Starting Electric Motors

Due to their simplicity, robustness and cost-effectiveness, squirrel-cage motors are the preferred choice of industry. During start-up, they develop currents of up to approximately eight times the rated current and the high starting torque linked to this. The high starting currents often lead to unwelcome voltage drops in the supply network and the high starting torque put the mechanical elements under considerable strain. Therefore, the electricity companies determine limiting values for the motor starting currents in relation to the rated operational currents. The permissible values vary from network to network and depend on its load-bearing capacity. With regard to mechanics, methods are required which reduce starting torque.
Various starters and methods can be used to reduce currents and torque:

- Star-Delta-Starting
- Auto-transformer-Starting
- Starting via chokes or resistors
- Multi-stage starting
- Starting using electronic soft starters
- Starting using frequency inverters

In the following passages, the main starting methods used in practice are explained further.

1 Traditional motor starting

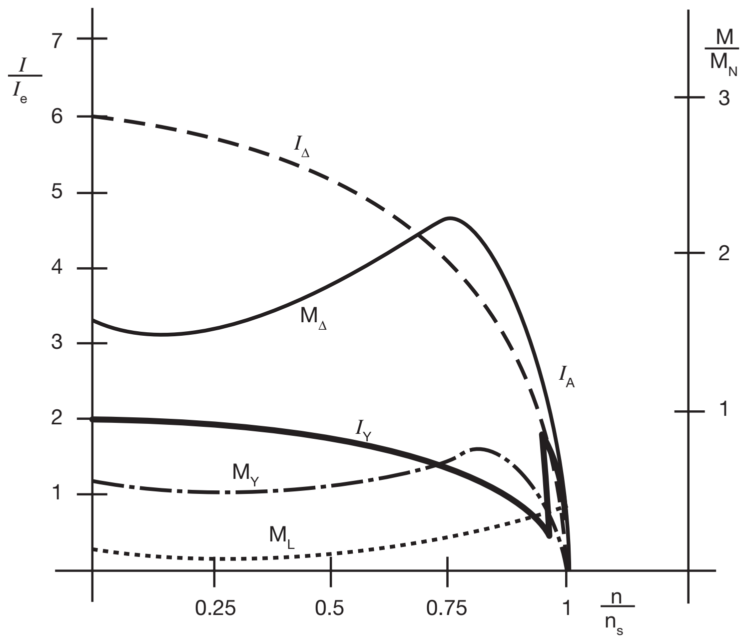
1.1 Star-delta starting

A difference is made between:

- Normal Star-Delta Starters
- Enhanced Star-Delta Starters
- Star-Delta Starters with uninterrupted switchover (closed transition)

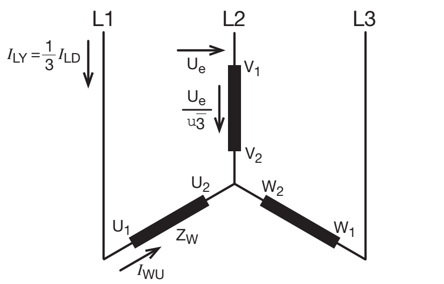
1.1.1 Normal star-delta starters

To enable the motor to start, the motor windings are configured in a star formation to the supply voltage. The voltage applied to the individual motor windings is therefore reduced by a factor of $1\sqrt{3} = 0.58$ this connection amounts to approximately 30% of the delta values. The starting current is reduced to one third of the direct starting current, i.e. typically to 2...2.5 I_e.
Due to the reduced starting torque, the star-delta-connection is suitable for drives with a high inertia mass but a resistance torque which is low or only increases with increased speed. It is preferably used for applications where the drive is only put under a load after run-up, i.e. for presses, centrifuges, pumps, ventilators, etc.

