

Handbook | VLT® Frequency Converters

Facts Worth Knowing about Frequency Converters



Preface

In 1968, Danfoss was the first company in the world to commence mass production of Frequency Converters, for variable speed control of three-phase induction motors. Today FC's are an increasingly important component for optimising motor operation, and the system attached to the motor. FC's are now used in an expanding range of applications, with the following main objectives in mind:

- Energy efficiency optimisation: Converting from fixed to variable speed in applications with varying load, delivers a step change in energy savings. In fact these days, modern motor technology always requires advanced control in order to run optimally at all speeds.
- Factory automation: Continuously escalating demand for factory throughput leading to a higher degree of automation implies a growing need for variable speed solutions.
- Process control and optimisation: Improved process control often requires variable speed motor control and leads to more precise control, higher throughput, or comfort, depending on the application.

The fundamentals of FC technology persist, but many elements are also rapidly changing. Increasingly, software is embedded in today's products, offering new functionalities and enabling the FC to play a larger role in the system. New motor types are appearing, placing additional demands on motor control. This in turn means the FC must be able to control an expanding variety of motor types, without burdening the end user with more complexity. In addition, new energy efficiency requirements lead to more variable speed applications, eventually making all motors variable speed and controlled by a FC.

With this latest update of "Facts worth knowing about frequency converters", we at Danfoss would like to continue the heritage from previous versions of this book. We are proud of what we do and are enthusiastic about FC's. With this book we hope to convey some of this enthusiasm to you!

If you would like to learn more, please feel free to contact Danfoss.

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0 Introduction

By definition, a Frequency Converter (FC) (or frequency changer) is an electronic device that converts alternating current (AC) of one frequency to another frequency. Traditionally, these devices were electro-mechanical machines (motor-generator set). They are sometimes referred to as “dynamic” FC’s. With the invention of solid state electronics, it has become possible to build completely electronic FC’s, which are often referred to as “static” FC’s (no moving parts).

Whilst the principle of converting fixed mains voltage and frequency into variable quantities has always remained virtually the same, there have been many improvements from the first FC’s, which featured thyristors and analogue technology, to today’s microprocessor-controlled, digital units.

Because of the ever-increasing degree of automation in industry, there is a constant need for more automated control and a steady increase in production speeds, so better methods to further improve the efficiency of production plants are being developed all the time.

Today, the FC-controlled, three-phase motor is a standard element in all automated process plants, commercial and public buildings. High-efficiency Induction motors, but especially motor designs such as Permanent Magnet motors, EC motors and Synchronous Reluctance Motors, need regulation with FC’s, many motors cannot even be operated directly from the 3 phase standard power supply.

0.1 Speed Control of Electrical Motors

Different terminologies are used for systems that can control or alter the speed of electrical motors. The most commonly used ones are:

- Frequency Converter (FC)
- Variable Speed Drive (VSD)
- Adjustable Speed Drive (ASD)
- Adjustable Frequency Drive (AFD)
- Variable Frequency Drive (VFD)

While VSD and ASD refer to speed control in general, AFD and VFD are directly connected to adjusting the feeding frequency of a motor. In this context, the abbreviation “drive” is used as well. Throughout this book, the terminology Frequency Converter will be widely used. This wording covers the power electronic part of the devices and the supporting components like current sensors, I/Os and Human Machine Interface (HMI).

0.2 Why use Speed Control?

There are numerous reasons for adjusting the speed of an application:

- Save energy and improve efficiency of systems
- Match the speed of the drive to the process requirements
- Match the torque or power of a drive to the process requirements
- Improve the working environment
- Reduce mechanical stress on machines
- Lower noise levels, for example on fans and pumps

Depending on the application one or the other benefit is predominant. However, speed control is proven to bring significant advantages in many different applications.

0.3 How to Adjust the Motor Speed?

There are three main technologies to realise speed control used in industry. Each has its unique features:

Hydraulic

- Hydro-dynamic type
- Static types

They are often favoured in conveyor applications especially for earth-moving and mining equipment. This is basically due to inherent “soft start” capability of the hydraulic unit.

Mechanical

- Belt and chain drives (with adjustable diameters).
- Friction drives (metallic)
- Variable speed gear

Mechanical solutions are still favoured by many engineers – especially mechanical engineers – for some applications, mainly because of their simplicity and low cost

Electrical

- FC with electrical motor
- Servo systems (for example servo amplifier and servo PM motor)
- DC motor with control electronics
- Slip-ring motor (slip control with wound-rotor induction motor)

Historically, electrical devices for speed control were complex to handle and expensive. They were used for the most challenging tasks where no alternatives were available. The provided list of technical solutions for speed control of motors is not exhaustive

and shall give an insight of the possibilities only. This book will focus on speed control of electrical motors by FC's.

0.4 Frequency Converters

Modern Frequency Converters can be applied to adjust and maintain the speed or torque of a driven machine with an accuracy within $\pm 0.5\%$. This is independent of the load when compared to fixed speed operation of the induction motor, where the speed can vary by as much as 3 – 5% (slip) from no-load to full-load operation.

Motor manufacturers employ a variety of concepts to achieve high efficiency in electrical motors. For users it can be difficult to see the main benefit from one technology to another, but the user will surely observe that energy efficient motors need high technology controls.

In principle, nearly all motors can be operated with control algorithms specially adapted to each motor type. Some manufacturers of FC's relate their design to a narrow group of motor technologies, but many manufacturers have the different algorithms built-in and selectable during commissioning.

For the commissioner it is important that the FC is easy to commission based on data, normally available for the motor type which is used. After commissioning the user must be confident that the system is really as easy as expected, thus online measurements of actual energy consumption and easy access to important data about the operation is essential.

To ease the selection and ensure the various Government aims of reduction of energy consumption, there is a big motivation for a complete set of regulations.

It must be borne in mind that all system components are important for potential energy savings. According to the German Association of Electrical and Electronics Manufacturers (ZVEI), approximately 10% of the savings can be achieved by using high-efficiency motors, 30% of the savings are achieved by variable speed, but as much as 60% of the potential savings are achieved by looking at the overall system and optimising accordingly.

With that in mind, please read all chapters in this book and remember you cannot judge a system by looking at only one or few of the components involved.

We wish you an interesting read.

1 Electric Motors

1.1 Overview

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. The reverse process of producing electrical energy from mechanical energy is performed by a generator.

The operating demands of the electric motor, especially in industry, have been enormous. Robustness, reliability, size, energy efficiency, and price are only some of these criteria. The differing needs have resulted in the development of different types of electric motors. The following diagram gives a general overview of the most commonly used electric motor technologies.

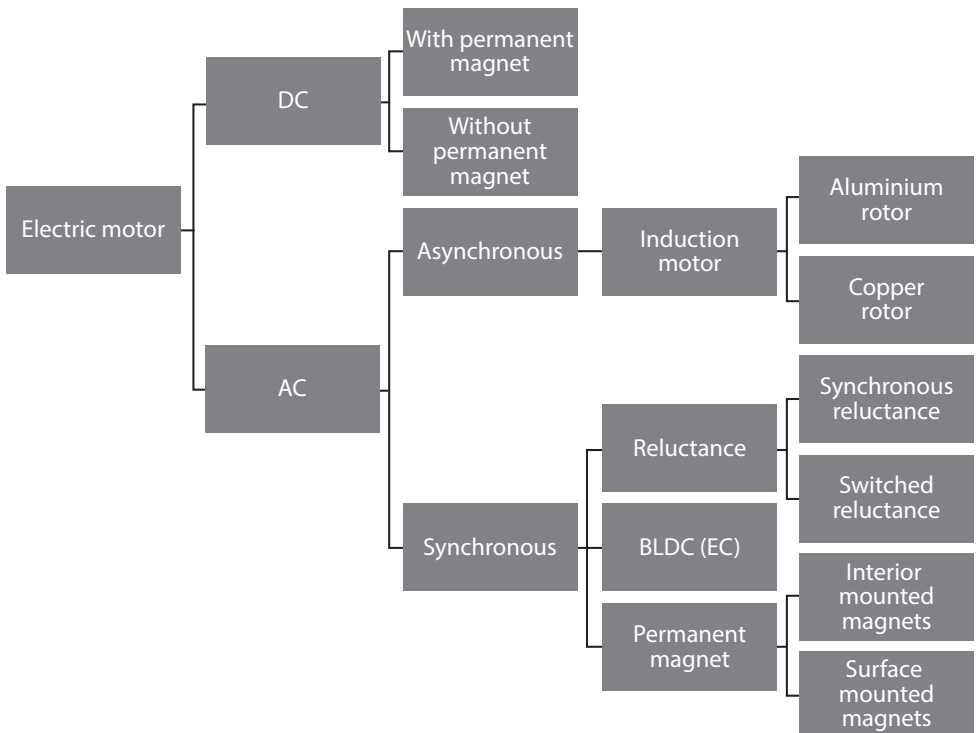


Fig. 1.1 Overview of the most common electric motor technologies

1.2 Fundamentals

1.2.1 Stator and Rotor

The construction of all rotating electric motors consists in principle of two main components.

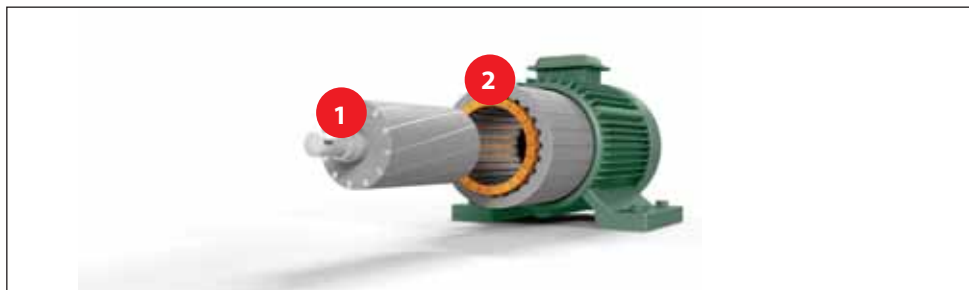


Fig. 1.2 Construction of the asynchronous motor

Stator

The stator (1) is the stationary part of the motor which holds packages of laminations where the electrical windings are placed.

