

Induction Motor Control

A much misunderstood yet vitally important facet of electrical engineering.

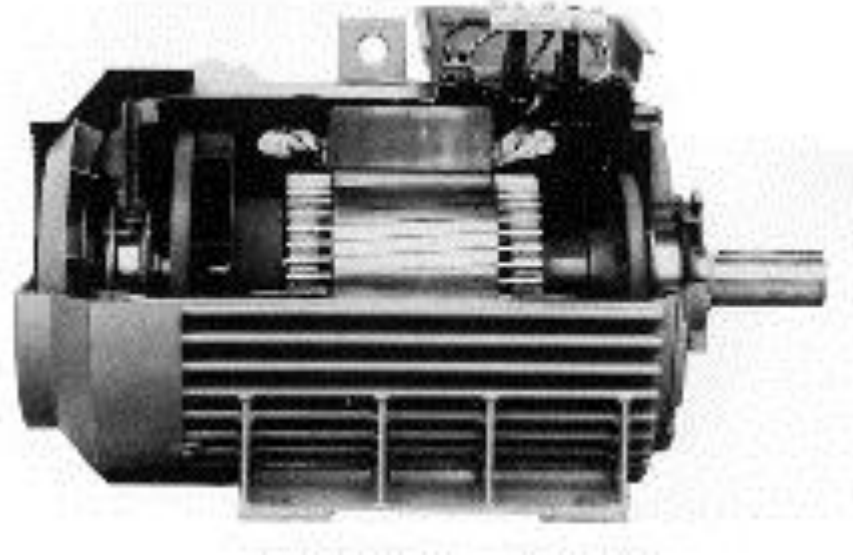


The Induction Motor

- A very major consumer of electrical energy in industry today.
 - The major source of rotational and linear motion in industry.
- Function 1 : To **convert Electrical Energy into Mechanical Energy** to accelerate the driven load to full speed.
- Function 2 : To **convert Electrical Energy into Mechanical Energy** and provide the mechanical power to do functional work.

The Induction Motor

- **Two major components**
 - Stator : Primarily determines run characteristics
 - Rotor : Primarily determines Start characteristics.



The Stator

- The Stator is a stack of steel laminations with slots to enclose the stator coils.
 - The stator coils are connected in star, or in delta for three phase motors
 - The Stator coils provide a run winding and a displaced start winding for a single phase motor.



The Stator

- The Stator comprises two or more windings, angularly displaced and fed by displaced AC voltages to provide a rotating magnetic field.
- The arrangement of the windings and the frequency of the AC voltage determine the rotational speed of the rotating field.
 - 2 pole stators at 50Hz result in a 3000 RPM field.
 - 4 pole stators at 50 Hz result in a 1500 RPM field.
- The maximum field strength is determined by the maximum allowable flux density of the stator iron.
 - An induction motor has a maximum V/Hz that can be applied to avoid saturation.

The Stator

- Induction motors can operate at a range of voltages and frequencies.
- Reduced frequency operation requires reduced voltage to limit the V/Hz ratio.
 - A motor designed for 480V 60Hz operation has a V/Hz ratio of 8. The same motor can operate at 400V 50Hz as the V/Hz ratio is the same; BUT the speed is reduced from 3600 RPM to 3000RPM and the KW rating reduces to 5/6 of the 60Hz rating.

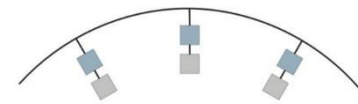
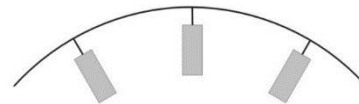
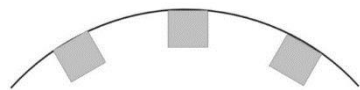
The Rotor

- The Rotor is a cylindrical stack of steel laminations pressed onto the shaft with a number of rotor bars imbedded in the rotor. The bars are shorted at each end.