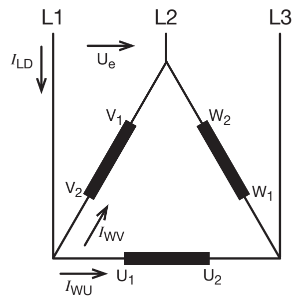


Typical Current and Torque Curve for Star-Delta-Starters

I	Motor current	n	Speed
I_e	Rated operating current of motor	n_s	Synchronous speed
M_D	Torque for delta connection	M_L	Load torque
M_E	Rated operating torque of motor	I_Y	Current in star connection
		I_D	Current in delta connection
		I_A	Current curve for star-delta start



Star Connection



Delta Connection

Current ratios for star and delta connections.

I_{LY}	Supply current for star connection
I_{LD}	Supply current for delta connection
I_W	Winding current
U_e	Mains voltage between lines
Z_W	Winding impedance

$$I_{LY} = I_{WU} = \frac{U_e}{\sqrt{3}\,Z_W}$$

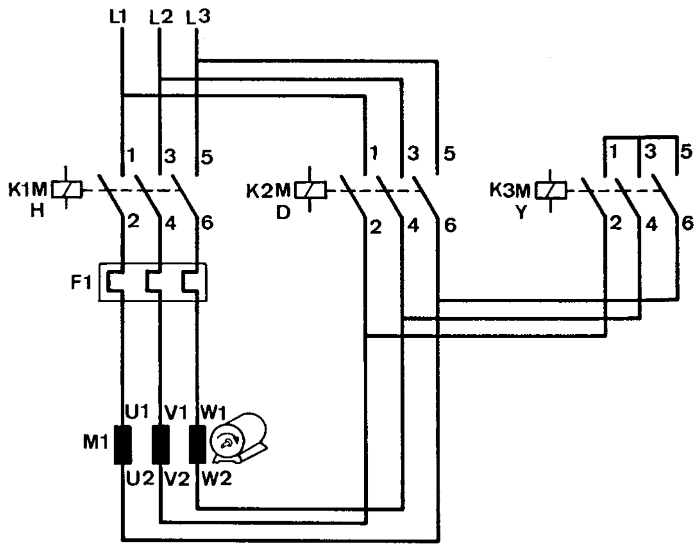
$$\vec{I}_{L1D} = \vec{I}_{WU} + \vec{I}_{WV}$$

$$I_{LD} = I_W\sqrt{3} = \frac{U_e}{Z_W}\sqrt{3} = 3\,I_{LY}$$

$$I_{LY} = \frac{1}{3}\,I_{LD}$$

After motor run-up, in most cases an automatic timing relay controls the switch-over from star to delta. The run-up using star connection should last until the motor has reached the approximate operational speed, so that after switching to delta, as little post-acceleration as possible is required. Post-acceleration in delta connection will instigate high currents as seen with direct-on-line starting. The duration of start in star connection depends on the motor load. During delta connection, the full mains voltage is applied to the motor windings.

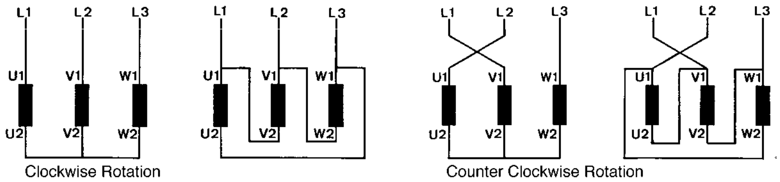
To enable a switch-over from star to delta, the six ends of the motor winding are connected onto terminals. The contactors of a star-delta starter switch over the windings accordingly.



Switch over from Star to Delta by means of Contactors

Starting in star, the main contactor connects the mains to winding endings U1, V1, W1. The star contactor shorts winding endings U2, V2, W2. After successful run-up, the star contactor switches itself off and the delta contactor connects terminals U1/V2, V1/W2, W1/U2.

When changing from star to delta, attention has to be paid to the correct phase sequence, i.e. the correct connection of the conductors to motor and starter. Incorrect phase sequence can lead to very high current peaks during the cold switch-over pause, due to the easy torque reduction following re-start. These peaks can damage the motor windings and stress the controlgear unnecessarily. The rotation of the motor has to be considered as well.