Rotor

The rotor (2) is the rotating part of the motor which is mounted on the motor shaft. Like the stator, the rotor is made of thin iron laminations which hold the rotor windings.

One variation is the outer rotor motor. Unlike the inner rotor design, the stator is placed in the middle of the motor and the rotor rotates around the stator. This construction is used in some fan applications where the fan blades are directly mounted on the rotor. Unless otherwise mentioned, all the following explanations are related to inner rotor design.

The connection dimensions of typical industrial motors are defined in IEC standards. However not all motors fulfill these requirements. For example, NEMA frame motor dimensions differ from IEC standards, due to the conversion from the metric to the imperial system.

1.2.2 Power and Torque

The rated output of electric motors is defined within a standard range. This standardisation allows users to choose between different motor manufacturers for specific applications. The “standard” output range and its increments differ from country to country and region to region. It is recommended to find out what manufacturers define as standard in their catalogues. On average, motors with frame size up to 315 (ca. 200 kW) can be regarded as standard motors with standard dimensions.

Horsepower [hp] is the imperial unit used for motor power. If this unit is specified, it can be converted as follows: 1 hp = 0.736 kW or 1 kW = 1.341 hp.

Table 1.1 shows the typical industrial standard rated output power in [kW] and [hp].

kW	0.18	0.25	0.37	0.55	0.75	1.10	1.50	2.20	3.00	4.00	5.50	7.50	11.0
hp					1.00		2.00	3.00		5.00	7.00	10.00	15.0
kW	15.0	18.5	22.0	30.0	37.0	45.0	55.0	75.0	90.0	110.0	132.0	160.0	200.0
hp	20.0		30.0	40.0	50.0	60.0	75.0	100					

Table 1.1 Rated motor output power

Besides power, torque is an important characteristic of the motor. Torque indicates the strength of rotation of the motor shaft. Power has a direct relationship to torque and can be calculated when torque and speed are known.

$$P = \frac{T \times n}{9.550}$$

P = Power [kW]

T = Torque [Nm]

n = Speed [RPM]

The factor 9.550 used in the formula results from the conversion of units:

- Power from the base units W (watt) to nameplate units kW (kilowatt)
- Speed from the base unit s^{-1} (revolutions per second) to nameplate min^{-1} (revolutions per minute)

1.2.3 AC and DC Motors

The first electric motor, a DC motor, was built around 1833. Speed control of this type of motor is simple, and met the requirements of many different types of applications at the time. The DC motor is controlled by supplying a DC voltage whose magnitude influences the speed of the rotor. Voltage applied to stator and rotor windings results in magnetic fields which attract or repel each other, leading to rotor movement. Energy supplied to the rotor is transmitted via brushes, typically made of graphite, to a commutator. The commutator ensures that the next winding is energised to achieve a continuous rotation. The brushes are subject to mechanical abrasion and require maintenance or periodic replacement. The importance of DC motors has decreased over time and they are rarely used in power ranges above a few hundred watts today.

Compared to DC motors, AC motors are much simpler and more robust. However, AC motors typically have a fixed speed and torque characteristic. Because of these fixed characteristics, for many years AC motors could not be used for many diverse or special applications. They are nonetheless used in most applications to transform electrical energy into mechanical energy.

The functional principle of AC motors is based on the effects of a rotating magnetic field. The rotating field is generated either from a multi-phase fed AC source (typically three-phase) or from a single phase source assisted by capacitors or inductances to achieve phase shift.

This book focuses on AC motors, particularly on asynchronous motors, as the requirements for operation with FC's in adjustable speed drive applications for various motor types can be derived from this motor technology. DC motors will not be addressed further.

1.2.4 Electromagnetic Induction

Most electric motors operate through the interaction of magnetic fields and current-carrying conductors to generate force. This is the reverse process of producing electrical energy from mechanical energy, performed by generators such as an alternator or a dynamo on a bicycle.

a) Generator principle, induction by motion

When a force (F) acts on a conductor and moves it across a magnetic field (B), a voltage is induced. If the conductor is part of a closed circuit, a current (I) flows, see Fig. 1.3 Principle for electromagnetic induction.

b) Motor principle

In motors, the induction principle is utilised in the reverse order: a current-carrying conductor located in a magnetic field is influenced by a force (F) which results in a movement.

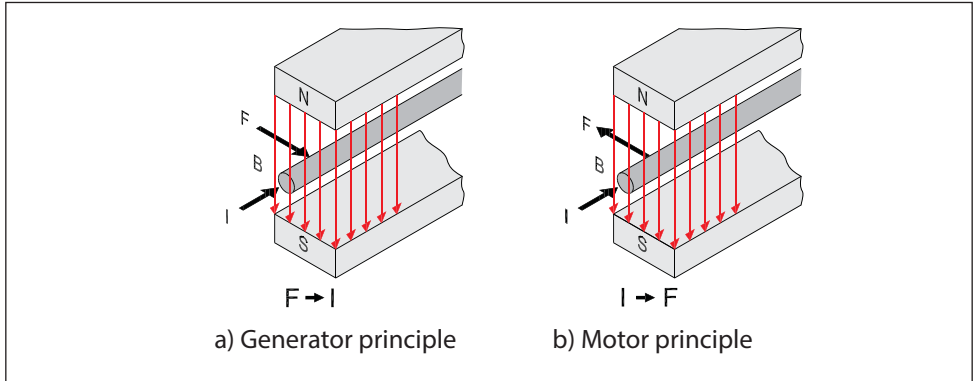


Fig. 1.3 Principle for electromagnetic induction

In both cases a magnetic field is required. In Fig. 1.3 Principle for electromagnetic induction the magnetic field originates from a permanent magnet, but in a motor the magnetic field is generated in the stator. Typically, this is achieved by applying voltage to the stator windings. The conductors affected by the electromagnetic force are located in the rotor.

1.2.5 Poles, Synchronous Speed and Asynchronous Speed

The synchronous speed of a motor can be calculated when the supply frequency and number of pole pairs are known.

$$n_0 = \frac{f \times 60}{p}$$

f = frequency [Hz]

n_0 = synchronous speed [min^{-1}]

p = pole pair number

While the frequency is determined by the grid or the FC, the number of poles is determined by the way the stator coils are connected.

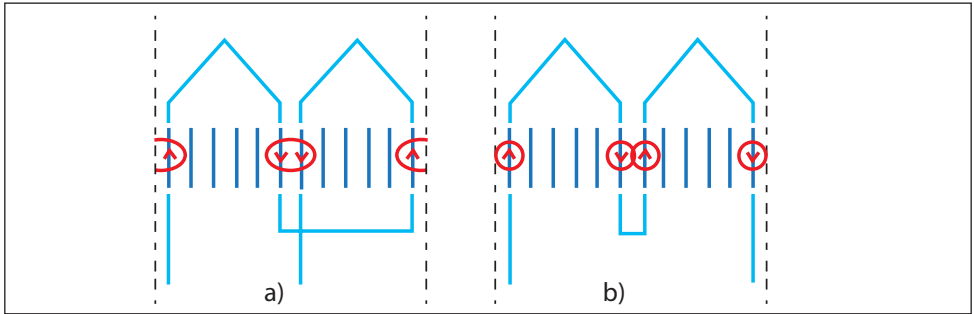


Fig. 1.4 Two coils in one phase connected in series to a) two poles b) four poles

Table 1.2 Pole pairs (p) or pole number and synchronous motor speed – lists the number of poles corresponding to synchronous speed (n_0) at 50 and 60 Hz supply. Higher pole numbers are possible but rarely used nowadays.

Pole pairs (p)	1	2	3	4	6
Pole number ($2p$)	2	4	6	8	12
n_0 [min^{-1}] (50 Hz supply)	3000	1500	1000	750	500
n_0 [min^{-1}] (60 Hz supply)	3600	1800	1200	900	600

Table 1.2 Pole pairs (p) or pole number and synchronous motor speed

Synchronous means “simultaneous” or “the same”. This means in synchronous motors the speed of the rotor is the same as the speed of the rotating field. If the rotor speed is affected by slip (see also section 1.3.3 Slip, Torque and Speed) and therefore lower than the speed of the rotating field, the motor is classified as asynchronous, meaning “not simultaneous” or “not the same”.

1.2.6 Efficiency and Losses

The motor draws electrical power from the mains. At a constant load, this power is greater than the mechanical power the motor can output to the shaft, due to various losses in the motor. The ratio between the output power P_2 and input power P_1 is the motor efficiency:

$$\eta = \frac{P_2}{P_1} = \frac{\text{output power}}{\text{input power}}$$

The efficiency depends on the motor principle, components (for example lamination quality), amount of active material (for example, due to lamination or use of magnets), size of the motor (rated power) and number of poles.

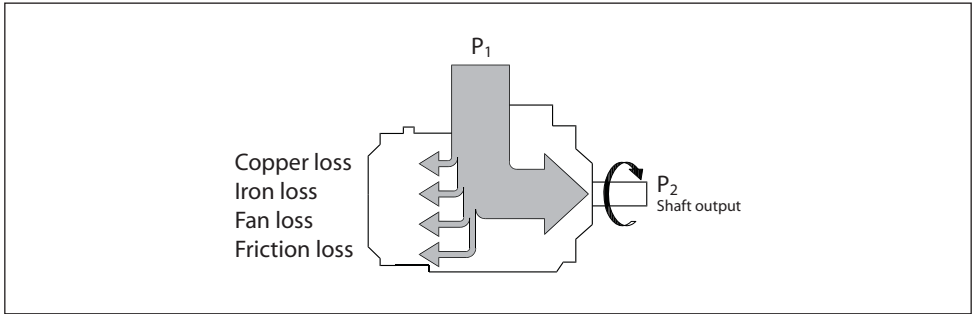


Fig. 1.5 Typical losses in the motor

The losses in the motor illustrated in Fig. 1.5 Typical losses in the motor comprise:

- Copper losses as a result of the resistances of the stator and rotor windings
- Iron losses consisting of hysteresis losses and eddy-current losses

Hysteresis losses occur when iron is magnetised by an alternating current (AC).