The Rotor

- The Rotor has an impedance that has Resistance and Inductance.
 - The resistance is determined by the length, cross sectional area and material of the bars.
 - The inductance is determined by the depth of the bar in the rotor and the frequency of the current flowing in the rotor.

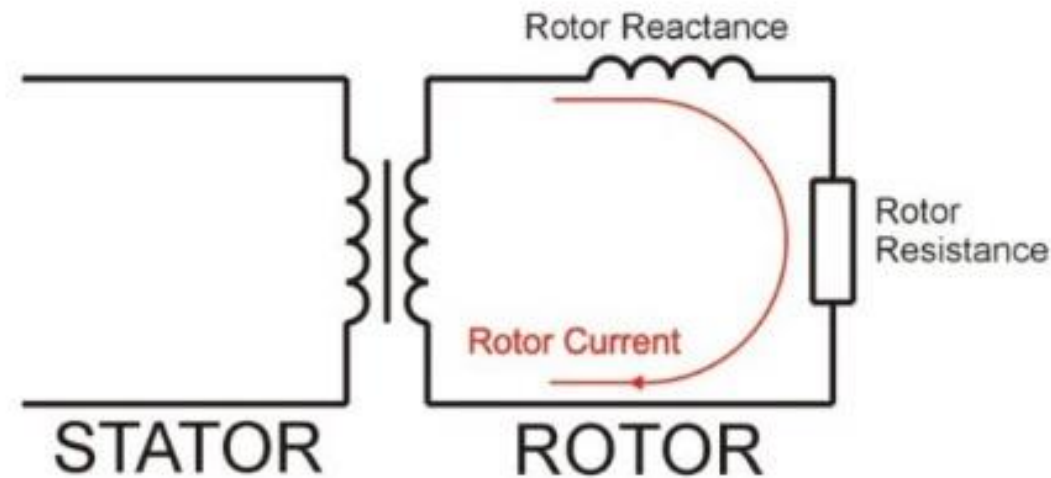


Induction Motor Operation.

- AC Voltage is applied to the stator winding, producing a rotating magnetic field at synchronous speed.
- Flux from the stator field, cuts through the rotor winding causing current to flow in the rotor.
- The rotor produces it's own magnetic field.
- The stator and rotor fields interact to produce a rotational torque on the rotor.
- The Rotor current frequency is the difference between the rotor speed and the stator rotating magnetic field. - SLIP.
 - If the rotor rotated at synchronous speed, the stator flux would not induce a current in the rotor winding, so there would be no torque. – Full load speed of the rotor is always less than synchronous speed.

Start Current and Start Torque

- The Start Current and Start Torque of a particular induction motor are a function of a) the rotor design and b) the voltage applied to the stator.
 - The Start Current at a given speed, is determined by the rotor impedance at that speed. $I = V / Z$



Start Current and Start Torque

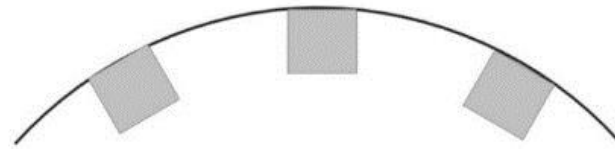
- The Start Torque at a given speed, is determined by the power dissipated in the rotor winding at that speed. $P = I \times I \times R$
- The Start Torque at a given speed, is a function of the effective rotor resistance at that speed.

Rotor Designs

- Classic rotor designs were specified and selected for particular applications.

- **Design A - shallow Bar**

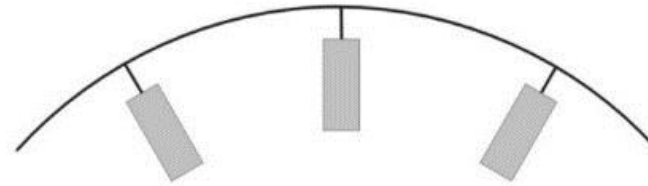
- Shallow bar
- low inductance,
- low resistance,
- High start current,
- low start torque,
- low full load slip.



