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Starting and control of three-phase asynchronous motors

Technical Paper
Jörg Randermann

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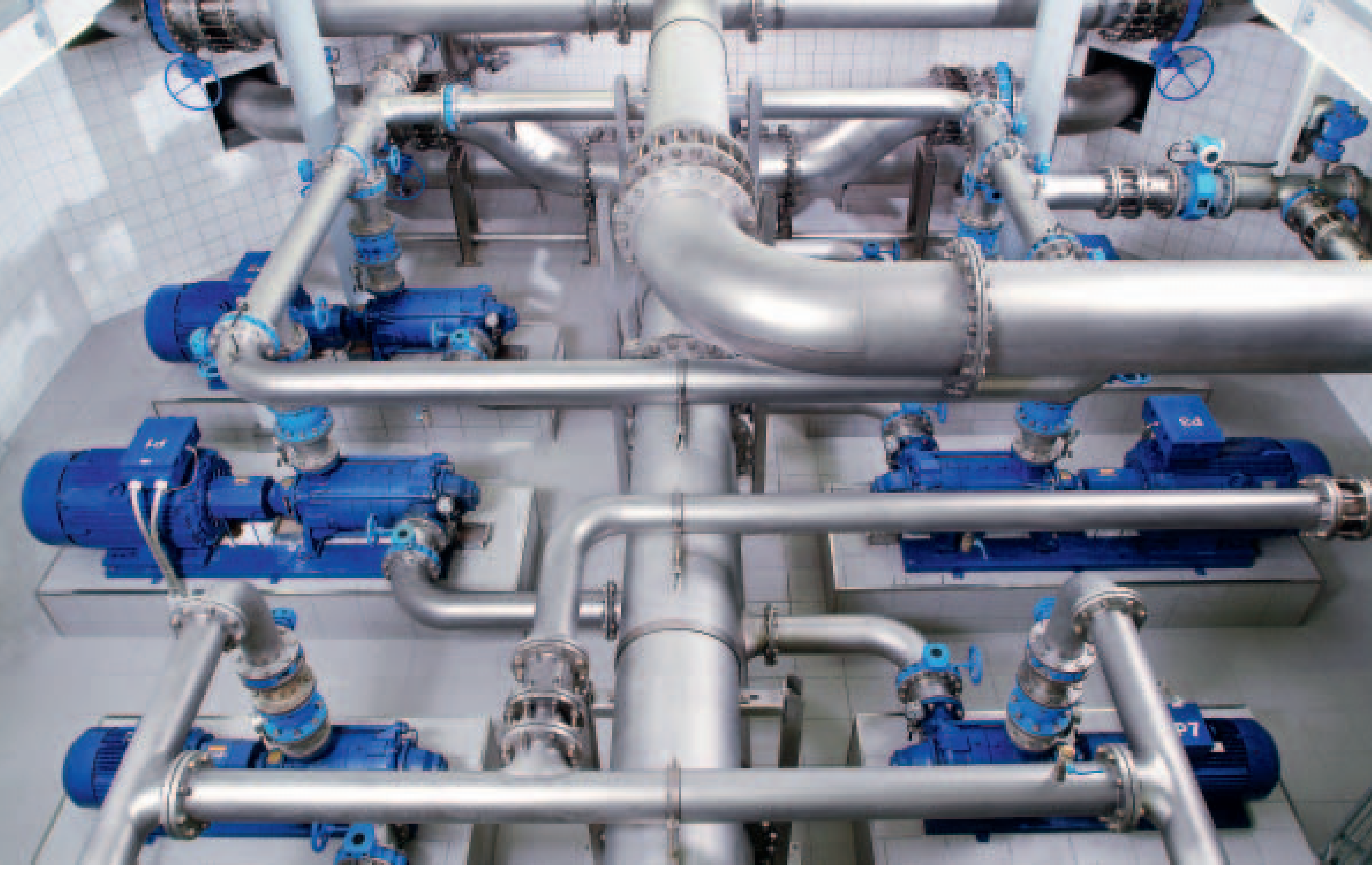


Preface

The three-phase asynchronous motor is the most widely used electric motor worldwide in industrial facilities and large buildings. Simple in terms of design and handling, flexible in diverse fields of application and economical to operate. It is the most favourable drive solution in terms of price and quality.

Characteristic for the three-phase motor is the high current load on the mains supply with direct-on-line starting. High starting and surge currents result when the full voltage is applied, causing troublesome voltage dips on the mains supply and transient torque effects in mechanical systems.

Since the invention of the three-phase motor – more than a century ago (1889) –, start-up solution concepts have been devised, which have intended to eliminate the unpleasant side-effects. Yet exactly which of these solution concepts fulfil the desire for satisfactory start-up and optimum operating performance is dependent on the application and ultimately the economic aspects as well.

To facilitate a simplified overview, the four most important and most well-known start-up methods for starting and controlling three-phase asynchronous motors used in practice are presented. In the process, we deliberately dispense with the description of the devices and functions, and general basic knowledge of electrical drive engineering is assumed.

Start variants for three-phase asynchronous motors

With regard to its construction and winding connection of its passive rotor, the three-phase asynchronous motor is also referred to as a squirrel-cage motor or squirrel-cage rotor (motor). Comparable with a rotating transformer and in accordance with its mode of action, the term induction motor is also generally used. Designs with separate stator windings are referred to as Dahlander-connection or pole-changing motors. A further variant is the slipring rotor (motor). In this case, the windings of the rotor are connected to three slip rings and are only interconnected using resistors outside the motor.

Just as diverse as the different forms and designations with the asynchronous motor is the diversity of the respective motor feeders for start-up and control. To facilitate a simplified overview, the four most well-known and important motor feeders are examined in the following. A three-phase AC current incoming mains supply earthed as the neutral point (3 / N / PE / AC 50/60 Hz) is assumed.

Eaton Moeller offers a complete range on the motor feeders for switching, protection and control of three-phase asynchronous motors for the entire range of start variants shown here.