The iron is magnetised and demagnetised repeatedly (that is, 100 times per second with a 50 Hz supply). Magnetising and demagnetising both require energy. The motor supplies power to cover the hysteresis losses, which increase with frequency and the strength of magnetic induction.

Eddy-current losses occur because the magnetic fields induce electric voltages in the iron core as in any other conductor (see Fig. 1.6 Eddy-currents are reduced by the laminated form of the motor core). These voltages produce currents that cause heat losses. The currents flow in circuits at right angles to the magnetic fields.

The eddy-current losses are dramatically reduced by dividing the iron core into thin laminations.

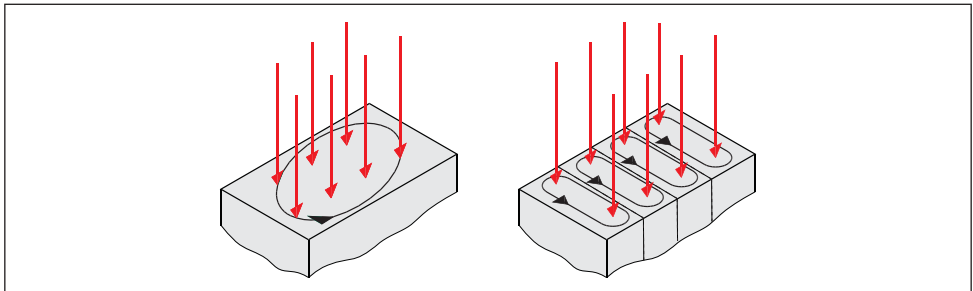


Fig. 1.6 Eddy-currents are reduced by the laminated form of the motor core

- Fan losses occur due to the air resistance of the motor fan
- Friction losses occur in the ball bearings holding the rotor

When determining the efficiency and motor output power, the losses in the motor are normally subtracted from the supplied power. The supplied power is measured, whereas the losses are often calculated or determined experimentally.

1.3 Asynchronous Motors

To understand clearly how an adjustable speed drive system works, it is necessary to understand the principles of operation of this type of motor. Although the basic design has not changed much in the last decades, modern insulation materials, computer-based design optimisation techniques as well as automated manufacturing methods have resulted in lower cost per kilowatt power and higher efficiency for a given motor size.

The information in this book will apply mainly to the so-called “squirrel-cage” three-phase asynchronous motor, which is the type commonly used with FC’s.

1.3.1 Rotating Field

When applying a multi-phase AC source (typically three-phase) to a suitable winding system, a rotary magnetic field is generated which rotates in the air gap between the stator and the rotor. If one of the phase windings is connected to a supply phase, a magnetic field is induced.

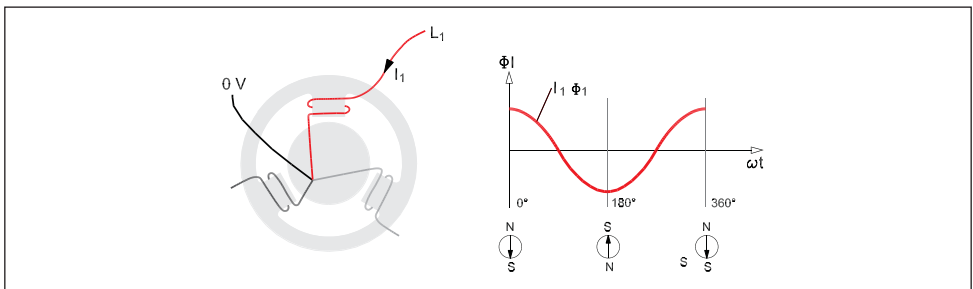


Fig. 1.7 One phase produces an alternating field

The magnetic field in the stator core has a fixed location, but its direction varies, as shown in Fig. 1.7 One phase produces an alternating field. The speed of rotation is determined by the supply frequency. At a frequency of 50 Hz, the field changes direction 50 times per second.

If two phase windings are connected to the respective supply phases, two magnetic fields are induced in the stator core. In a two-pole motor, one field is displaced by 120 degrees relative to the other. The maximum field values are also displaced in time, as shown in Fig. 1.8 Two phases produce an asymmetrical rotating field.

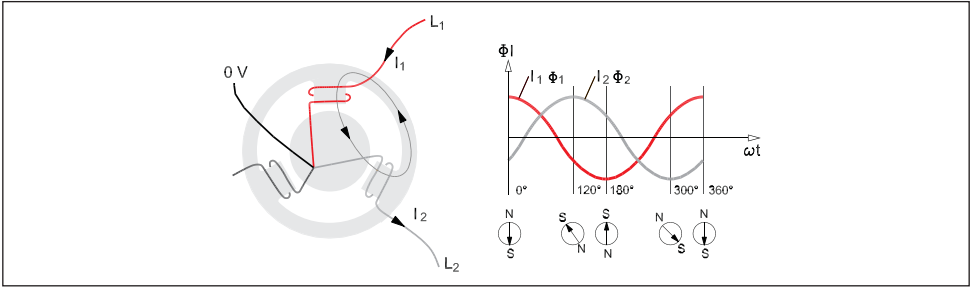


Fig. 1.8 Two phases produce an asymmetrical rotating field

This produces a rotating magnetic field in the stator which is highly asymmetrical until the third phase is connected. When the third phase is connected, there are three magnetic fields in the stator core. There is a 120° displacement between the three phases, as shown in Fig. 1.9 Three phases produce a symmetrical rotating field.

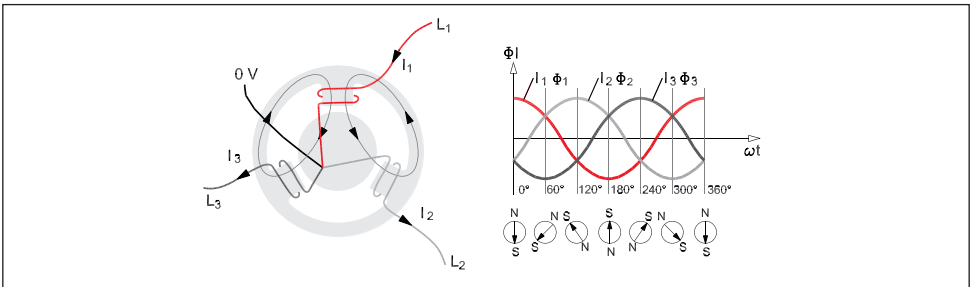


Fig. 1.9 Three phases produce a symmetrical rotating field

The stator is now connected to the three-phase supply. The magnetic fields of the individual phase windings form a symmetrical rotating magnetic field. This magnetic field is called the rotating field of the motor.

The amplitude of the rotating field (φ) is constant and 1.5 times the maximum value (φ_{\max}) of the alternating fields. It rotates at the synchronous speed resulting from the pole pair number and supply frequency (see also section 1.3.3 Slip, Torque and Speed).

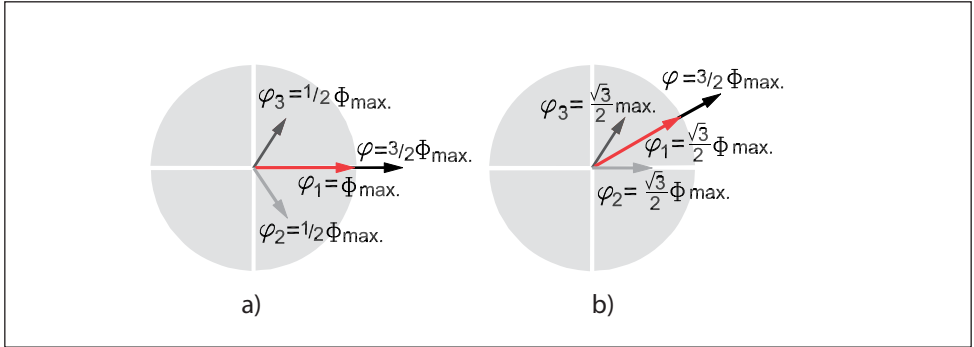


Fig. 1.10 Magnetic field components

The representation of the rotating field as a vector with a corresponding angular velocity describes a circle, shown in Fig. 1.10 Magnetic field components. The magnitude of the magnetic field φ as result of the components (φ_1 , φ_2 , φ_3) is constant also at different moments (a and b). As a function of time in a coordinate system, the rotating field describes a sinusoidal curve. The rotating field becomes elliptical if the amplitude changes during a rotation.

With single phase motors the phase shift which determines the rotation direction of the motor is created by a capacitor or an inductance which also results in an elliptical field.

1.3.2 Squirrel-cage Motor

The squirrel-cage rotor is the most frequently-used rotor type, and is used in the squirrel-cage motor. Unlike the stator, where the coils have many windings, in the squirrel-cage motor, only one winding is placed in the slots of the rotor lamination. This is typically done with aluminium or copper rods. The rods are short-circuited at each end of the rotor by a ring made out of the same material. Copper has the advantage that it has a better conductivity than aluminium which results in lower losses and a higher efficiency. Drawbacks compared to aluminium are higher prices, lower starting torques and higher melting temperature which complicate the casting and leads to a higher tooling efforts.

A variant of the squirrel-cage rotor is the slip-ring rotor which has wound coils for each phase. The coils are connected to slip-rings. Brushes sliding on the slip-ring allow the connection of external resistors which modifies the motor behaviour (see also section 1.3.5 Changing Speed). If the slip-rings are short-circuited, the rotor acts as a squirrel-cage rotor.