Rotor Designs

- Design B - Deep Bar Rotor

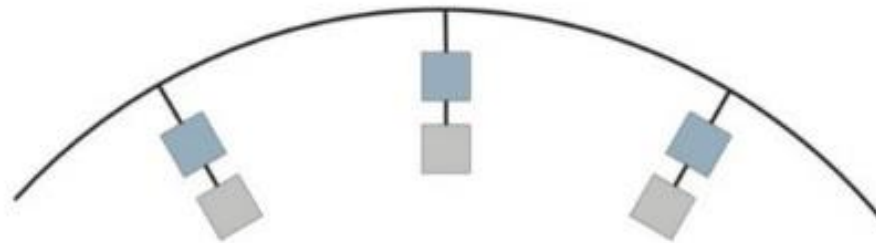
- High inductance.
- Higher Resistance.
- Lower Start Current.
- Higher Start Torque.



Rotor Designs

- **Design D – Double Cage**

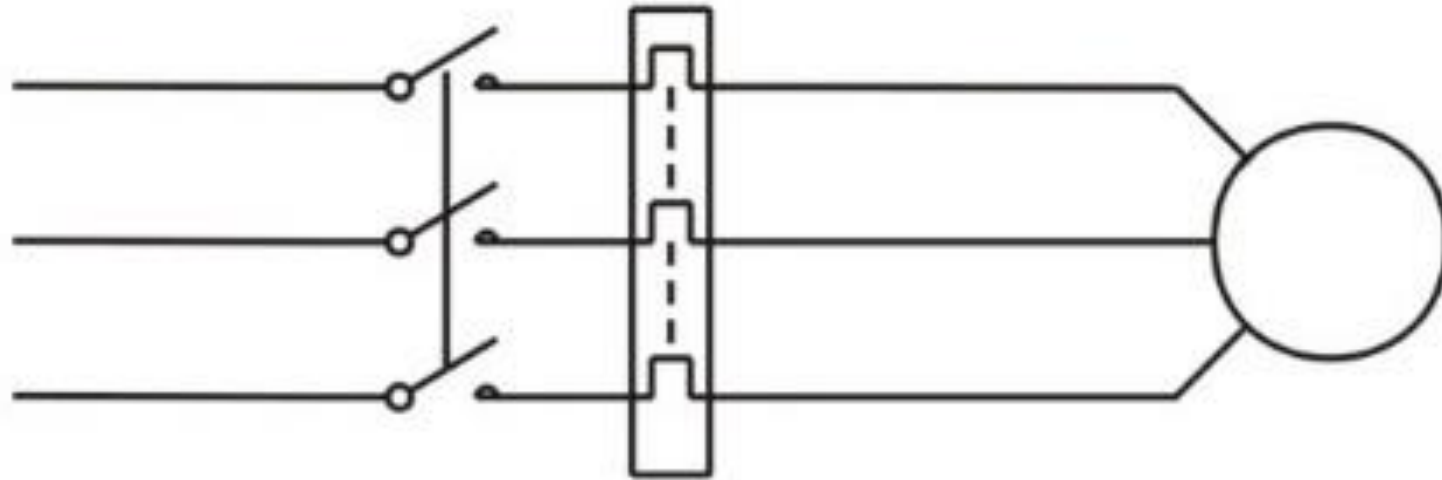
- Low resistance, High inductance inner winding (cage).
- High resistance, (commonly brass), Low inductance, outer winding.
- Low Start Current.
- High Start Torque.



Rotor Losses

- Power is dissipated in the rotor during start
 - Total power dissipated in the rotor during start, is the full speed kinetic energy of the driven load.
 - High inertial loads have a high kinetic energy. – significant rotor heating.
- Power is dissipated in the rotor during run
 - Power dissipation is equal to the shaft torque times the running slip.
1% slip results in 1% rotor losses.