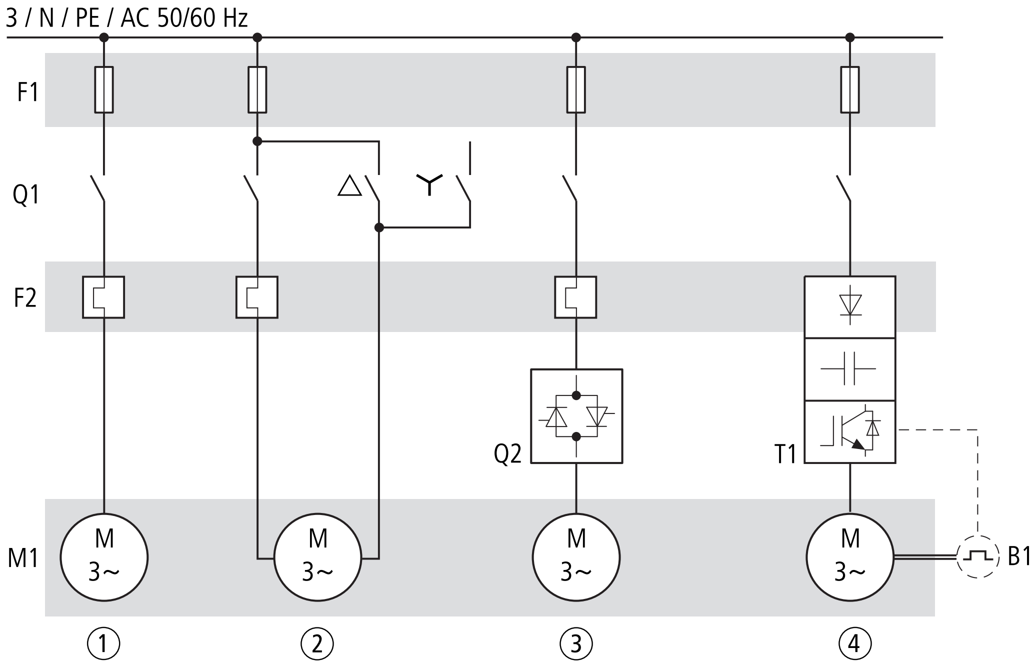


Figure 1: Motor start variants

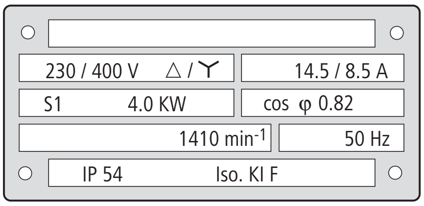
F1 = fuse (short-circuit and line protection)
Q1 = switching (contactors)
F2 = motor protection (protection against thermal overload, overload relay)
M1 = three-phase asynchronous motor

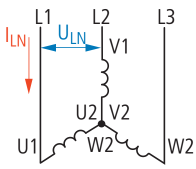
1 Direct-on-line motor start.
2 Star-delta starter, the most well-known and used starting variant.
3 Soft starter (Q2), the continuous and stepless motor start. A modern, electronic alternative to the star-delta starter.
4 Frequency inverter (T1), controlled, stepless motor start with rated-load torque. Frequency inverters also enable stepless speed control and feature integrated electronic motor protection (I_2t). Depending on the characteristic, they also allow exact speed control (option, pulse generator B1) on the otherwise slip-dependent asynchronous motors.

Connection of the three-phase motor

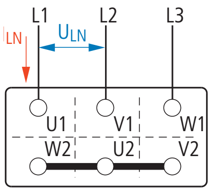
When the three-phase motor is connected to the mains, the data on the rating plate must correspond with the main voltage and mains frequency. The connection is implemented via six screw terminals (standard version) in the terminal box of the motor and distinguishes between two types of circuit, the star connection and the delta connection. Example for a mains supply voltage of 3 AC 400 V, 50 Hz (see figure 2).

Star connection



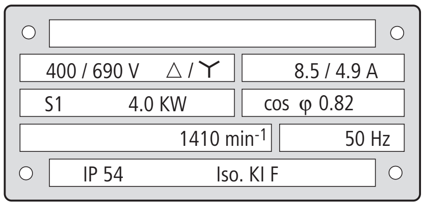


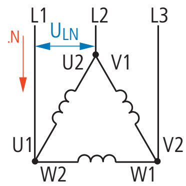
$U_{LN} = \sqrt{3} \cdot U_W$ | $I_{LN} = I_W$



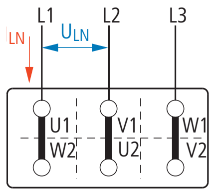
- With its voltage specification of 230/400 V, this motor must be connected to the three-phase supply (U_{LN} = 400 V) in a star configuration.
- The voltage in a motor winding is designed for a maximum of 230 V here.
- The three winding phases (W2-U2-V2) are configured in the terminal box to the so-called star point. The voltage for the individual phases to the star point is 230 V.

Delta connection





$U_{LN} = U_W$ | $I_{LN} = \sqrt{3} \cdot I_W$

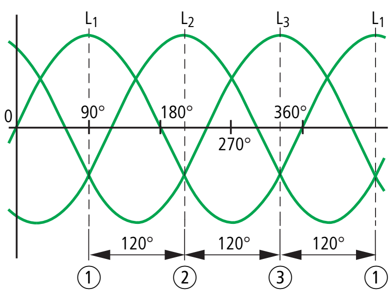


- With its voltage specification of 400/690 V, this motor must be connected to the three-phase supply (U_{LN} = 400 V) in a delta configuration.
- Every motor winding is configured for a maximum phase voltage of 400 V and can be directly connected.
- For direct-on-line starting, the ends of the phase windings are connected in the terminal box (U1-W2, V1-U2, W1-V2) to the individual phases.

Figure 2: Motor connection circuit, clockwise

Generally, the properties of a three-phase motor are defined in standards (DIN/VDE 0530, IEC/EN 60034). However, the constructive design is the manufacturers' domain. For example, in the price-sensitive market for smaller motor output ratings (<4 kW) – particularly those used with pumps and fans – time and again you will find motors without a terminal box. Here the windings are connected internally in the motor to a star point, and only three connection cables are made available for the assigned rated voltage.