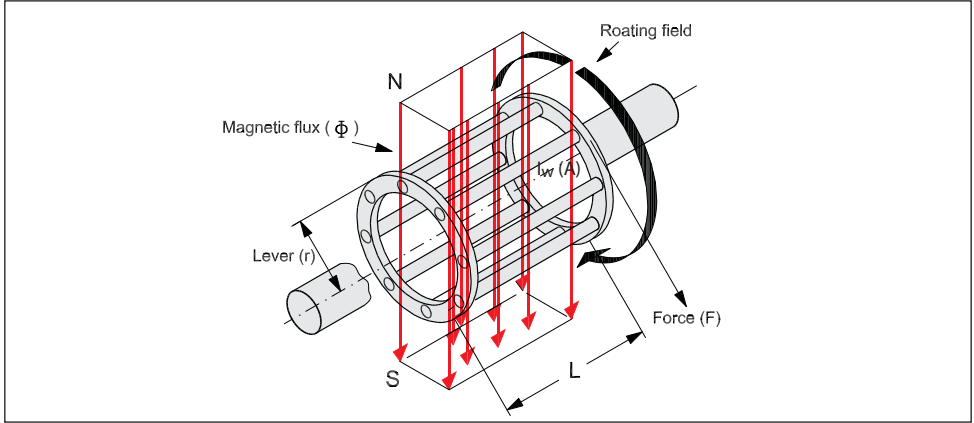


Fig. 1.11 Operational field and squirrel-cage rotor

The rotor movement of the squirrel-cage motor is created as follows:

A rotor rod placed in the rotating field is passed by a series of magnetic poles, as shown in Fig. 1.11. The magnetic field of each pole induces a current (I_w) in the rotor rod, which is influenced by a force (F). This force is determined by the flux density (B), the induced current (I_w), the length (L) of the rotor within the stator, and the angle (θ) between the force and the flux density. Assuming that $\theta = 90^\circ$, the force is:

$$F = B \times I_w \times L$$

The next pole passing the rod has an opposite polarity. It induces a current in the opposite direction to the previous one. Since the direction of the magnetic field has also changed, the force acts in the same direction as before as shown in Fig. 1.12b Induction in the rotor rods.

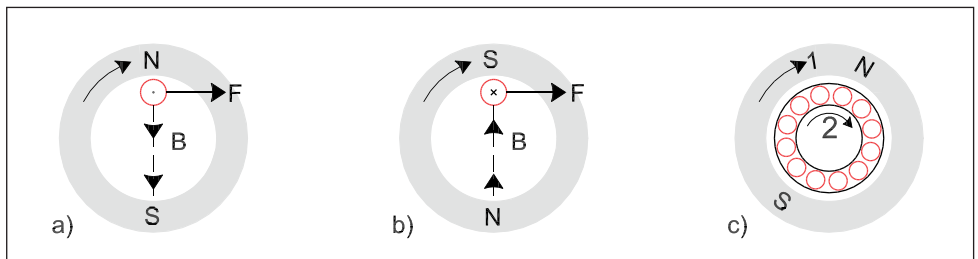


Fig. 1.12 Induction in the rotor rods

When the entire rotor is located in the rotating field, see Fig. 1.12c Induction in the rotor rods, the rotor rods are affected by forces that cause the rotor to rotate. The rotor speed (2) does not reach the speed of the rotating field (1) since no currents are induced in the cage bars when it is rotating at the same speed as the field.

1.3.3 Slip, Torque and Speed

As described in sections 1.2.5 Poles, Synchronous Speed and Asynchronous Speed and 1.3.2 Squirrel Cage Motor, under normal circumstances the rotor speed (n_n) of asynchronous motors is slightly lower than the speed (n_0) of the rotating field. The difference between the speed of the rotating field and the rotor is called slip (s) where:

$$s = n_0 - n_n$$

The slip is often expressed as a percentage of the synchronous speed and is typically between 1 and 10 percent.

$$s = \frac{(n_0 - n_n) \times 100}{n_0}$$

The individual forces in the rotor rods combine to form the torque (T) on the motor shaft (see section 1.3.2 Squirrel Cage Motor). With a given value of force (F) and radius (r) the motor torque is: $T = F \times r$.

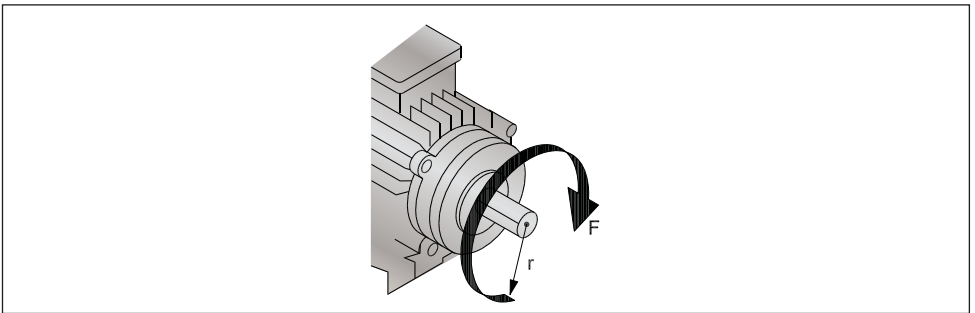


Fig. 1.13 Torque on the motor shaft is the force (F) x radius (r)

The relationship between motor torque, speed and current of asynchronous motors has a characteristic curve, shown in Fig. 1.14 Principal motor current and torque characteristics. This curve depends on the rotor slot design and the rod material.

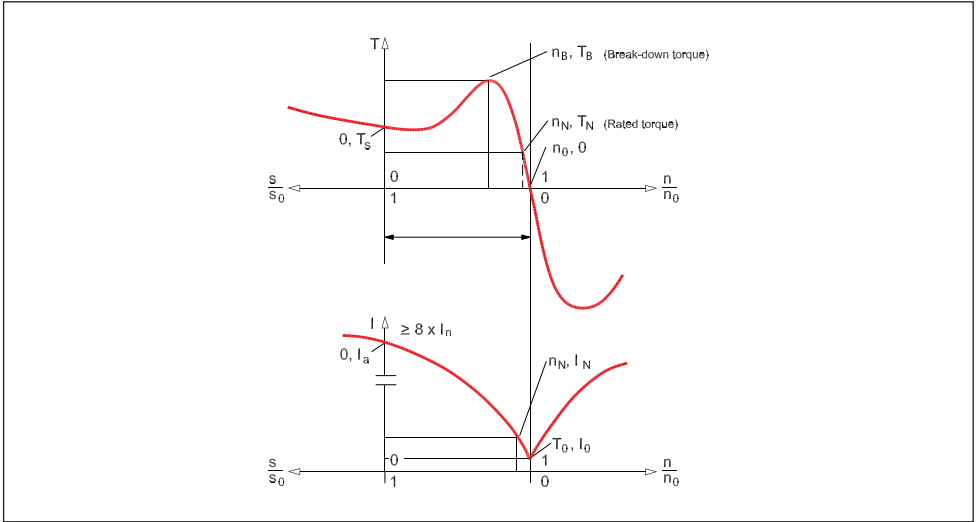


Fig. 1.14 Principal motor current and torque characteristics

The motor operating range ($0 < n/n_0 < 1$) can be split up into two ranges:

- Starting range ($0 < n/n_0 < n_B/n_0$)
- Operating range ($n_B/n_0 < n/n_0 < 1$)

These ranges have the following characteristics:

Starting torque T_a . This is the torque the motor produces with the rated voltage and rated frequency applied at standstill.

Stall torque T_B at stall speed n_B . This is the highest torque the motor can produce when the rated voltage and rated frequency are applied.

Rated motor torque T_n at nominal speed n_n .

The rated values of the motor are the mechanical and electrical values for which the motor was designed in accordance with the IEC 60034 standard. The rated values, also called motor specifications or motor ratings, are stated on the motor nameplate.

The rated values indicate the optimal operating point for the motor, when connected directly to the mains.

Apart from the normal motor operating range, there are two braking ranges.

- $n/n_0 > 1$: the motor is driven by the load above its synchronous speed (n_0) operating as a generator. In this region, the motor produces a counter torque and simultaneously returns power to the supply grid.
- $n/n_0 < 0$: braking is called regenerative braking or plugging.

If two phases of a motor are suddenly interchanged, the rotating field changes direction. Immediately afterwards, the speed ratio n/n_0 is 1. The motor, previously loaded with torque T , now brakes with its braking torque. If the motor is not disconnected at $n = 0$, it will continue to run in the new rotational direction of the magnetic field.

1.3.4 Typical Operating Conditions

In principle, asynchronous motors have six coils: three coils in the stator and three coils in the squirrel-cage rotor (which behaves magnetically as if consisted of three coils). A subset of these coils can be used as the basis for generating an equivalent circuit that makes the operating principle of the motor easier to understand, especially when the frequency of the supply voltage changes or varies.

