manufacturer specifications
Max. starting time	s	Manufacturer specifications
Tolerances		Established in standards
Type of design		
Switching		For star-delta starting, always
Delta, star		specify delta
Rotor type		
Cage rotor, wound rotor		
Model	IM..	IEC 34-7, Part 7
Type of protection	IP..	IEC 34-7, Part 7
Type of cooling		
Natural, inner cooling		
Self, surface cooling		
Separate, closed circuit cooling		
Insulation class		
B, F, H		Indicate temp. limit, if required
Vibration amplitude		Normal or reduced
Noise level	db	
Special regulations		Elect. and mech. regulations
Terminal box		Indicate type of protection and design if necessary
Shaft ends		Indicate type of protection and design if necessary
Built-on, built-in components		Indicate switch or plug, if necessary
Brakes, tachogenerator		
Separately ventilation, space heater		
Temperature measuring instruments		For bearings or stator windings
- Thermistor protection		
- Bimetallic switch		Make contacts or break contacts
- PTC resistors		

Table 4.5.1 Catalog data for motors

Data to be defined		Remarks
Counter-torque	**Nm**	Convert for motor shaft if nec.
- constant		
- quadratically increasing		
- special curve		Discuss with manufacturer, if necessary
Moment of inertia of load	kgm^2	Convert for max. motor speed
Type of starting		
- star-delta		Intensified star-delta starting, if req.
- full load starting		
- no-load starting		
- other methods		Soft starter or load controller, if req.
Electrical braking		Plugging or dynamic braking
Operating mode		
S1		Continuous operation
S2	min	Temporary duty
S3	%	Intermittent periodic duty-type without starting
S4	%, c/h	Intermittent periodic duty with starting
S5	%, c/h	Intermittent periodic duty with starting and electrical braking
S6	%	Continuous-operation duty type
S7	c/h	Continuous operation-duty with starting and electrical braking
S8	%, c/h	Continuous-operation periodic duty with related load /speed changes
S9		Duty with nonperiodic load and speed variations
Ambient temperature	^oC	
Altitude	meters above sea level	
Direction of rotation		clockwise, counterclockwise, or both
Speed adjustment		method and from...to...
Climatic influences		Also consider relative humidity
Bearing and shaft load		
Axial force	N	Force direction with respect to shaft position
Radial force	N	Indicate distance from shaft shoulder
Rotary forces	N	

Table 4.6.1 Important data for motor design

4.2 Dimensioning using load torque

The load torque M_L results from the counter-torque of the driven machine plus the efficiency η with which all mechanical losses are recorded.
According to the load characteristics the load torque during acceleration can

- gradually build up (for example, fan)
- reach the rated value at the start (for example, hoists)
- be present only after acceleration (for example, wood-working machines)
- be present constantly or intermittently

For a constant load torque M_L = const. and rated speed n, the calculation is done using the following relation:

$$\textbf{Power P} = \frac{\mathbf{M \cdot n}}{\mathbf{9.55} \cdot \eta}$$

P = power in W
M = torque in Nm
n = speed/min
η = efficiency

In a hoist, for lifting power P with a certain speed v and force F, and with consideration of efficiency η, we find:

$$\textbf{Power P} = \frac{\mathbf{F \cdot v}}{\eta}$$

P = lifting power in W
F = lifting force in N
v = lifting speed in m/s
η = efficiency

At any time during acceleration the load torque M_L must be lower than the respective motor torque M_M. If this is not the case, no acceleration to higher speeds takes place.

4.3 Calculation using acceleration torque or acceleration time

4.3.1 Acceleration torque

A load can only be accelerated when the driving motor provides a greater torque than the load requires at the time. The difference is called the *acceleration torque* M_B. The acceleration torque and the flywheel moment of the motor, transmission, and system to be accelerated yield the acceleration time t_A. In many cases the simplified assumption is made that the load torque is constant during acceleration. This assumption is reached by calculating an average load torque and replacing the variable motor torque by a constant mean acceleration torque which is determined from the characteristic.