Regardless of the design configuration (with/without terminal box), the connections of the three-phase motor must be denoted, so that their alphabetical sequence (e.g. U1, V1, W1) corresponds with the mains voltage sequence (L1, L2, L3) and causes the motor to rotate clockwise. The direction of rotation is specified by looking directly at the drive end (shaft of the motor). On motors with two shaft ends, the driving end is denoted with D, the non-driving end with N (D = Drive, N = No drive). Anti-clockwise rotation of the three-phase motor is



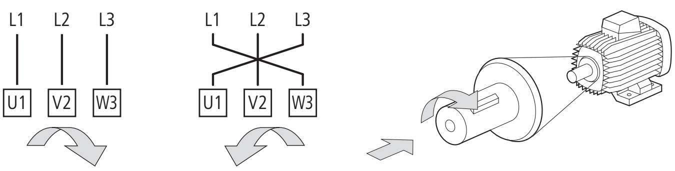


Figure 3: Clockwise rotation: phase sequence – terminal box – drive end

implemented by exchanging two connection cables (mains phases).

The operating point (M_M) of the three-phase asynchronous motor is described by the rated voltage range and the corresponding frequency (e.g. 400 V / 50 Hz). The (rotational) speed is determined by the frequency of the mains supply (n ~ f). It is load-dependent and is only maintained as long as the motor torque (M_M) and load torque (M_L) have the same magnitude.

The electrical and mechanical rating data of the operating point must be specified on the motor rating plate. The operation data are unstable during the starting process (acceleration process). Steady-state operation of the drive is only permissible in the operating point (M_M) range.

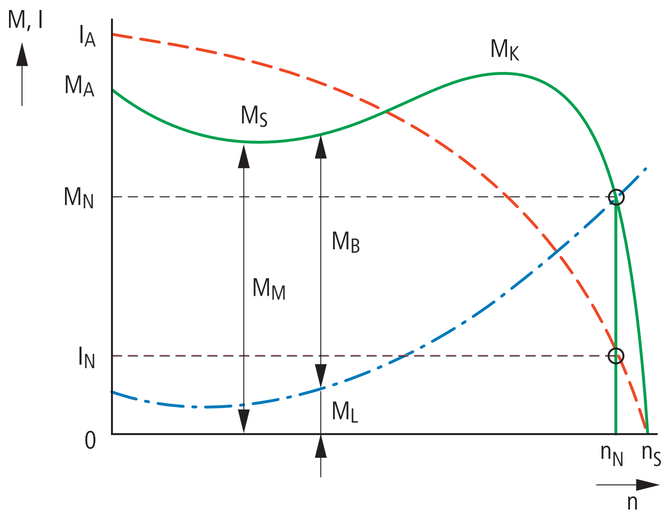


Figure 4: Characteristic starting curve of the three-phase asynchronous motor

I_A = starting current
I_N = rated current at the operating point
M_A = starting torque
M_B = acceleration torque ($M_M > M_L$)
M_K = breakdown torque
M_L = load torque
M_M = motor torque (operating point)
M_N = rated-load torque, steady-state intersection point of the three-phase speed-torque characteristic with the load characteristic
n = speed (actual value)
n_N = rated speed at the operating point
n_s = synchronous speed ($n_s - n_N$ = slip speed)

$$P = \frac{M_N \cdot n}{9550} \qquad P = [kW] \quad M_N = [Nm] \qquad f = [Hz] = 1/sec \quad n = [min^{-1}] \quad 1\ min = 60\ sec$$

$$n = \frac{f}{p} \cdot (1 - s) \qquad s = \frac{n_s - n}{n_s} \cdot 100\,\%$$

Direct-on-line motor start

The direct-on-line motor start is the easiest method for starting up three-phase asynchronous motors. The stator windings are directly connected to the mains supply in a single switching process.

Large starting currents (surge currents) result by applying the full mains voltage, which in turn cause troublesome voltage changes on the mains supply. For this reason, the electricity supply companies limit the permissible rated powers of motors connected to the mains supply. These limit values can vary from grid to grid. In public electrical power grids, these limitations are generally met when the three-phase motor that is occasionally started has an apparent power of less than 5.2 kVA or at higher apparent powers, the starting current does not exceed 60 A. At a mains voltage of 400 V and an 8-fold starting current, this corresponds with a rated current of 7.5 A or a delivered motor output of 4 kW (shaft output power).

On motors with occasionally higher starting currents than 60 A and motors with starting currents of more than 30 A, which cause feedback disturbances on the public supply, e.g. by a heavy-duty start, frequent switching or varying current consumption (elevators, reciprocating saws), further measures for avoidance of the disruptive voltage variations must be undertaken. Motors with powers exceeding 4 kW and voltages rated at 400/690 V can be stated in this case using a star-delta configuration.

Direct-on-line start imposes the motor windings to thermal stresses and, when only briefly, to momentary electro-dynamic forces. Very frequent, direct-on-line starting reduces the life of the windings on a standard motor (e.g. periodic intermittent operation).

Blockage of the rotor (locked rotor) is a serious malfunction that can lead to thermal destruction of the three-phase asynchronous motor. Every motor feeder must be protected by a current-dependent protective device to prevent against this type of thermal overload. An attractively priced solution here is the use of overload relays, better known as motor protection relays or bimetal relays.

These overload relays are referred to as motor-protective circuit-breakers in combination with a contact module. The synonym for this is the PKZM. In the motor feeder, it protects the switchgear (contactor DILM), incomers and motor windings against destruction due to thermal overload (locked rotor protection) and short-circuit, even when one of the main poles (L1, L2, L3) has been lost. For this purpose, the rated current of the motor must be set on the motor-protective circuit-breaker, and the connection cables in the motor feeder must be rated for this setting value.

The design of the components in the main circuit of the motor feeder is undertaken in accordance with the rated operational current (I_e) of the motor and the utilization category AC-3 (standard IEC/EN60947-4-1); AC-3 = squirrel-cage motors: start-up, switch off during operation.