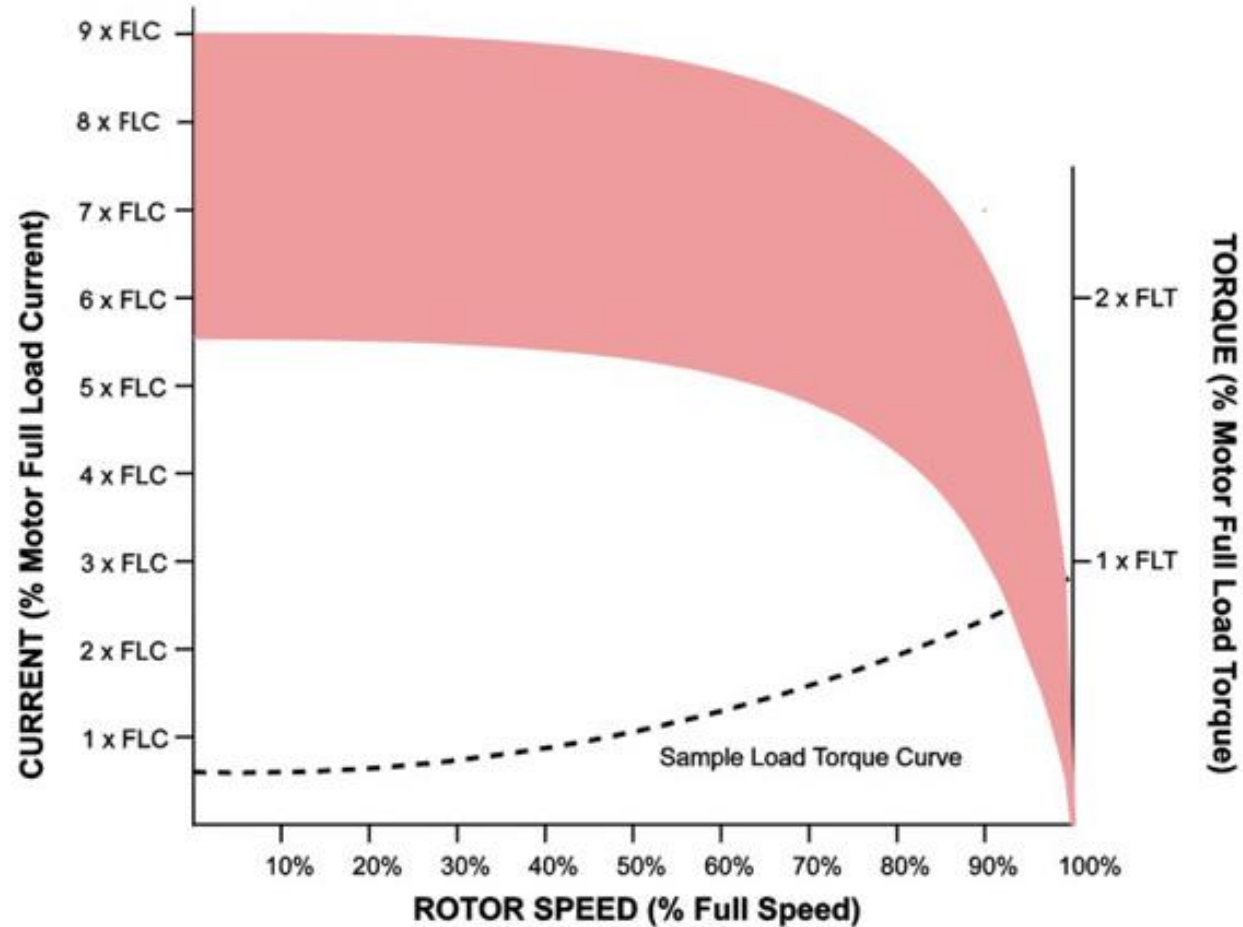
DOL Starter



Full Voltage Start Current (DOL)

- The Full voltage start current is a function of the motor (rotor) design and the applied voltage.
- The FV start current is independent of the coupled mechanical load.
 - The start current when the rotor is not turning, is the Locked Rotor Current LRC or LRI and is commonly expressed in percent.
550% - 950% (wound rotor motors with rotor shorted 1200% - 1400%)
- The Start time is a function of the start torque and the load inertia.