Correct Motor Connection

A sufficient time period has to be maintained between the star contactor's de-energisation and the energisation of the delta contactor, in order to safely extinguish the star contactor's disconnecting arc before the delta contactor is energised. During a switch-over which is too fast, a short circuit may develop via the disconnecting arc. The switch over time period, however, should be just long enough for an arc disconnection, so that the speed decreases as little as possible. Special timing relays for a star-delta switch over fulfil these requirements.

Motor Protection and Contactor Sizing
The overload relay is situated in the motor line. Therefore, the current to be adjusted is lower than the motor's rated current by a factor of $1\sqrt{3} = 0.58$. Due to the third harmonics currents circulating in the motor windings, a higher setting of the overload relay may be required. This may only be carried out on the basis of utilising a measuring device which records the correct r.m.s. value. Conductor cross-sectional areas must be of a suitable size in order that they will be protected against temperature rises resulting from overload conditions. Therefore, the conductor size selected must be in accordance with the protective device(s) rating.

For motor protection by means of power circuit breakers with motor protection characteristics, the power circuit breaker is switched into the network supply lines, as it also carries out short circuit protection of starter and lines. In this case, the current is set to the rated motor current. A correction of the set value because of the third harmonics is irrelevant under these circumstances. The lines are to be thermally proportioned depending on the power circuit breakers setting.

For normal star-delta starting, the controlgear must be sized in accordance with the following currents:

- Main contactor K1M $0.58\ I_e$
- Delta contactor K2M $0.58\ I_e$
- Star contactor K3M $0.34\ I_e$

For starting times exceeding approximately 15 seconds, a bigger star contactor has to be selected. If the star contactor is equal to the main contactor, start times of up to approximately one minute are permissible.

1.1.2 Enhanced star-delta starting

If the torque during normal star-delta starting is insufficient to accelerate the drive in delta connection to the approximate operational speed, then the enhanced star-delta start is utilised. With an increased torque, however, the current consumption during start-up also increases.
A difference is made between:

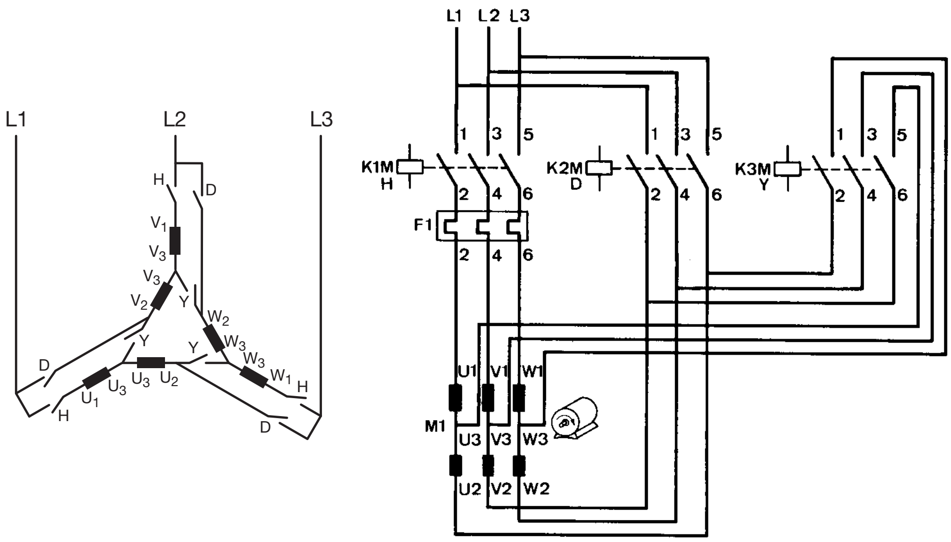
- combined star-delta starting
- partially wound star-delta starting

Both types require motors with accordingly tapped windings.

The same guidelines for normal star connected starters apply to motor connection, contactor operation, motor protection and thermal conductor sizing.

1.1.2.1 Combined star-delta starters

In this case, the motor windings are usually divided into two equal halves. During start, half a winding is switched in delta, the other half in star. Therefore, the term "combined" is used. The star starting current is approximately 2...4 I_e. This results in a correspondingly higher starting torque.