The selection of a suitable motor-protective circuit-breaker is decisive for the functional safety and service life of a motor. The motor-starter combination (MSC) offers an ideal complete solution for direct start on the motor feeder. The MSC in its standard design consists of a motor-protective circuit-breaker PKZM0 with plug connector and a contactor DILM. In the ver-

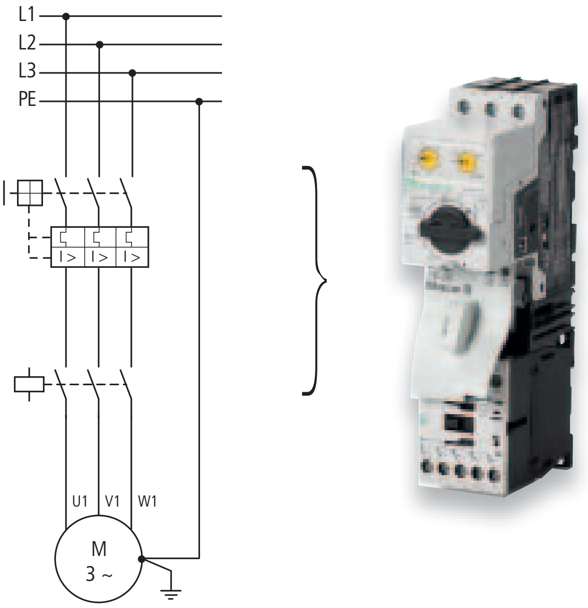


Figure 5: Motor feeder, direct-on-line starter, clockwise (forward) rotation, example of MSC

sion MSC-DE, the electronic motor-protective circuit-breaker PKE for motor currents up to 65 A offers an innovative alternative to bimetal solutions (PKZM0). With its high-level of flexibility and the same accessory components, the MSC-DE fulfils the customer demands for exchangeable “standard“ devices.

Star-delta motor start

With a star-delta motor start, the start-up of the three-phase asynchronous motor is implemented by a changeover of the windings. The jumpers in the motor terminal box are omitted, and all 6 winding connections are connected to the mains supply using a so-called star-delta switch (manually actuated switch or automatic contactor circuit).

During the operating connection, the windings of the motor are connected in delta. The winding voltage (U_W) must therefore be equal to the phase voltage (U_{LN}) of the three-phase system. For example, at a mains supply voltage of 3 AC 400 V the voltage ratings on the rating plate of the motor must be specified as 400/690 V.

In a star connection, the mains voltage (U_{LN}) on the individual motor windings is reduced by a factor of $1/\sqrt{3}$ (~ 0.58). For example: $400\ V \cdot 1/\sqrt{3} = 230\ V$. Starting torque and inrush current are (in the star connection) reduced to about a third of the values for the delta connection. Typical starting current: 2...2.5 I_e.

Due to the reduced starting torque, the star-delta configuration is only suitable for drives with smaller load torques or load torques (M_L) that increase with speed, such as is the case with pumps and fans (ventilators/blowers). They are also used where the drive is only subject to a load after it has accelerated up to speed, for example, with presses and centrifuges.

With the changeover of the circuit configuration from star to delta, the current drops to zero, and the speed of the motor reduces depending on the load. The changeover to delta then causes a dramatic rise in the current, as the full mains voltage is now applied to the motor windings. Voltage dips will result on unreliable or weak supply systems. The motor torque also jumps to a higher value during changeover, which causes additional loading on the entire drive system. If, for example, pumps are operated with star-delta starters, a mechanical damper is often used to provide system damping and to prevent a critical “water hammer” to the system.

Automatic changeover from star to delta is usually controlled by a timing relay on the contactor circuit. The time required for starting in the star connection is dependent on the load on the motor and should continue until the motor has reached about 75 to 80 % of its operating speed (n_N) to ensure that the least possible post-acceleration is necessary after changeover to delta. This post-acceleration is associated in delta configuration with high currents just as is the case with direct-on-line starting.

Switching over too quickly between star and delta can result in disconnection arcing (on the switching contacts) and can cause

Motor contactor in star and delta configuration
Bimetall relay
0.58 x I_e
$t_a \leq 15$ s

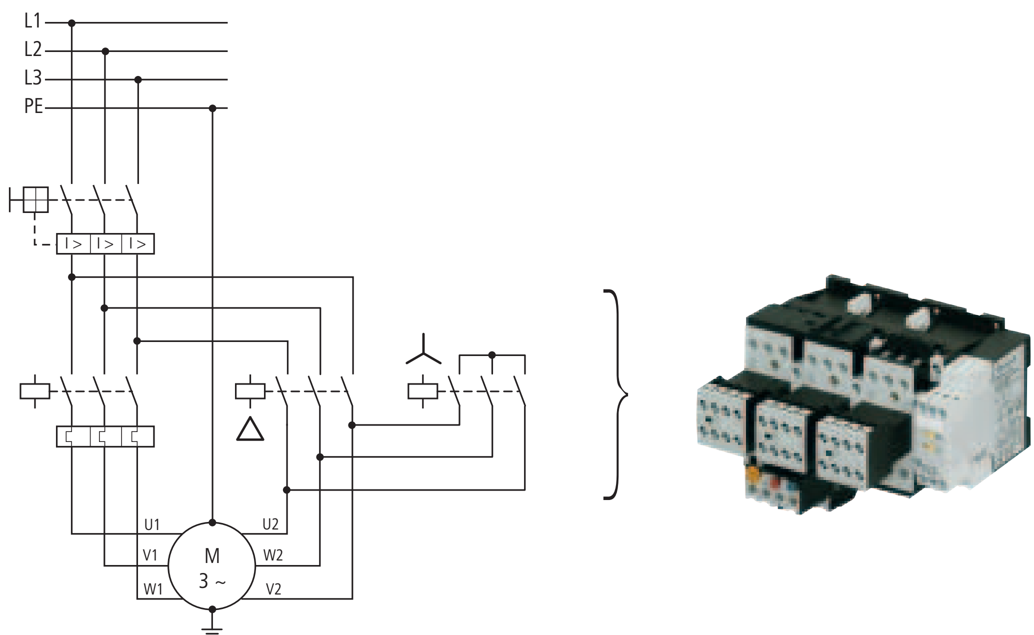


Figure 6: Motor feeder, star-delta starter, clockwise (forward) rotation, example of SDAINL

a short-circuit. The changeover time interval should be selected so that it is long enough to quench the arcs. At the same time, the speed of the drive should be reduced as little as possible. Special timing relays for star-delta changeover fulfil these demands.

The correct phase sequence (see figure 6) for the changeover from star to delta must be observed when connecting the conductors to the motor and starter. The operating direction of the motor must be considered and observed. Incorrect connection of the phases can cause very high peak currents at restart, because of the slight drop in speed during the de-energized changeover interval. The current peaks endanger the motor windings and stress the switchgear contacts unnecessarily.