For a certain starting time t_A the required acceleration torque M_B is computed as follows:

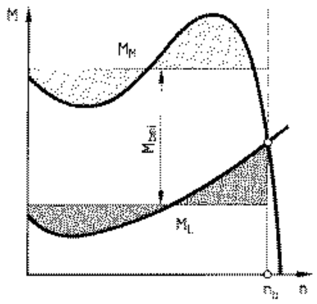
Acceleration torque

$$\mathbf{M_B = M_m - M_L = J' \cdot \alpha = J' \cdot \frac{\omega}{t_A} = \frac{J' \cdot 2\pi \cdot n}{60 \cdot t_A} = \frac{J' \cdot n}{9.55 \cdot t_A}}$$

M_M	= motor torque in Nm		M_L	= load torque in Nm
t_A	= starting time in s		α	= angular acceleration/s²
n	= motor speed/min		ω	= angular speed/s
M_B	= mean acceleration torque in Nm			
J'	= moment of inertia in kgm² reduced to the motor shaft			

4.3.2 Acceleration time

The acceleration time t_A can be determined from the relation above, if the mean acceleration torque M_B is known. A relatively simple method of determining it is shown in **Figure** 4.8.1. The motor torque M_M and load torque M_L are plotted on graph paper and then the mean torques can be defined graphically, e.g., by counting the squares. The final diagram will show the mean acceleration torque M_B.



M_M	motor torque
M_L	load torque
M_{bmi}	mean acceleration torque
n_b	operating speed

Figure 4.8.1 Determining the mean acceleration torque by balancing the area on graph paper

Acceleration time in s $t_A = \dfrac{J' \cdot n}{9.55 \cdot M_B}$

M_B = mean acceleration torque in Nm
J' = moment of inertia reduced to the motor shaft in kgm²
n = motor speed/min

Example: Let a two-pole motor with n = 2980 rpm, P = 110 kW, J = 1.3 kgm² at no-load have an average acceleration torque $M_B = 1.5 \,.\, M_n$. How long is

a) the starting time at no-load?

b) the starting time together with a load of J_L = 1000 kgm² at a speed of n_L = 300 rpm if it continuously demands the rated torque during acceleration?

Solution: a) Starting time at no-load

Rated torque of the motor $M_n = \dfrac{P \cdot 60}{2\pi \cdot n} = \dfrac{110\,000 \text{ W} \cdot 60}{2\pi \cdot 2\,980/\text{min}} = 352.5 \text{ Nm}$

Acceleration torque $M_B = 1.5 \cdot M_n = 1.5 \cdot 352 \text{ Nm} = 528.7 \text{ Nm}$

Acceleration time $t_A = \dfrac{J \cdot n}{9.55 \cdot M_B} = \dfrac{1.3 \text{ kgm}^2 \cdot 2\,980 \text{ VPM}}{9.55 \cdot 528.7 \text{ Nm}} = \mathbf{0.76\ s}$

b) Acceleration time with load

The moment of inertia of the load converted to the motor speed is:

$J' = J_L \cdot (n_L/n)^2 = 1000 \text{ kgm}^2 \cdot (300 \text{ rpm}/2980 \text{ rpm})^2 = 10.1 \text{ kgm}^2$

The effective acceleration moment together with the load can be derived from the difference of the mean acceleration torque of the motor minus the continuously demanded rated torque of the load:

$M_B = 1.5M_n - M_n = 0.5 \cdot M_n$

Acceleration time $t_A = \dfrac{(J' + J_{Mot}) \cdot n}{9.55 \cdot M_B} = \dfrac{(10.1+1.3) \text{ kgm}^2 \cdot 2\,980 \text{ rpm}}{9.55 \cdot 0.5 \cdot 352.5 \text{ Nm}} = \mathbf{20\ s}$

In choosing the motor the acceleration time t_A, with consideration of the change-over frequency, must be shorter than the maximum time specified by the manufacturer. Unloaded motors and motors with only little additional centrifugal masses such as clutches. etc. reach their idle speed very quickly. This is also generally the case in starting with a load. Only when large centrifugal masses must be accelerated are starting times very long. This is called *heavy starting*, which is the case, for example, in centrifuges, ball mills, calenders, transport systems and large fans. These applications often require special motors and the corresponding switchgear. **Figure** 4.10.1 shows the reference values for the starting time of standard motors as a function of rated power.