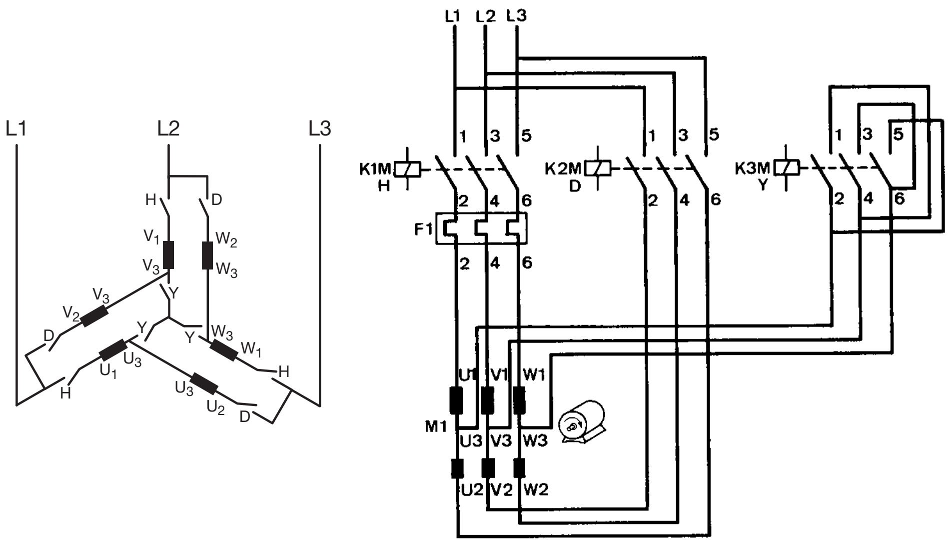
Combined Star-Delta-Starting

Sizing of controlgear:

- Main contactor K1M 0.58 I_e
- Delta contactor K2M 0.58 I_e
- Star contactor K3M 0.34 I_e

1.1.2.2 Partially wound star-delta starting

In this case, the motor windings are also subdivided. During star connection only the main winding, i.e. a part of the entire winding, is used. Therefore, the term “partially wound” is used. The star starting current - depending on the tapping - amounts to 2...4 I_e, which also results in a higher starting torque.



Partially Wound Star-Delta Starting

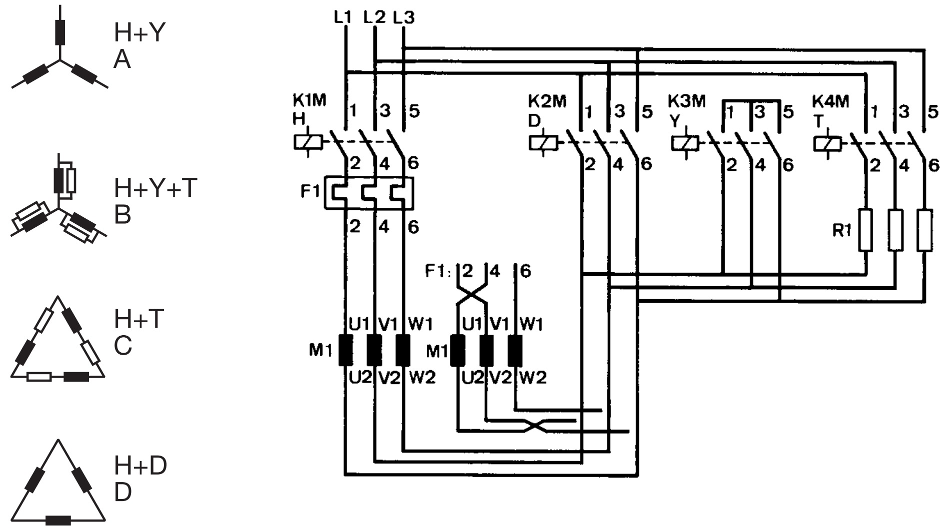
Sizing of Controlgear:

• Main contactor	K1M	0.58 I_e
• Delta contactor	K2M	0.58 I_e
• Star contactor	K3M	0.5 - 0.58 I_e (depending on starting current)

1.1.3 Uninterrupted star-delta starting

This connection prevents a drop in the motor speed during the switch-over from star to delta, and therefore, the following current peak is kept low.