When starting in the star connection, the star contactor first of all connects the winding ends U2, V2, W2. Then the main contactor applies the mains voltage (U_{LN}) to the winding ends U1, V1, W1. After the set starting time has timed out, the timing relay switches off the star contactor, and the delta contactor connects terminals U2, V2 and W2 to the mains voltage.

The design of the components in the main circuit of the motor feeder is undertaken in accordance with the rated operational current (I_e) of the motor and the utilization category AC-3 (standard IEC/EN60947-4-1); AC-3 = squirrel-cage motors: start-up, switch off during operation. The overload relay is then switched into the winding phase of the main contactor. The current to be set is therefore factor $1/\sqrt{3}$ (~ $0.58 \cdot I_e$) less than the rated current of the motor. The main and delta contactors are also selected with this reduction factor (~ $0.58 \cdot I_e$). The star contactor is designed for starting times up to 15 seconds for a third (~ $0.33 \cdot I_e$) of the rated motor current. At starting times (>15 s) of up to 60 seconds, the star contactor must be selected to be equal to the magnitude of the main contactor.

Soft starters

In many cases, the direct-on-line start and the staged star-delta start of the three-phase asynchronous motor is not the best solution, as high peak currents influence the electrical supply, and torque surges subject the mechanical components of the machine or system to high levels of stress.

The soft starter provides a remedy. It enables a continuous and surge-free increase in torque and also offers the opportunity for a selective reduction in starting current. The motor voltage is also increased within the adjustable starting time from a selected starting voltage to the rated motor voltage. The soft starter can also control the run down of the drive by reduction of the voltage.

The characteristic curve of the three-phase asynchronous motor only applies when the full mains voltage (U_{LN}) is available. If a lower voltage is applied, there is a quadratic reduction in torque ($M \sim U_2$). When compared, for example, to the star-delta start-up, the motor voltage is reduced to 58 % (~ $1/\sqrt{3}$), and the torque is reduced to about 33 % (one third).

The difference between the load characteristic (M_L) and torque characteristic of the motor (M_M), and accordingly the acceleration force, can be influenced by adjusting the motor voltage. The soft starter should be preferred for all applications with start-up under load (load cannot be connected after start-up) to the star-delta configuration. It is a good replacement for the star-delta configuration for economic reasons and also for energy-conservation reasons, particularly for high-power drives.

The motor voltage in a soft starter is modified by phase angle control of the sinusoidal half waves. For this purpose, two thyristors in the phases are connected in anti-parallel; one of them for the positive half wave and the other for the negative half wave.

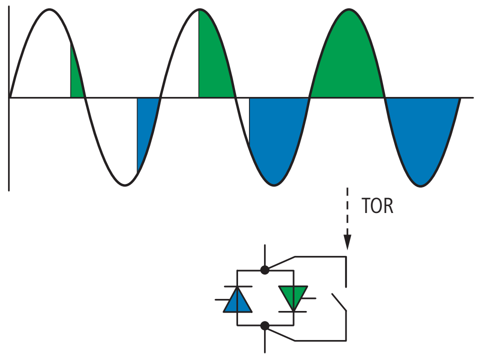
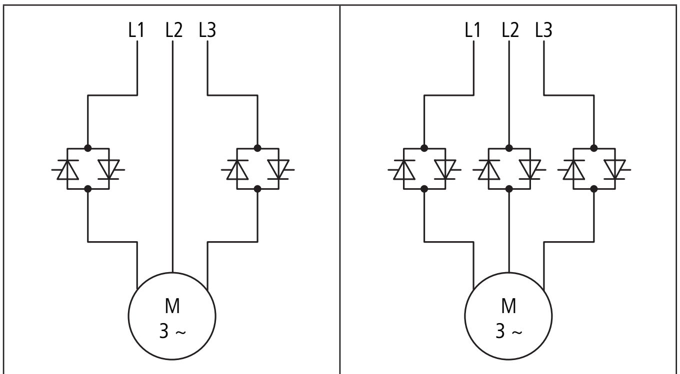


Figure 7: Phase angle control and bypass contact

After the set start time (t_{Start}) has timed out, the thyristors are fully controlled (full sinusoidal half wave => Top Of Ramp: TOR).

As the thyristors are only active during the acceleration phase or during the deceleration phase, they can be bypassed by so-called bypass contacts during continuous operation. The losses on the soft starter can be reduced by the considerably lower contact resistance of the mechanical switching contacts.

On soft starters, a differentiation is made today between two principle variants in the configuration of the power sections (figure 8).



• Two-phase controlled • Simple handling, with three setting values (t_{Start}, U_{Start}, t_{Stop}), • Time-controlled, linear voltage ramp • Generally with internal bypass contacts • Attractively priced alternative to the star-delta starter • Only in-line configuration possible • For smaller to medium motor ratings (< 250 kW)	• Three-phase controlled • For demanding tasks • Preset applications (characteristics) • Programmable • Control and closed-loop circuits • With current limitation (I^2t) and motor protection functions • Communication enabled (Fieldbus interface) • In-line and in-delta configuration possible • For motor ratings from approx. 7.5 kW

Figure 8: Features of the soft starter variants

The acceleration time of a drive with a soft starter results from the settings of the start voltage (U_{Start}) and the ramp time (t_{Start}) for the linear increase up to full mains voltage (U_{LN}). The start voltage determines the breakaway torque of the motor. High start voltages and short ramp times correspond approximately to the direct-on-line start. In practice, the required breakaway torque (U_{Start}) and then the shortest possible ramp time (t_{Start}) are initially set for the required soft start.

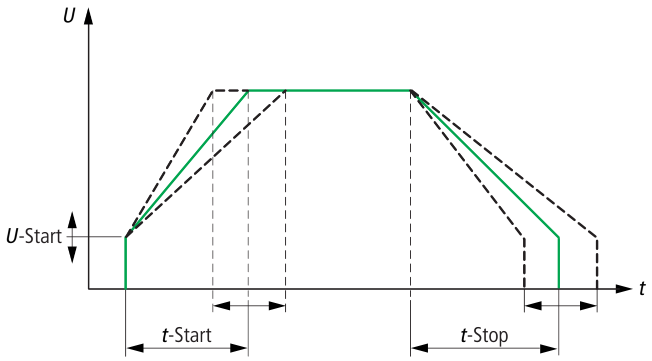


Figure 9: Voltage curve in a soft starter

The set ramp time (t_{Start}) is not the actual acceleration time of the drive. This is dependent on the load and the breakaway torque. The ramp time only controls the change in the voltage. In the process, the current rises to its maximum and then falls to the rated current, after the rated motor speed is achieved. The maximum current now sets to suit the drive (motor plus load) and cannot be determined in advance. As a result, drives subject to high loads in conjunction with long ramp times can lead to highly excessive thermal loading of the thyristors.