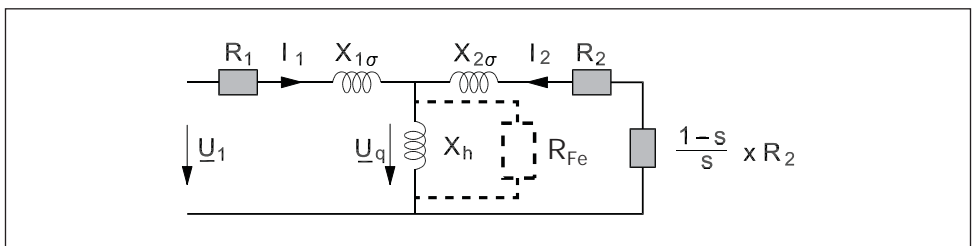


Fig. 1.15 Equivalent circuit diagram (one phase) for a motor operating under load

Applying a supply voltage (U_1) results in a current in the stator (I_1) and the rotor (I_2) which is limited by the resistance in stator (R_1) and rotor (R_2) and the reactance in stator ($X_{1\sigma}$) and rotor ($X_{2\sigma}$). While the resistance is independent of the supply frequency the reactance has an influence.

$$X_L = 2 \times \pi \times f \times L$$

X_L = reactance [Ω]

f = frequency [Hz]

L = inductance [H]

The coils mutually influence each other by means of magnetic induction. The rotor coil induces a current in the stator coil and vice versa. This mutual effect means that the two electric circuits can be interconnected via a common element consisting of R_{Fe} and X_{lr} , which are called the transverse resistance and reactance. The current the motor draws for magnetising the stator and the rotor flows through this common element. The voltage drop across the "transverse link" is the induction voltage (U_q). As R_{Fe} is very small and is neglected in the following explanations.

Standard operation

When the motor operates in its normal operating range, the rotor frequency is, due to the slip, lower than the rotating field frequency. In the equivalent circuit diagram, the effect is described by a change in the rotor resistance R_2 by the factor $1/s$. R_2/s can be expressed as $R_2 + R_2 \times (1 - s)/s$ where $R_2 \times (1 - s)/s$ represent the mechanical motor load.

No-load situation

The slip s is small at no-load (idle) operation. This means that $R_2 \times (1 - s)/s$ is high. Consequently, almost no current can flow through the rotor. Ideally, this is comparable to removing the resistor that represents the mechanical load from the equivalent circuit.

The induced voltage (U_q) is often confused with the motor terminal voltage. This is due to the simplification of the equivalent circuit diagram to make it easier to understand various motor conditions. However, the induced voltage only approximately corresponds to the terminal voltage in no-load operation.

Locked rotor situation

The slip increases when the motor is operating under load. Therefore $R_2 \times (1 - s)/s$ will decrease. When the rotor is locked the slip is 1 and hence the current which increases with the load reaches its maximum.

The equivalent circuit diagram thus corresponds to the conditions applicable to the asynchronous motor in normal practice. It can be used in numerous cases for describing conditions in the motor.

1.3.5 Changing Speed

The motor speed n is dependent upon the rotational speed of the magnetic field and can be expressed as:

$$n = n_0 - n_s = \frac{(1 - s) \times f}{p}$$

The motor speed can therefore be changed by changing:

- The pole pair number p of the motor (for example, pole-changing motors)
- The motor slip s (for example, slip-ring motors)
- The motor supply frequency f (for the motor)

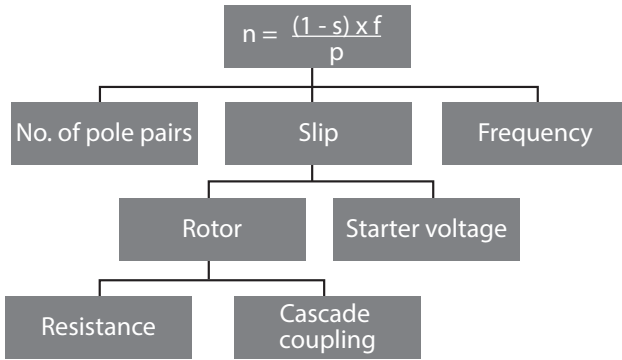


Fig. 1.16 Different options for changing the motor speed

Pole number control

The rotational speed of the magnetic field is determined by the number of pole pairs in the stator. In the case of a two-pole motor, the rotational speed of the magnetic field is 3000 RPM at a motor supply frequency of 50 Hz. For a four-pole motor the speed is 1500 RPM.

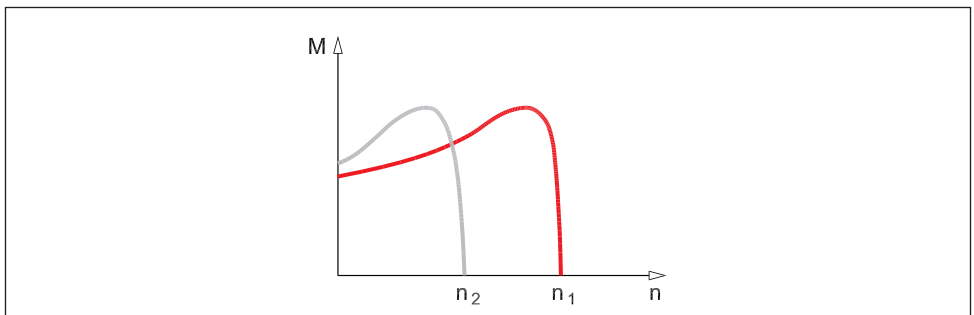


Fig. 1.17 Torque characteristics when changing pole number

Motors can be designed to have two or more different pole-pair numbers. This is done by using a special arrangement of the stator windings (Dahlander winding) in the slots and/or by using more separate and isolated windings in the slot.

The speed is changed by switching the stator windings to change the number of pole pairs in the stator. By switching from a small pole-pair number (high speed) to a high pole-pair number (low speed), the actual motor speed can be dramatically reduced, for example, from 1500 to 750 RPM. With rapid switching from higher to lower speed, the motor runs through the regenerative range. This places a considerable load on the motor and the mechanism of the driven machine which can cause damage to motor and machinery.

Slip control

Controlling the motor speed using slip can take place in two different ways: either by changing the stator supply voltage or by modifying the rotor. It should be mentioned that these methods involve considerable thermal losses. Please refer to other sources of information if more is needed.

Rotor control

Controlling the motor speed using the rotor can be made in two different ways:

- Resistors are inserted in the rotor circuit. These types of motors are called “slip-ring” motors. The trade-off using this method is higher power losses in the rotor.
- Rotor circuits are cascaded with other electrical machines or rectifier circuits. The rotor circuit is then connected via slip rings to DC machines or to controlled rectifier circuits instead of resistors. The DC machine supplies the rotor circuit with additional variable voltage making it possible to change the rotor speed and magnetisation.

Frequency regulation

With a variable frequency supply, it is possible to control the motor speed with minor additional losses. The rotational speed of the magnetic field and hence the rotor speed changes with the frequency. To maintain the motor torque, the motor voltage must change together with the frequency as shown in Fig. 1.18 Torque characteristics with voltage/frequency control.

With a constant ratio of motor supply voltage to frequency, the magnetisation in the rated motor operating range is also constant.

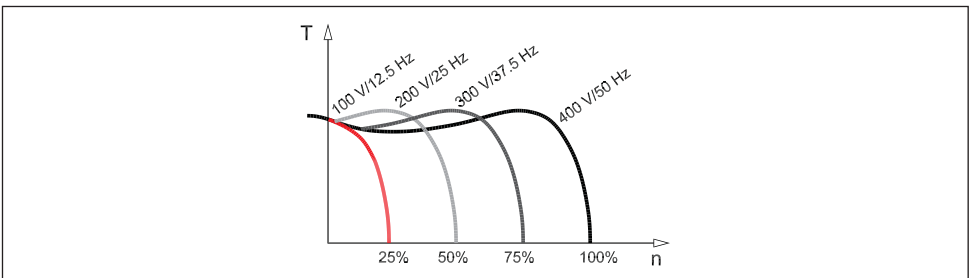


Fig. 1.18 Torque characteristics with voltage/frequency control

At low speed the ratio must be adjusted to compensate for the ohmic losses. Further forced cooling may be required in this speed range.

1.3.6 Motor Nameplate and Star or Delta Configuration

Normally the motor has a nameplate on it which has all essential motor data. Additional data are available in the motor catalogue or can be obtained from the manufacturer.

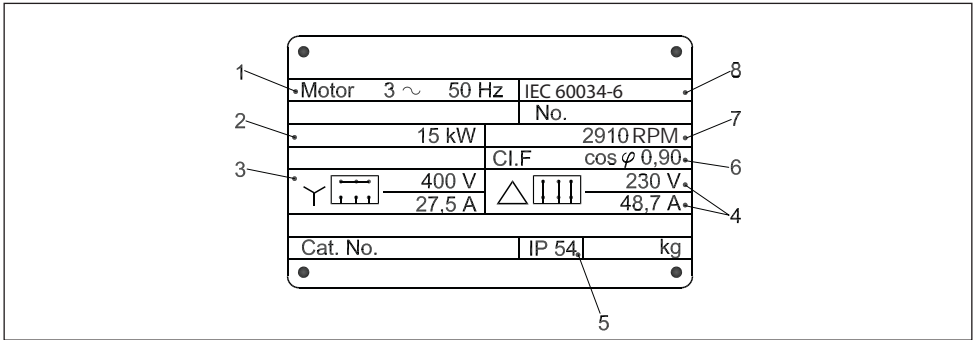


Fig. 1.19 Motor nameplate shows essential data

The nameplate shown has the following information:

1. It is a three-phase AC motor with a rated frequency of 50 Hz
2. Rated output (shaft) power is 15 kW
3. The stator windings can be connected in series (star) with a rated voltage of 400 V and rated (apparent) current of 27.5 A
4. Alternatively, the stator windings can be connected in parallel (delta) with a rated voltage of 230 V and rated (apparent) current of 48.7 A
5. It has an IP 54 protection
6. Insulation class F (155 °C) and a power factor (cos. φ) of 0.90.
7. Rated speed 2910 RPM (a two-pole motor) is the motor speed at the rated voltage, rated frequency and rated load
8. Fulfils the IEC 60034-6 standards

Some motor data (torque, efficiency, etc.) can be calculated using the nameplate data. For example the power factor can be used to calculate the active and reactive components of the motor current.

Pay special attention to the rated motor voltages in star and delta. If the supply voltage is higher than the rated voltage of the applied configuration, the motor will be damaged. The connection itself can be often changed by rearranging the jumpers at the motor terminal.