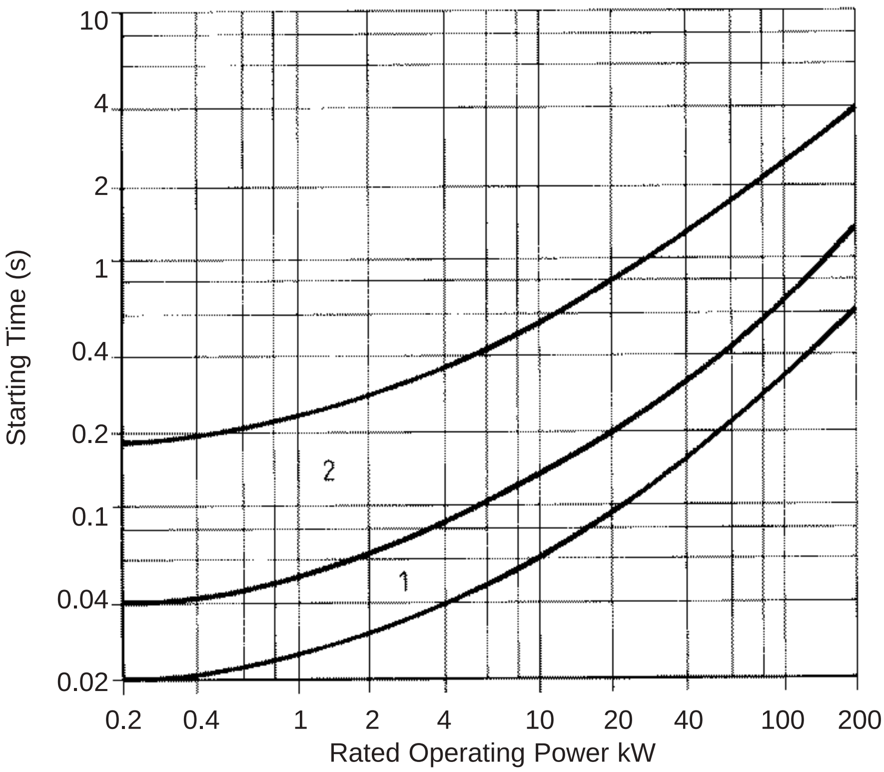


Figure 4.10.1 Typical reference values for starting time of standard motors as a function of rated operating power
1 no-load starting (motor + clutch)
2 starting under load (without large centrifugal mass)

If the curve of the load torque M_L is complex and the motor torque M_M is not constant, it is advantageous to divide the computation into individual zones as shown in **Figure** 4.11.1 Then the acceleration times for the individual zones plus the average acceleration torques which take effect in the segment are computed and added for the individual speed segments (for example, 20% speed increase per segment).

Acceleration time for non-constant torques

$$\mathbf{t_A = \frac{\sum J' \cdot \Delta n}{9.55 \cdot M_B}}$$

t_A = starting time in s
J' = moment of inertia reduced to the motor shaft in kgm²
Δn = speed difference in rpm
M_B = acceleration torque in Nm

4.4 Calculation using change-over frequency

Frequent starting of motors is called *switching mode* and the maximum *change-over frequency per hour* must be checked. The manufacturer's data usually show the allowable no-load switching per hour, i.e., the number of change-overs at which the motor reaches its maximum temperature without load and without an additional flywheel moment during idle operation. The frequency of change-over plays an important role in operating mode S4.
The allowable frequency of change-over of a motor is determined by its temperature limit. It is derived from the square mean value of current from the cycle characteristic. This mean value may not exceed the rated current of the machine.

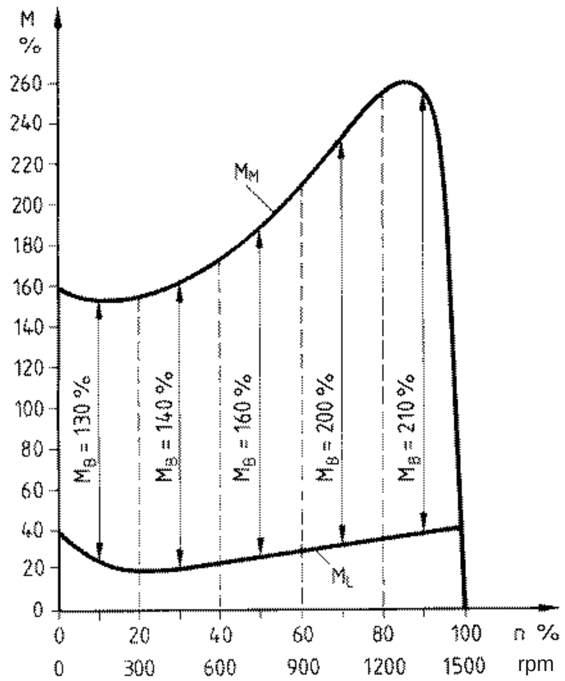


Figure 4.11.1 Acceleration torque for computing the acceleration time when the motor torque M_M and the load torque M_L are not constant and exhibit a dramatically different behavior.