If a determined current level is not to be exceeded, a soft starter featuring a current limit must be selected. This start-up variant is frequently stipulated by the electricity supply companies, when large drives are connected to the public supply (e.g. elevating pumps, fans for tunnel ventilation systems).

Soft starters also enable a time-controlled reduction of the motor voltages and thus a controlled run down of the motors.

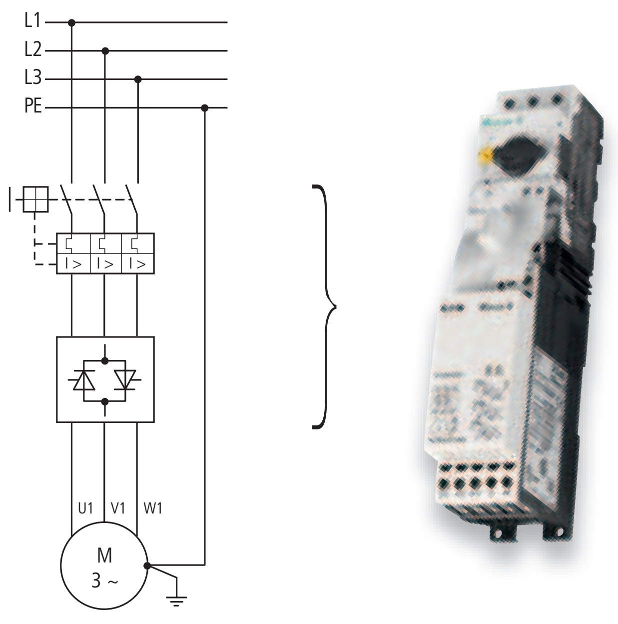


Figure 10: Motor feeder, soft starter DS7, in-line configuration, combined with PKZM0

The set stopping time (t_{Stop}) must be longer than the load-dependent, free run down time of the machine. This process is also load-dependent just as the acceleration. The thyristors of the soft starter are also subject to the same thermal stresses that were present during the start-up process. If, for example, the delay time is also activated for a soft starter with 10 permissible starts per hour, 5 starts per hour (plus 5 stops per hour) are permitted. The stop ramp time (t_{Stop}) can be selected independently of the start time, which is frequently required on pumps to prevent pressure waves (water hammer). Jerky movements during an uncontrolled run down, which, for example, can cause higher wear on drive belts, drive chains and bearings, can also be prevented.

The design of the switchgear and protection devices (electromechanical components) in the main circuit of the motor feeder is undertaken in accordance with the rated operational current (I_e) of the motor and the utilization category AC-3 (standard IEC 60947-4-1). The design of the soft starter is undertaken in accordance with the rated operational current (I_e) of the motor and the utilization category AC-53a or AC-53b (standard IEC/EN60947-4-2):

- AC-3 = squirrel-cage motors: start-up, switch off during operation.
- AC-53a = control of a squirrel-cage motor: eight-hour duty with starting currents for start processes, manoeuvring, operation.
- AC-53b = control of a squirrel-cage motor: intermittent operation (intermittent operation means that the soft starter is bypassed externally during continuous operation, e.g. by a bypass contactor).

The in-line configuration corresponds with the motor feeder during direct-on-line start. Only three cables lead to the motor and are connected to U1, V1 and W1 in the terminal box. The winding ends are switched as star or delta in accordance with the available motor and supply voltage.

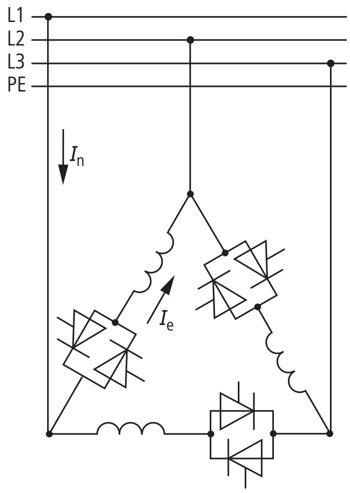
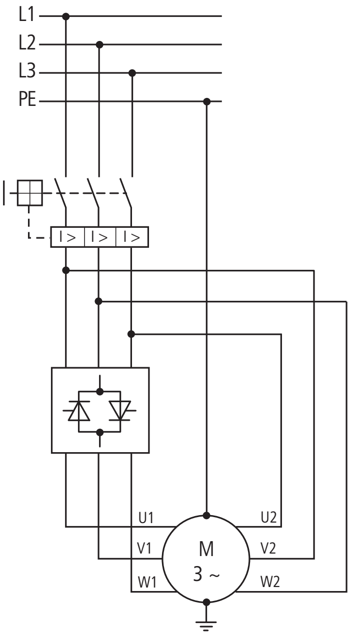


Figure 11: In-delta configuration

The in-delta configuration to this effect is only possible with three-phase controlled soft starters. Hereby, the individual motor windings are connected in series with the delta thyristors. The soft starter design in this configuration can be a factor $1/\sqrt{3}$ (~ $0.58 \cdot I_e$) less than the rated current of the motor. From



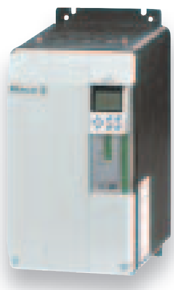


Figure 12: Motor feeder, soft starter, in-delta configuration

an economic standpoint, this is an interesting connection variant with higher motor ratings.

The overload relay used can also be included in the winding phase of the soft starter and can also be reduced by the factor $1/\sqrt{3}$ (~ $0.58 \cdot I_e$) lower rated current of the motor. If the overload relay is installed on the mains supply incomer, it will need to be rated just like the contactor or the switchgear on the mains supply side to the rated operational current (I_e) of the motor.

Frequency inverters

The frequency inverter is ultimately the best solution for continuous and stepless starting of the three-phase asynchronous motor. The adjustable current limitation prevents high current peaks in the electrical mains supply and abrupt loads in the mechanical parts of the machine and systems.