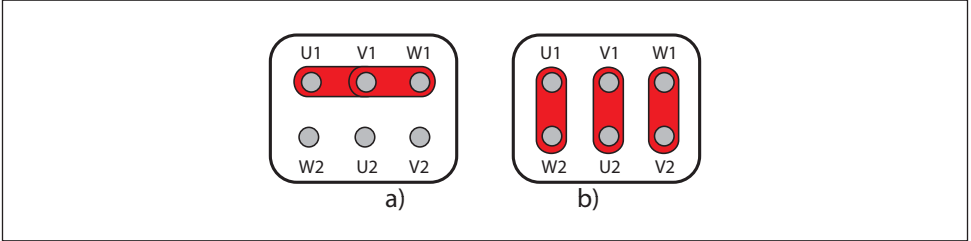


Fig. 1.20 Star (a) and delta (b) configuration of motors via jumpers on the terminal block

In delta connection the full supply voltage is applied to each motor phase but the current is reduced by the factor $\sqrt{3}$. In star connection the current is maintained, and the voltage is reduced. Therefore the power is the same regardless of the connection due to the fact that the feeding voltages are different.

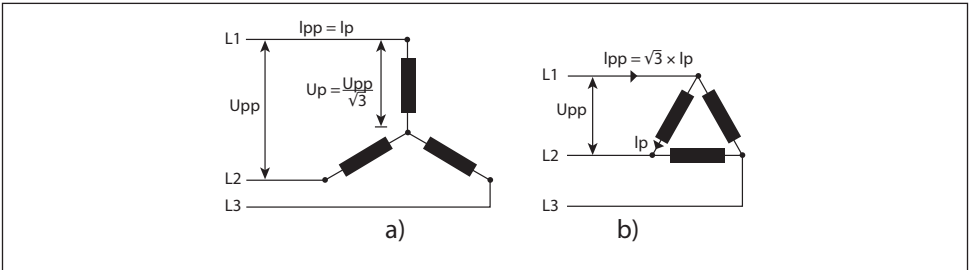


Fig. 1.21 Current and voltage distribution in star (a) and delta (b) configuration

So-called star/delta starters utilise this behaviour for reducing the starting current of a motor. In delta connection, the motor must suit the supplying mains. This means on 400 V mains the motor must have a 690 V star and a 400 V delta rating. At start the motor will be connected in star, reducing current, power and torque to one-third. After the motor has been accelerated the connection will be changed to delta.

Motor voltages in catalogues are often expressed by mentioning the star and delta voltages together (example: 400/230 V Y/Δ or 690/400 V Y/Δ). The lower voltage is always related to delta and the higher to the star connection.

The relation of the current is vice versa: the lower current relates to star configuration, and the higher current relates to delta configuration.

1.4 Synchronous Motors

The synchronous motor is defined by the fact that the rotor rotates at the same speed as the magnetic field created by the stator windings. The design of the stator is in many cases similar to that of asynchronous motors, with distributed windings. Some manufacturers use concentric windings (in slot) which enable a more compact motor design and require less copper. The energy savings achieved by the reduced use of copper are however often eaten up by additional losses, which result in harmonics in the air gap flux caused by the construction.



Fig. 1.22 Distributed windings.

1.4.1 Permanent Magnet (PM) Motors

The simplest way to build a permanent magnet motor (PM motor) is to replace the squirrel-cage rotor of an asynchronous motor with a rotor which is equipped with permanent magnets. When applying a suitable voltage to the stator, a rotating magnetic field will be created in the air gap. The rotor will follow the field at synchronous speed because the magnets are attracted by the rotating field. If the difference between rotor speed and the speed of the magnetic field is too big the motor falls out of synchronicity and the motor will stop. Therefore a suitable controller is required which ensures that speed changes are done by adjusting the feeding frequency continuously and not by switching from one speed to another. In the past PM motors were often used in servo applications with focus on fast and precise operation. These servo motors are typically slim and long in order to have a low inertia for high dynamic applications. To utilise the high-efficiency characteristic of PM motors in other applications the principle has been transferred to motors in IEC frame sizes. Standard frequency converters can be used in the majority of PM motor systems for operation if suitable control algorithms are implemented in the device.

In order to magnetise the motor in the best way the controller needs to know the rotor angle at any point in time. In many applications sensorless strategies for determining the rotor angle are sufficient. If the controller is not capable of sensorless control or in high dynamic servo applications, external position feedback devices are used.

In the equivalent diagram the magnets are represented by a voltage source U_p because turning the rotor will result in a voltage induced in the stator. This voltage is called back EMF, see section 1.4.1.1 Back EMF. The absence of motor slip, rotor resistance and inductance indicates that no losses are created in the rotor which results in the very good efficiency.

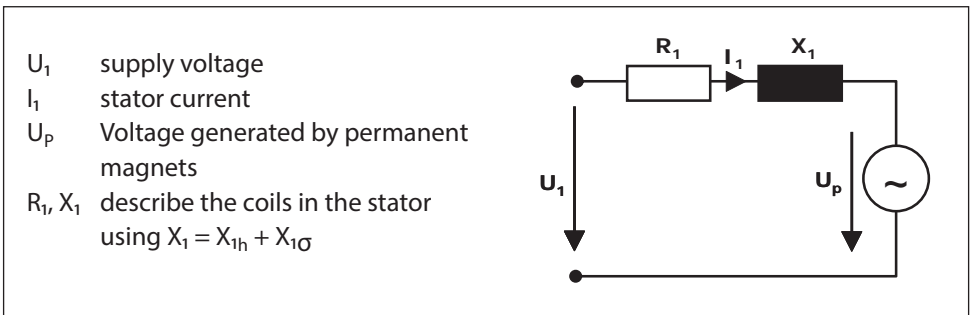


Fig. 1.23 Simplified PM motor equivalent circuit diagram

In general PM motors can be divided into motors with rotors where the magnets are placed on the surface (SPM motor) or internally (IPM motor). The placement of the magnet results in different shapes of the resulting magnetic field and is described by the inductances L_d and L_q .

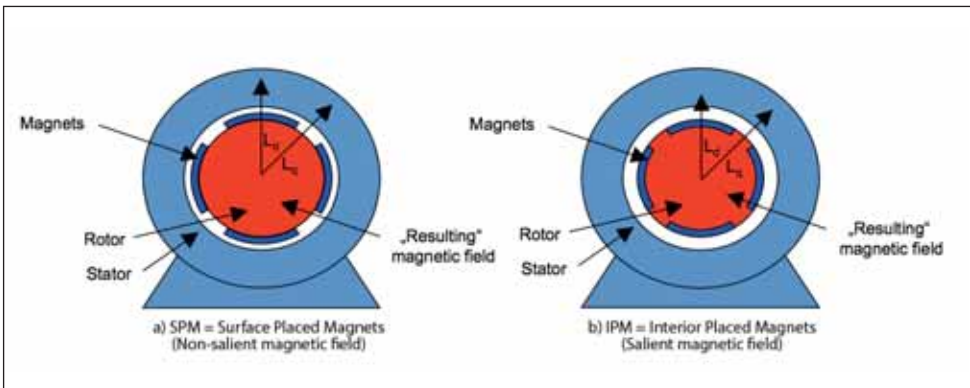


Fig. 1.24 Magnet placement a) SPM and b) IPM

As the magnets behave like air in relation to the resulting magnetic field, salient and non-salient fields are created. With SPM motors L_d and L_q have the same value resulting in a non-salient field while the different L_d and L_q of an IPM creates a salient field which produces an additional torque in field-weakening.

1.4.1.1 Back EMF

When the shaft of a PM motor is turned, the motor produces a voltage at its terminals. This voltage is called back EMF (EMF = electromotive force), and describes an important characteristic of the motor. The higher the voltage, the better the motor efficiency. Depending on the connection and placement of the windings, the shape of the back EMF can be trapezoidal or sinusoidal. For trapezoidal voltage so-called block commutation is required which is easy to realise in the electronics but has drawbacks like noise and torque ripples. Typically PM motors have sinusoidal back EMF and will be operated via sinusoidal commutation.

Given that the motor actively generates a voltage must be considered, not only during operation but also when the feeding FC is disconnected from mains (power loss, breakdown, switched off), because the motor can potentially generate sufficient energy to power up the device while the shaft is rotating (for example, when coasting). The voltage needed for powering the FC depends on the mains voltage the FC is designed for.

Example: Required speed of a PM motor with 200 V back EMF to power on a 400 V mains FC (required DC link voltage approx. 320 V).

$$\eta_{\text{power on}} = \frac{\frac{U_{\text{DC on}}}{\sqrt{2}}}{U_{\text{BackEMF}@1000\text{RPM}}} \times 1000 \text{ RPM} = \frac{320\text{V}}{200\text{V}} \times 1000 \text{ RPM} = 1134 \text{ RPM}$$

If the voltage generated by the motor is too high the converter can be destroyed. Practically this can happen when the controlling FC is switched off while the motor is operating at very high speed. During operation the FC limits the voltage coming back from the motor. When the control is suddenly switched off the full back EMF voltage can be seen at the terminals immediately. This critical speed depends on the back EMF of the motor and the voltage the FC is designed for.

Example: 400 V mains, $U_{\text{Back EMF @ 1000 RPM}} = 100 \text{ V}$, $U_{\text{DC critical}} = 1000 \text{ V}$

$$n_{\text{critical}} = \frac{U_{\text{DC critical}}}{U_{\text{BackEMF@1000 RPM}} \times \sqrt{2}} \times 1000 \text{ RPM} = \frac{1000 \text{ V}}{100 \text{ V} \times \sqrt{2}} \times 1000 \text{ RPM} = 5656 \text{ RPM}$$

A brake resistor can be used to overcome such critical situations.