Excessive change-overs which cause a response of protective devices or even destruction of the motor often occur during the commissioning phase, adjustments, and jogging.
Often an *additional inertia mass* causes a load condition. In this case the number of allowable switchings z_z per hour can be computed based on the switching mode energy principle:

Allowable switching operations with additional mass

$$\mathbf{z_z = \frac{z_0 \cdot J_M}{J_M + J_z}}$$

z_z = allowable switching operations per hour with additional mass
z_0 = allowable no-load switching operations per hour
J_M= Massenträgheitsmoment des Motors in kgm^2
J_z= reduced additional mass moment of inertia in kgm^2

In switched duty with an existing load moment M_L the number of allowable switchings z_L per hour is determined as follows:

Allowable switchings with load torque

$$\mathbf{z_L = \frac{z_0 \cdot (M_M - M_L)}{M_M}}$$

z_L = allowable switchings per hour with load torque
z_0 = allowable no-load switching operations per hour
M_M = mean motor torque during acceleration in Nm
M_L = mean load torque during acceleration in Nm

In practice there are usually a load flywheel J_z and an additional load torque M_L. Thus the following applies to the number z_{Zul} of allowable switchings per hour:

$$z_{Zul} = z_z \cdot \frac{z_L}{z_0} = z_0 \cdot \frac{J_M \cdot (M_M - M_L)}{(J_Z + J_M) \cdot M_M}$$ and converted:

Allowable switchings with additional load and flywheel moment

$$z_L = z_0 \cdot \frac{1 - M_{Lmi} / M_{Mmi}}{1 + J_z / J_M}$$

z_L = allowable switching operations per hour with load flywheel and load torque
z_0 = allowable no-load switchings
M_{Mmi} = mean motor torque during acceleration in Nm
M_{Lmi} = mean load torque during acceleration in Nm
J_z = reduced additional mass moment of inertia in kgm^2
J_M = mass moment of inertia of the motor in kgm^2

P_n Rated power kW	2-pole	4-pole	6-pole	8-pole
0.09...1.5	1500...4000	2500...8500	5500...8000	7000...11000
2.2...18.5	400...1000	800...4000	1500...5000	2000...10000
22	200	600	800	1200
30...55	50...150	200...400	300...600	500...900
75...160	30...40	90...130	170...260	270...400

Table 4.13.1 Typical no-load change-over frequency z_0 per hour

4.5 Choosing with the use of catalog data

Using the mean values for power P_{mi}, torque M_{mi} and current Imi that were computed for less demanding conditions a motor can be chosen using catalog data, whereby the corresponding catalog data may not be less than the computed averages:

$P_{mi} \leq P_n$, $M_{mi} \leq M_n$, $I_{mi} \leq I_n$

Most motor applications can be assigned to the 9 duty types S1 through S9. In more complex situations, where a definite selection is not possible, a similar duty type can be defined and then converted to S1. This method, however, requires detailed knowledge with respect to thermal time constants and cooling conditions. The motor manufacturer can supply these data.

5 Equation Symbols

Symbol	Meaning	Unit	Remark
f	frequency	s^{-1}	line frequency
FI	factor of inertia		
h	ratio of ventilated/ unventilated heat release		
I	current	A	supply line current
I_{mi}	mean current (I_{eff})	A	effective value
I_n	rated current	A	maximum continuous current
J'	moment of inertia reduced to the motor shaft	kgm^2	
J_{ext}	load moment of inertia in reference to the motor shaft	kgm^2	
J_M	moment of inertia of motor	kgm^2	
J_{mot}	motor moment of inertia	kgm^2	
J_Z	reduced additional mass moment of inertia	kgm^2	
J_{zus}	additional moment of inertia	kgm^2	
k_0	ratio of equivalent load/no-load losses		
k_g	counter-torque factor	Nm	
k_L	load factor	Nm	
M	torque	Nm	
M_A	breakaway torque	Nm	
M_B	acceleration torque	Nm	
M_K	pull-out torque	Nm	
M_L	load torque	Nm	
M_{Lmi}	mean load torque during acceleration	Nm	
M_M	motor torque	Nm	
M_{Mmi}	mean motor torque during acceleration	Nm	
M_{mi}	mean torque	Nm	
M_n	rated torque	Nm	
M_S	pull-up torque	Nm	