In addition to the smooth start-up, the frequency inverter also enables stepless speed (frequency) control of the three-phase asynchronous motor. Whereas motors connected directly to the mains supply can only achieve the ideal operating conditions at the steady state operation point (= rating plate specifications), they can be utilized over the entire speed range with frequency control, for example, from 4 V at 0.5 Hz to 400 V at 50 Hz. The constant ratio of voltage to frequency (U/f) guarantee independent operating points with rated-load torque (M_M).

When compared to the previously described solutions, the frequency inverters appear to be the most expensive solution at first glance. Higher acquisition costs and the necessary additional installation measures (shielded motor cables and RFI filter for electromagnetic compatibility, EMC) are the main reasons. But during operation at the very latest, the soft motor start in addition to the energy efficiency and process optimisation shows the economic benefits. This is especially true for pumps and fans. By the matching of rotation speed to the production process and the compensation for external interference, the frequency controlled drive unit guarantees a longer service life and functional security.

Further advantages of the frequency inverters include the higher speed stability with fluctuations in the load (speed fluctuations less than about one percent) and the option for a direct change in the direction of rotation. As the rotating field in the frequency inverter is generated electronically, a simple control command is all that is required to change the phase sequence and the direction of motor rotation. The electronic motor protection (I^2t control) integrated into frequency inverters also assures safe operation without the need for additional safety measures (overload relays). Depending on the method of implementation, parameterised temperature models in the frequency inverter provide a higher level of motor heat protection. So-called full motor protection is also possible in conjunction with thermistors. Overload and underload detection also enhance the operational safety of the drive unit.

The frequency inverter operates as a power converter in the main circuit of a motor feeder. Separated from the power of the DC link, the power converter draws active power via the rectifier from the mains supply and supplies the connected motor with active and reactive power via the inverter. The reactive power required for motor operation is provided by the capacitors in the DC link. As far as the electrical supply is concerned, the frequency-controlled drive behaves virtually like a resistive load ($\cos \varphi \sim 1$).

The power conversion and the associated current types must be considered in the design of the switchgear and protective devices on the motor feeder. For this purpose, the electromechanical components (e.g. fuses, line reactors, mains contactors) on the mains supply side of the frequency inverter are dimensioned in accordance with the input current (active current) and the utilization category AC-1 (standard IEC60947-4-1). The components on the frequency inverter output (e.g. motor reactors, sinewave filters, motor cables) are dimensioned in accordance with the rated operational current of the connected motor and the utilization category AC-3.

During motor operation, the frequency inverters differ through the method of operation of the inverter that can be adjusted by the user. In addition to the standard U/f control with a linear or

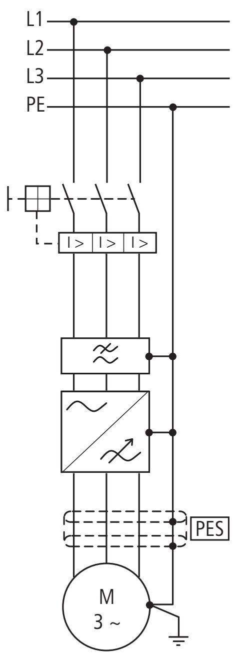
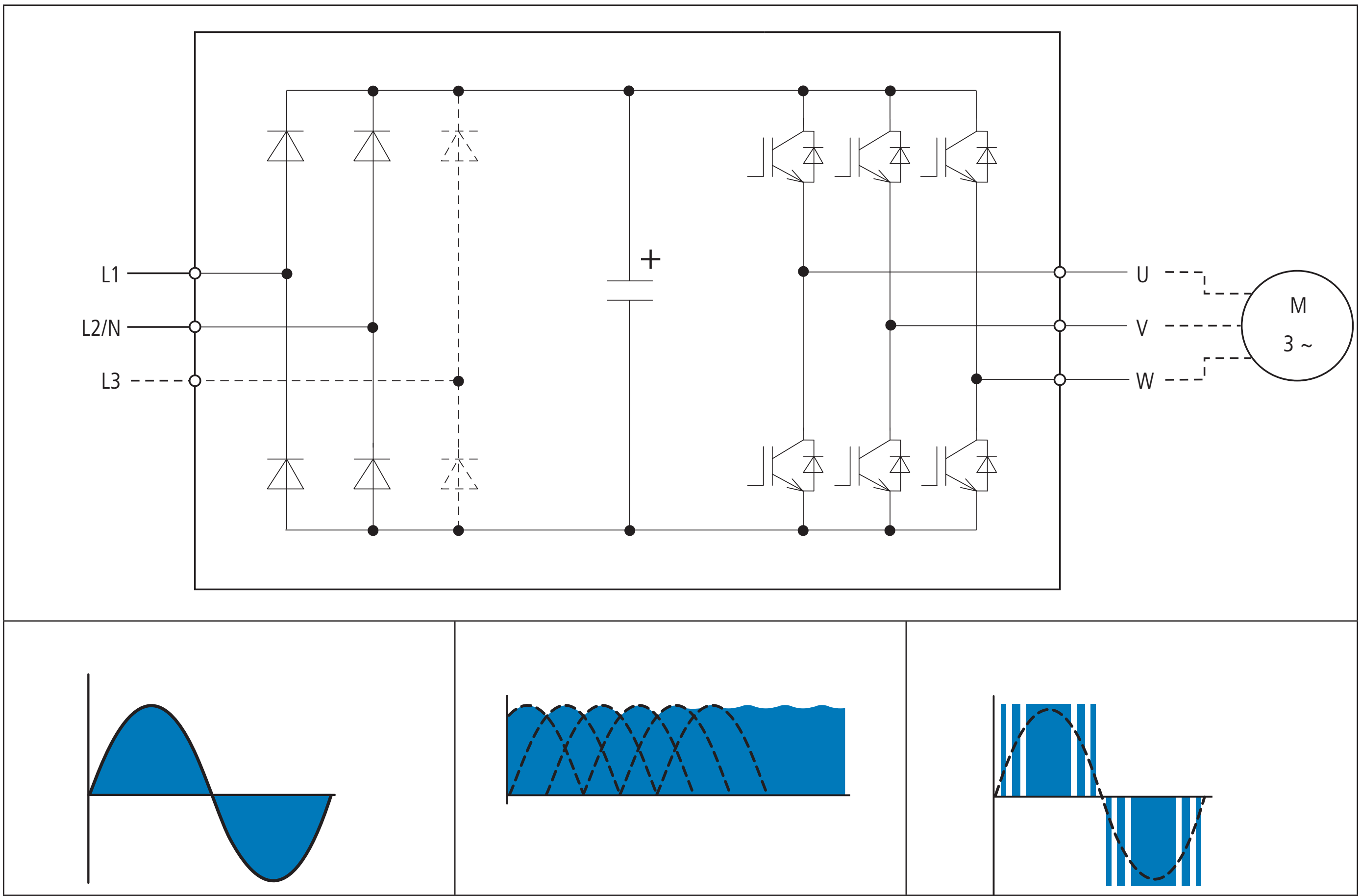