Before the star contactor opens, a fourth (transition contactor) K4M closes the motor circuit via resistors in delta. This prevents an interruption of the motor current during switch-over and the motor speed remains practically constant. Afterwards, the delta contactor K2M creates the final switching status and throws off transition contactor K4M.



Uninterrupted Star-Delta Starting

Sizing of Controlgear:

• Main contactor	K1M	0.58 I_e
• Delta contactor	K2M	0.58 I_e
• Star contactor	K3M	0.58 I_e
• Transition contactor	K4M	typ. 0.27 I_e (depending on transition current)
• Transition resistors	typ. 0.35...0.4 U_e/I_e	

The star contactor must have the same dimensions as the main and delta contactor, and this is different from a normal star-delta connection, because it has to switch off the motor's and transition resistor's star current. A current of approximately 1.5 I_e flows in the resistors. Therefore, a correspondingly higher switching performance is required.

The same guidelines for normal star connected starters apply to motor connection, contactor operation (connection differs due to activation of transition contactors), motor protection and thermal conductor sizing.

1.2 Autotransformer-starting

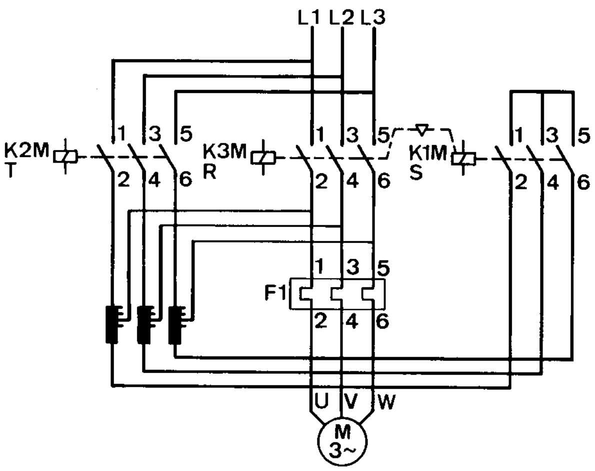
An autotransformer starter enables the start of squirrel-cage motors using a reduced starting current, since the voltage is reduced during start. Contrary to a star-delta connection, only three wires to the motor and 3 motor connections are required. This connection is particularly widely used in English-speaking countries.

During start-up, the motor is connected to the autotransformer's tappings. This means that the motor starts up with a reduced voltage and a correspondingly low current. The autotransformer reduces the current in the mains supply line further and in accordance with its ratio. Like the star delta connection, the autotransformer starter has a favourable torque-current take-up ratio.

In order to adapt the motor start characteristics to the torque requirement, auto-transformers are usually equipped with three selectable tappings (e.g. 80%, 65%, 50%).

When the motor has almost reached its rated torque, the star connection on the transformer is opened. The transformer's partial windings act as chokes in series to the motor windings, and therefore, like the uninterrupted star delta connection, the motor speed does not drop during switch over. After the main contactor has been switched in, the motor windings are applied to the full mains voltage. Finally, the transformer is disconnected from the mains.

Depending on tapping and the motor's starting current ratio, the starting current amounts to 1 - 5 x I_e. The available torque is reduced in ratio to the starting current.



Auto-transformer starter with uninterrupted switch over (Korndorfer-connection)

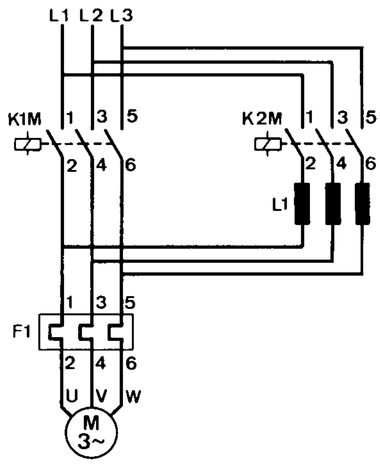
1.3 Start via chokes or resistors

The voltage applied to the motor is reduced by ballast chokes or resistors, as is the starting current. The starting torque is reduced by the square of the current reduction.