Unfortunately there is no standard used by motor manufacturers to provide information about the back EMF. Some manufacturers state back EMF related to 1000 RPM while others use nominal speed of the motor. Sometimes the value of factor k_e is given in radians and must be converted to RPM.

$$U_{\text{EMF}} = k_e \times \frac{1000}{60} \times 2\pi$$

Where peak values are provided the voltage must be divided by square root of two in order to get the RMS value.

Also advanced motor data like motor resistance and inductances are stated in differing ways. Sometimes they are given as phase/phase values, and sometimes as phase/star values.

$$U_{\text{RMS}} = \frac{U_{\text{Peak}}}{\sqrt{2}}$$

1.4.1.2 Torque and Speed Range

The torque of a PM motor is proportional to the motor current, and its speed is proportional to the feeding frequency. At nominal torque and speed, a certain voltage is required. If the FC can deliver a higher voltage, the speed can be increased further. This results in a higher power at constant torque. When the voltage has reached an upper limit, the motor enters the field weakening area. Operation in field weakening is only possible with suitable frequency converters. Motor mechanics and insulation must support the higher speed and withstand the higher voltage.

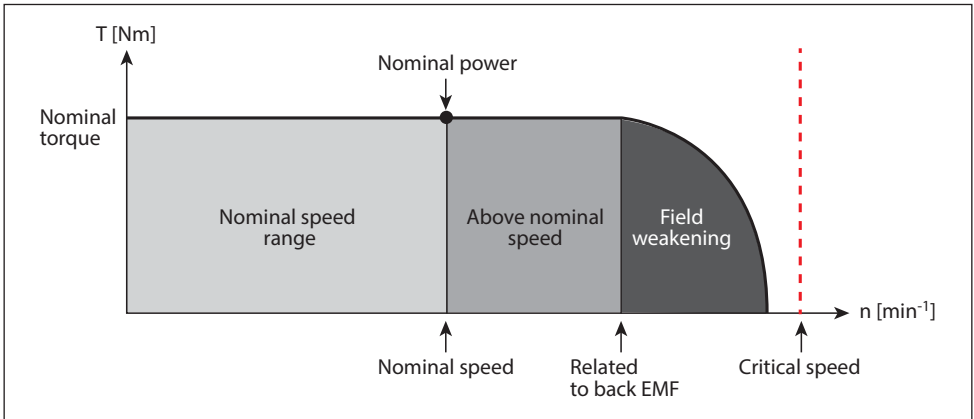


Fig. 1.25 Operation in field weakening area

The greatest risk in field weakening operation is switching off the motor control at too high speed, as the high back EMF can destroy the FC (see section 1.4.1.1 Back EMF).

Another possibility for extending the speed range is to change the star configuration of a motor to delta, if the motor provides this feature. Similar to asynchronous motors, a delta connection results in a higher voltage on the windings, because it is not reduced by the factor 1.73 or $\sqrt{3}$ as for a star configuration.

1.4.2 Brushless DC (BLDC) or Electronically Commutated (EC) Motors

EC (Electronically Commutated Motor) and BLDC (Brushless DC) are basically different names for the same technology. In the original BLDC concept only two phases were energised with a trapezoidal voltage. Compared to a distribution over three phases this result in 1.22 time higher current. For determining the rotor position Hall sensors have been used. Drawbacks of the concept were worse torque ripples and iron losses.

In practice there are many different types of EC motors, such as small servo motors with power ratings of a few watts or motors in building automation systems up to approximately 10 kW. In general BLDC/EC has a reputation for extremely high efficiency. This is fully deserved, in particular for very small devices – the original application area for these motors – where they are distinctly better than universal or split-pole motors (efficiency approximately 30%). Above a few hundred watts the efficiency is comparable to standard PM motors.

Modern EC/ECM utilise the same control principles as the PM motors. In building automation EC motors are often used as hubs in EC fans. This results in a very compact fan unit with a very efficient motor. Unfortunately the placement of the motor in the middle of a centrifugal fan creates air turbulences which reduce the total fan efficiency. In comparison to a direct-driven fan the difference at same motor efficiency can be in the range of 3-6%.

1.4.3 Line Start PM Motor (LSPM motor)

A line start PM motor is a hybrid of a squirrel-cage asynchronous motor and a PM motor where the magnets are placed internally to the rotor.

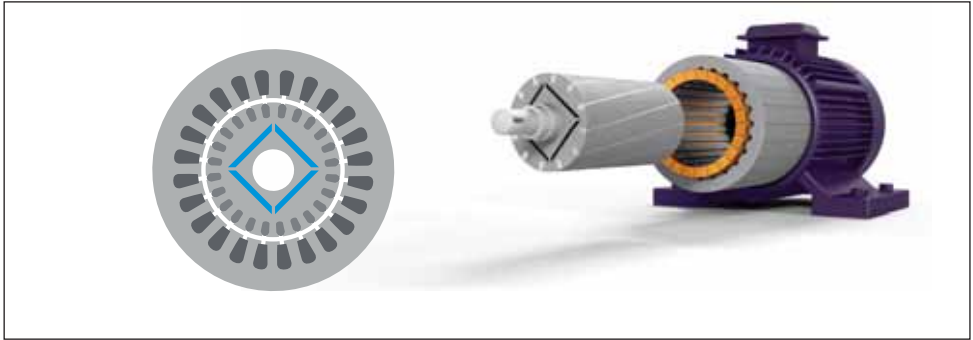


Fig. 1.26 The position of magnets in the rotor influences the motor characteristics

When connected to a three phase grid the motor develops a torque and accelerates like a standard asynchronous motor to near synchronous speed, if the motor torque is greater than the load torque throughout acceleration. When the rotor has roughly reached the speed of the rotating field, a synchronising torque (reaction torque) is produced due to magnetic coupling between the rotating stator field and the rotor poles, which pulls the rotor into synchronism.

After synchronisation, the motor continues to run at synchronous speed. As there is no speed difference between the magnetic field and the rotor, no currents are induced in the cage. This results in a high efficiency with a good power factor. When load changes take place the squirrel cage is still working as a damper. This is also the case when the motor is operated by a FC where the additional damper can reduce the efficiency by approximately 5-10%.

If the motor is loaded with a torque that is greater than its synchronous stalling torque, it is pulled out of synchronism and continues to operate like an asynchronous motor at a load-dependent speed. Depending on the design, the motor is more or less

sensitive to under-voltage situations which can also result in falling out of synchronism. Renewed synchronisation takes place automatically when the load torque is lower than the synchronising torque. However, the rotor will stop if the motor is loaded with a torque that is greater than its induction stalling torque.

Drawbacks of the concept are the influence of the magnets while starting the motor. Torque oscillations and torque peaks, paired with noise, arise during the start up. Furthermore the starting torque is lower compared to an asynchronous motor as the magnets create a negative torque component (1).

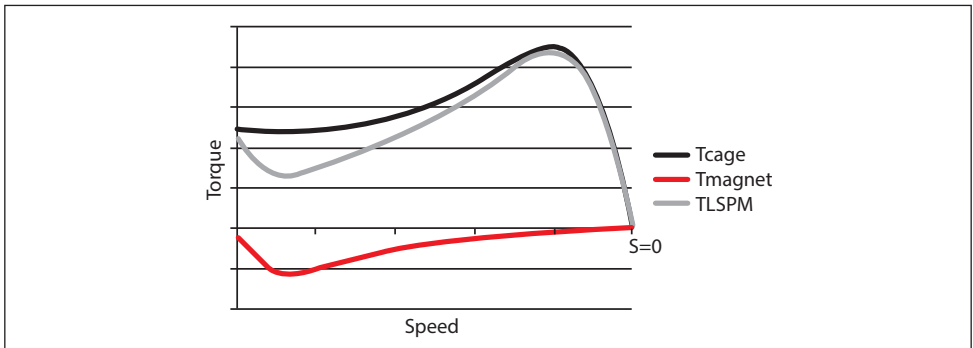


Fig. 1.27 Starting torque of LSMP is reduced compared to the pure squirrel cage torque

LSPM motors are typically used in fans and pumps, available in the power range up to approximately some 10 kW, but can also be used in low inertia applications.

1.4.4 Reluctance Motors

For creating a motor movement these types of motors utilise magnetic reluctance, which is also called magnetic resistance. Similar to electric circuits the magnetic flux follows the path of the lowest resistance. As in asynchronous motors, the magnetic field is created by applying a suitable voltage to the stator windings. The rotor rotates towards the position with minimum magnetic reluctance. If the rotor is now forced out of this position a torque is created in order to move it back to the position where the reluctance is minimised. The torque resulting from the magnetomotive force depends on the relationship between the inductances in the d-axis and q-axis, known as the saliency ratio.

The saliency ratio results directly from the rotor lamination design. Cut-offs in the lamination are utilised to shape the equivalent air gap of the machine by controlling

(1) Source – 2014. J Sorgdrage, A.J Grobler and R-J Wang, *Design procedure of a line-start permanent magnet synchronous machine.*

the flux paths. They also influence how the d-axis and q-axis inductances vary with the magnetisation current. As these cut-offs increase the equivalent air gap, a higher magnetising current is required which leads to a worse $\cos \varphi$. As illustrated in Fig. 1.28 Maximum power factor vs. saliency ratio, the maximum power factor depends on L_d/L_q ratio. The higher the ratio the better the $\cos \varphi$ becomes. Modern rotor designs have a ratio in the range from 4 to 10.