Symbol	Meaning	Unit	Remark
n	speed	rpm	
n	operating speed	rpm	
n_0	no-load speed	rpm	
n_n	rated speed	rpm	
n_s	synchronous speed	rpm	
p	pole pair number (pole number/2)		
P	power	kW	
P_2	output power	kW	
P_1	input power	kW	
P_{Cu}	load loss	kW	
P_{CuR}	ohmic loss in rotor	kW	square function of current
P_{CuS}	ohmic loss in stator	kW	square function of current
P_{Fe}	core loss in stator	kW	roughly constant in operation
P_{La}	bearing friction loss	kW	roughly constant in operation
P_{Lu}	windage loss	kW	roughly constant in operation
P_{mech}	motor mech. limit rating	kW	
P_{mi}	average power	kW	
P_n	rated power	kW	
P_{th}	thermal limit rating	kW	
P_v	losses	kW	
P_{VR}	loss in rotor	kW	
P_{zus}	stray loss	kW	roughly constant in operation
s	slip	kW	
S1	continuous duty		
S2	temporary duty		
S3	intermittent periodic duty-type		...without starting
S4	intermittent periodic duty		...with starting
S5	intermittent periodic duty		...with starting and electrical braking

Symbol	Meaning	Unit	Remark
S6	continuous-operation duty type		... with interucittent periodic load
S7	continuous-operation duty		... with starting and electrical braking
S8	continuous-operation periodic duty		... with related load /speed changes
S9	duty		with non-periodic load and speed variations
t	time	s, min, h	
T	thermal time constant	min	
t_A	starting time	s, min	
t_B	load time, operating time	s, min	
t_B	operating time	s, min	
t_{Br}	braking time	s, min	
t_L	no-load time	s, min, h	
t_r	relative duty cycle	%	
t_S	cycle duration	s, min, h	
t_{St}	stopping time	s, min, h	
U	voltage	V	
z_0	no-load change-over		
	frequency	h^{-1} (per hour)	
z_A	no-load starting		
	frequency	h^{-1}	
z_L	allowable switching operations per hour with load torque and possible additional mass	h^{-1}	
z_z	allowable switching operations per hour with additional mass	h^{-1}	
z_{zul}	allowable change-over frequency	h^{-1}	
η	efficiency	%	
ϑ	temperature	°C	
ϑ_{max}	maximum temperature	°C	
Δn	speed differential	rpm	
$\cos\varphi$	power factor		

Table of symbols and units

More than 350,000 possibilities for improving your automation system

Power equipment
Power contactors and motor starters
Motor protection
Motor control centers
Power monitoring
Control and load switches
Relays

Sensor technology
Limit, photoelectric and proximity switches
Pressure and temperature sensors
Identification systems (HF)
Bar code reader systems
Encoders
Image processing systems

Controllers
Control devices and signalling units
Text and LCD displays
Control consoles
Industrial computers
Visualization software

Drive engineering
Soft starters
Frequency converters
AC and DC drives
Axis controls and servo drives
CNC controls

Automation
Programmable controls
Digital and analog I/O
Intelligent peripheral modules

Communications
Networks and field bus systems
Open communications networks (MAP)

System solutions
Custom developments
Process/batch controls
Burner controls
Die-casting and press controls
SCADA

Quality assurance
Statistic data acquisition and analysis

Service
Worldwide service and support
Customer training
Repair and spare parts service
Technical consultation

Germany

Rockwell Automation GmbH
Zweigniederlassung der
Rockwell International GmbH
Düsselberger Straße 15
D-42781 Haan
Telephone 02104-960-0
Fax 02104-960-121

Austria

Rockwell Automation GmbH
Bäckermühlweg 1
A-4030 Linz
Telephone 07-38909
Fax 07-385 651 61

Switzerland

Rockwell Automation AG
Verkaufszentrum Gewerbepark
Postfach 64
CH-5506 Mägenwil
Telephone 062 889 77 77
Fax 062 889 77 66

Reach us now at www.rockwellautomation.com

Wherever you need us, Rockwell Automation brings together leading brands in industrial automation including Allen-Bradley controls, Reliance Electric power transmission products, Dodge mechanical power transmission components, and Rockwell Software. Rockwell Automation’s unique, flexible approach to helping customers achieve a competitive advantage is supported by thousands of authorized partners, distributors and system integrators around the world.

Americas Headquarters, 1201 South Second Street, Milwaukee, WI 53204, USA, Tel: (1) 414 382-2000, Fax: (1) 414 382-4444
European Headquarters SA/NV, avenue Herrmann Debroux, 46, 1160 Brussels, Belgium, Tel: (32) 2 663 06 00, Fax: (32) 2 663 06 40
Asia Pacific Headquarters, 27/F Citicorp Centre, 18 Whitfield Road, Causeway Bay, Hong Kong, Tel: (852) 2887 4788, Fax: (852) 2508 1846

Publication WP-Motors, Nov. 96

Printed in Switzerland