Figure 13: Motor feeder, frequency inverter, with the M-Max as an example

squared curve characteristic, sensorless speed control with slip compensation and the torque-increasing vector control are known methods currently in use today. Whereas U/f control enables parallel operation of several motors – even with different output ratings – on the output of the frequency inverter, speed and vector control are only intended for operation with individual motors. Hereby, the load-dependent operating behaviour of the (individual) three-phase asynchronous motor is optimised automatically by the frequency inverter through an electronic motor model.

The detailed description of this specific operation procedure with frequency inverters would however exceed the desired simplified overview of the most well-known starting methods for starting and controlling three-phase asynchronous motors.

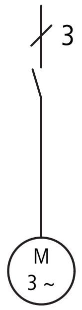
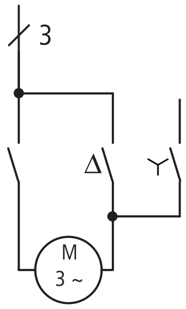
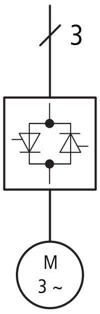
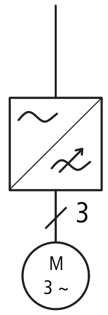
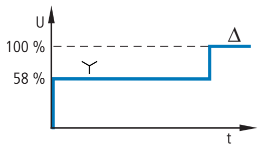
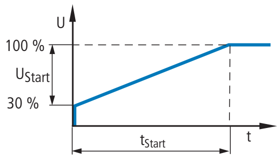
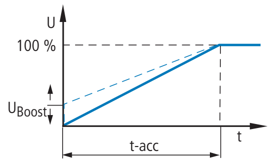
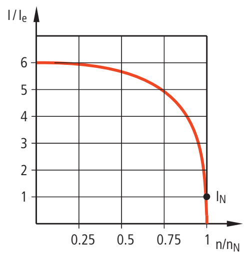
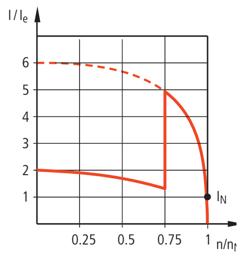
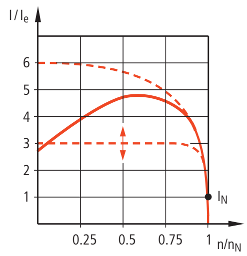
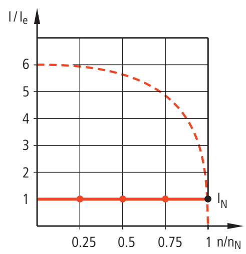
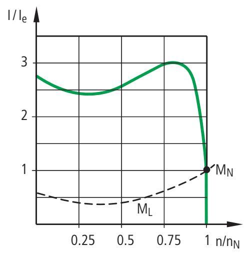
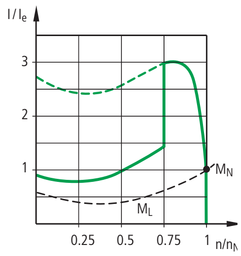
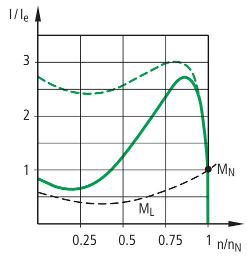
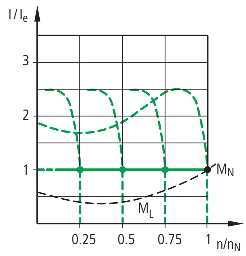


• Rectifier for single-phase (up to about 2.2 kW) or three-phase mains supply • Integrated radio interference filter for electromagnetic compatibility (EMC)	• DC link • DC link capacitors smooth the pulsed voltage of the rectifier and provide the required reactive power for motor operation • Control current supply of the frequency inverter (switching mode power supply)	• Inverter with IGBT (Insulated Gate Bipolar Transistor) • Switched-mode DC voltage with sinusoidal-weighted pulse width modulation (PWM) • Shielded motor cables • U/f characteristic control, slip control, vector control

Figure 14: Main components of the frequency inverter

Summary

Usage and application determine the selection of the start variant on the motor feeder for a three-phase asynchronous motor. Comparison of the characteristic features of the starting methods described here:

	DOL motor starter	Star-delta starter	Soft starter	Frequency inverter
Block diagram				
Voltage curve				
Load on mains at start-up	high	medium	low to medium	low
Current curve				
Relative starting current	4 … 8x I_e (motor-dependent)	1.3 … 3x I_e (~1/3 compared to direct-on-line-start)	2 … 6x I_e (reduced by voltage control)	≤1 (… 2x) I_e (adjustable)
Torque characteristic				
Relative starting torque	1.5 … 3x M_N (motor-dependent)	0.5 … 1x M_N (~ 1/3 compared to direct-on-line-start)	0.1 … 1x M_N (M ~ U^2, square-law, reduced by voltage control)	~0.1 … 2x M_N (M ~ U/f, adjustable torque)
Features	– High acceleration with high starting current – High mechanical loading	– Start-up with reduced current and torque – Current and torque peak at changeover	– Adjustable starting characteristic – Controller run out possible	– High torque at low current – Adjustable starting characteristic
Area of application	Drives on stable supplies that allow high starting currents (torques)	Drives that are only subject to load after acceleration up to speed	Drives that require soft torque progression or current reduction	Drives that require controlled soft start and stepless speed adjustment

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