1.3.1. Starting via chokes

During the off state, the motor resistance is low. A large percentage of the mains voltage is reduced at the ballast chokes. Therefore, the motor's starting torque is considerably reduced. As the torque increases, the voltage applied to the motor increases due to a reduction in current consumption and the vectoral voltage division between motor and the ballast reactance. This leads to an increased motor torque. After a successful run-up, the chokes are short-circuited.

The starting current is reduced depending on the required starting torque.



Start via Chokes

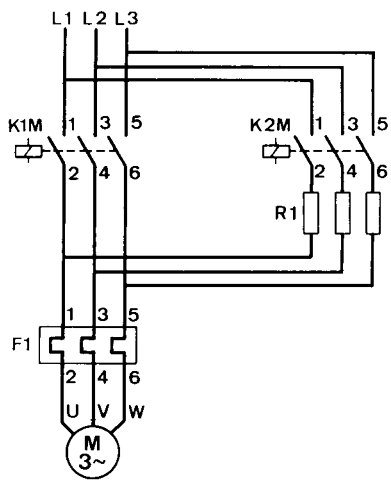
1.3.2. Start via resistors

In this case, cost-efficient resistors are used instead of the above-mentioned chokes.

This method is less helpful in reducing the starting current for the same torque requirement, because the motor torque reduces as a value of the square of the voltage and the voltage applied to the motor increases only due to the motor's reduced current consumption during increasing speed.

It is better to reduce the ballast resistor step by step during start. But this requires considerably more switch gear.

Another possibility is the use of encapsulated wet (electrolytic) resistors. For these resistors, the ohmic resistance reduces in line with the temperature increase caused by the starting current's heating capability.



Start via Resistors

1.4 Multi-speed motors

For asynchronous motors, the speed is determined by the number of poles and the supply frequency.

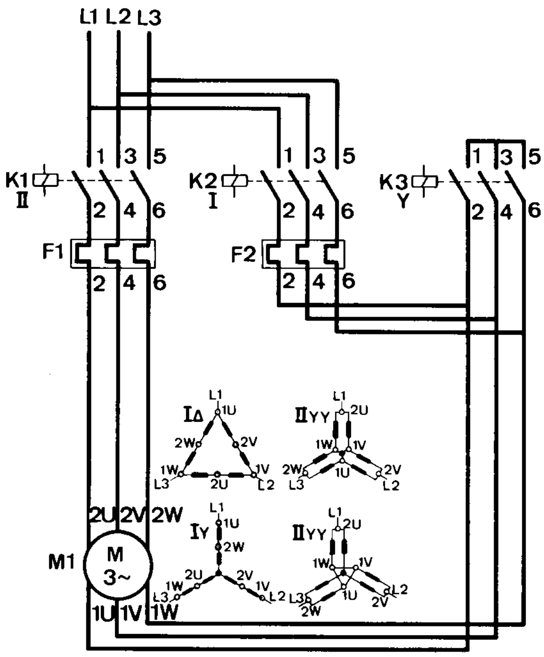
2 poles	=	3000 min -1	(synchronous speed)
4 poles	=	1500 min -1	
6 poles	=	1000 min -1	
8 poles	=	750 min -1	

etc.

Motors with two or more speeds can be built by a suitable switch-over of tapped windings or by separate windings per speed in the same motor. The Dahlander connection, which can achieve two speeds with a 1:2 ratio with only one winding, is especially cost-efficient.

Multi-speed motors can be professionally operated at both speeds and are used, for example, for ventilators to change the output. This is their main application area.

Depending on the design and switching of the windings, there are motors which achieve approximately the same output or torque at different speeds. For lower speeds, the same torque results in lower currents, which makes starting with a high torque requirement and small current consumption manageable.



Multi-speed motor