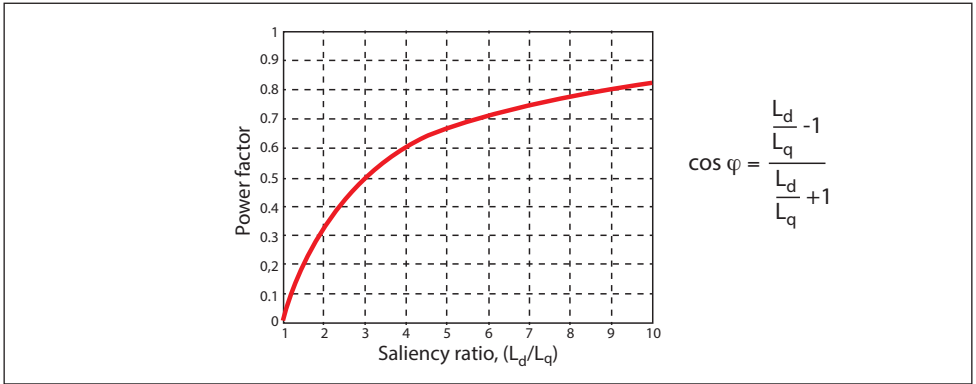


Fig. 1.28 Maximum power factor vs. saliency ratio

Even if reluctance motors require a higher $\cos \varphi$, the energy efficiency is reasonably high. Losses arise in the rotor mainly by harmonics in the air gap between stator and rotor.

The reluctance principle was first used around the year 1840. Over time various optimisations resulted in different motor principles and designs. In the next chapters the three most common types of reluctance machines are described.

1.4.5 Synchronous Reluctance Motor with Squirrel Cage

The stator of this three-phase reluctance motor is identical to that of a standard three-phase squirrel-cage motor. The rotor design is modified by removing the windings and cutting pole gaps on the circumference of the laminated rotor core. The gaps are filled again with aluminium and the end windings are shorted.

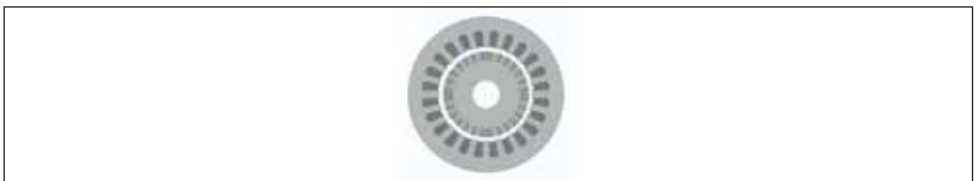


Fig. 1.29 Rotor with pole gaps on the circumference placed in the stator

Similar to a LSPM motor design, (see section 1.4.3 Line Start PM Motor (LSPM Motor)) the motor accelerates to near synchronous speed when connected to a three phase grid, if the produced torque is sufficient for the load. When approaching the synchronous speed the rotor is pulled into synchronism and runs at synchronous speed despite the absence of rotor excitation.

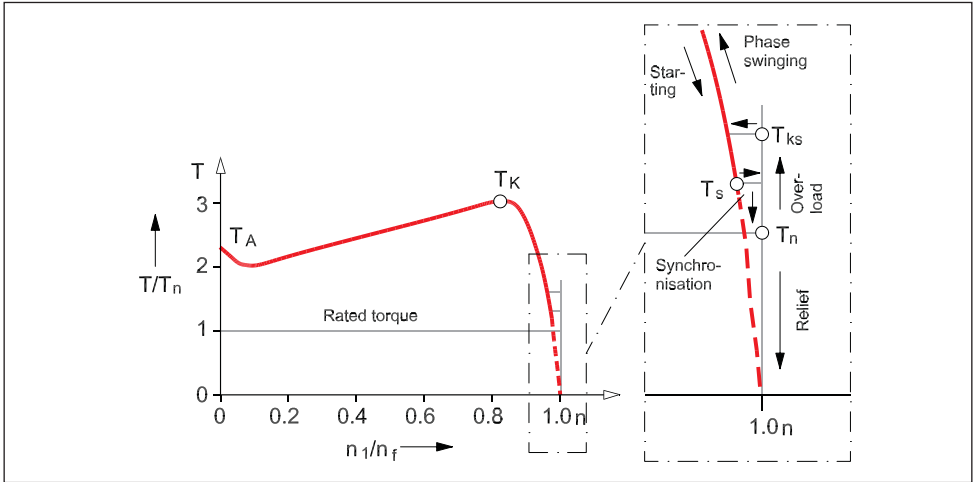


Fig. 1.30 Torque characteristic of a reluctance motor

Under load, the salient rotor poles lag behind the stator rotating field by the load angle. Again the behaviour is similar to LSPM when the load torque becomes too high. The motor is pulled out of synchronism, continues to operate like an asynchronous motor and regains synchronisation automatically when the load torque is lower than the synchronising torque.

The possibility to start direct on line (DOL) and run at synchronous speed make the motor interesting for several applications. Power range ends often at approximately 10 kW. The drawback is a reduced efficiency, especially when operated by FC's, as the rotor windings act as an additional damper.

1.4.6 Synchronous Reluctance Motor (SynRM)

The design of a new generation of reluctance motors focuses on energy efficiency. This highly efficient motor type is often meant when synchronous reluctance motors are addressed and should not be confused with reluctance motors which focus on high torque density or the possibility to start on mains. The key to the efficiency is the new rotor design.



Fig. 1.31 Special rotor lamination design results in high efficiency at low torque ripples

The stator construction and the windings are similar to an asynchronous motor. By applying a suitable voltage to the distributed windings, a harmonic field is created which creates low harmonic losses. Also the design of the rotor is optimised to reduce harmonic losses and operate with low torque ripples.

As the motor cannot start directly on mains, a frequency converter is required to control the motor. For magnetising the cut-offs in the rotor lamination, higher apparent power is required than for an Asynchronous motor (see section 1.4.4 Reluctance Motors). If the converter and the capacitors in the intermediate circuit are suitably sized they will deliver the additional apparent current. In this case the grid is not loaded with the higher apparent power and the low $\cos \varphi$.

For operating the motor, the FC needs to know the rotor angle. Depending on the angle, the converter will energise the different windings. The determination of the rotor angle is often done sensorless without an additional device. In order to achieve an energy efficient control, the converter must also take care of the L_d and L_q behaviour in operation.

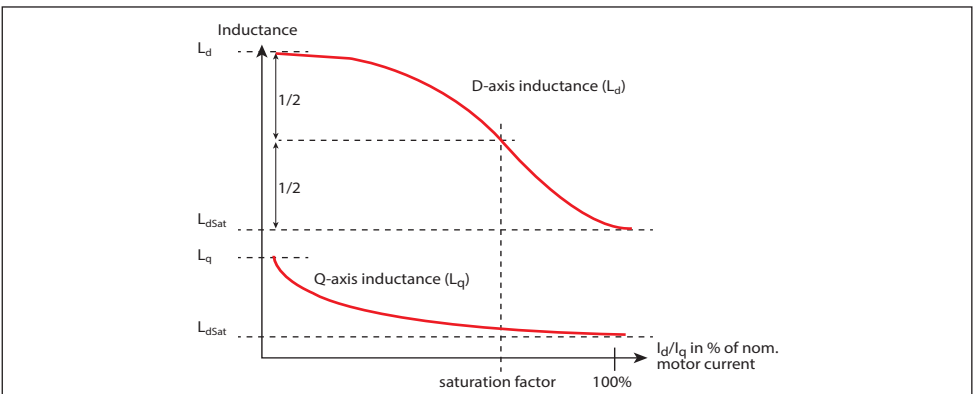


Fig. 1.32 Example of L_d/L_q relationship to I_d/I_q

The inductance components of the SynRM rotor change depending on the load because of saturation effects. Therefore the individual inductances L_d and L_q depend on I_d and I_q current ($L_d(I_d, I_q)$ and $L_q(I_d, I_q)$). If this is taken into account, very high energy efficiency operation of the motor is possible. Over a certain power range the part-load efficiency has advantages against other concepts.

For decades, asynchronous motors were state of the art, while other technologies were only used in niches. The trend towards more energy efficient motors and the opportunities provided by FC's has resulted in innovative technologies like the improved SynRM. More improvements and optimisations are in development.

1.4.7 Switched Reluctance Motor (SRM)

Construction of the stator is very similar to that of DC motors as concentric windings are used. This can result in a compact housing. The rotor lamination design has a very clear shape with low inertia where the number of poles can easily be counted. While on two pole motors the rotor poles are aligned with the stator poles, the pole ratio is typically different. This principle is also applied on other motor types but it is very obvious on switched reluctance motors.

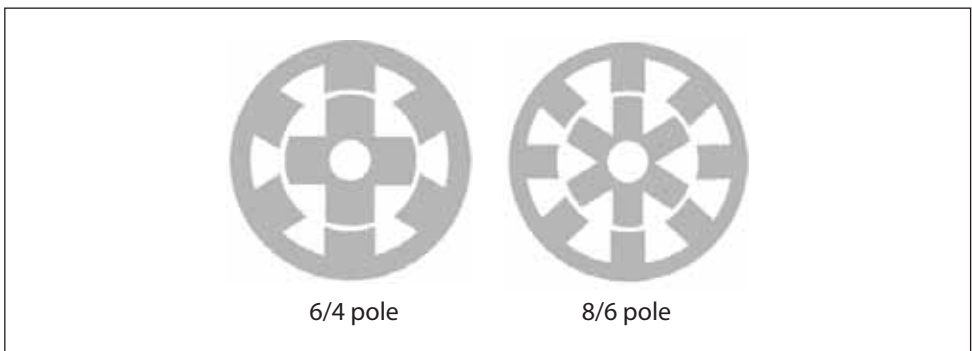


Fig. 1.33 Switched reluctance motor configuration examples

To run the motor a suitable controller is required, which energises the stator coils in a sophisticated way. The phases are energised one after the other. When the coils of a phase are supplied with a voltage, a flux is established through the stator poles and the rotor, which results in rotor movement. After the rotor has started moving the voltage will be switched to the next phase and so on.

Starting the motor directly on mains is not possible. The design allows 100% torque at stall indefinitely and achieves high efficiency even in part-load operation. The double salient construction in rotor and stator is very robust, but results typically in high torque ripples and low dynamics at higher noise.