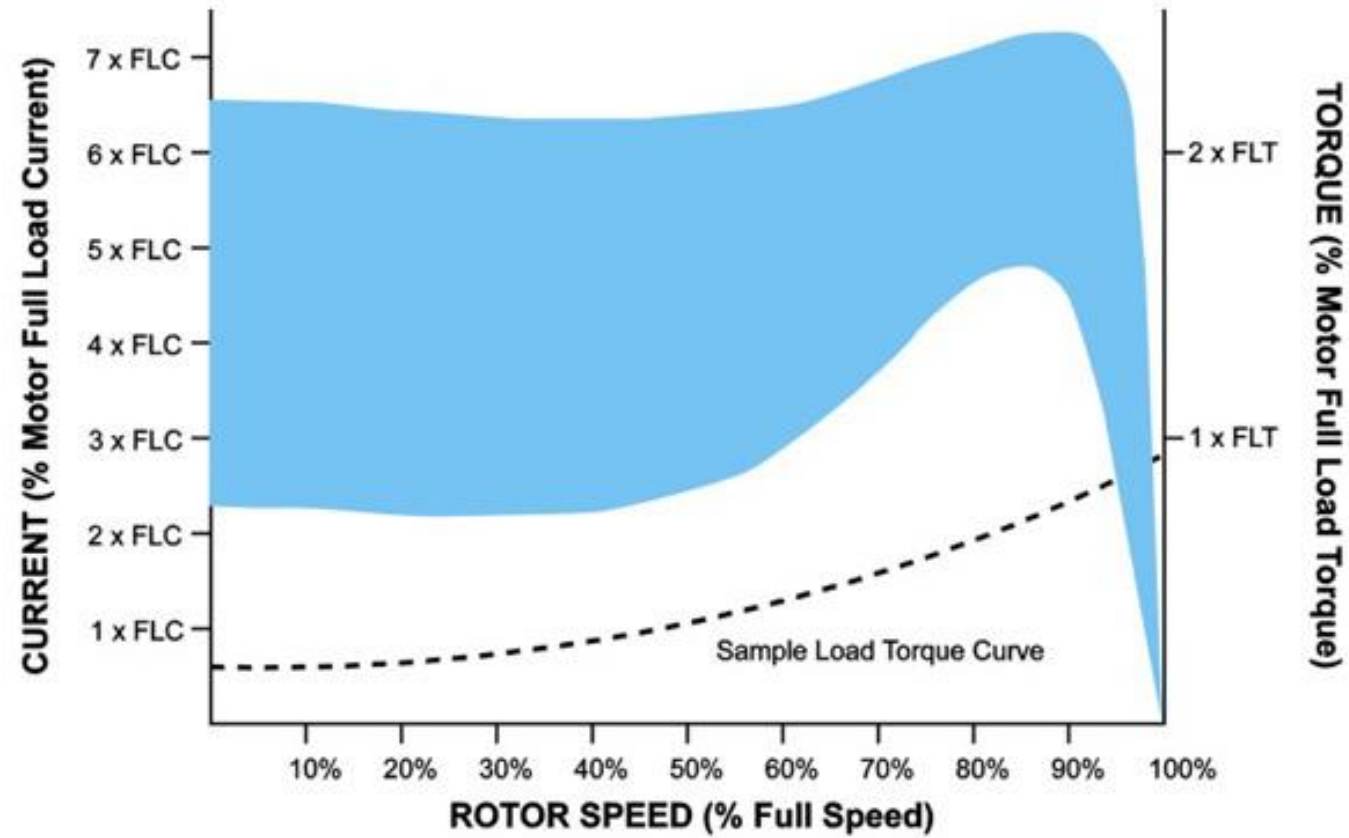
Full Voltage Start Current



Full Voltage Start Torque

- The Full voltage start torque is a function of the motor (rotor) design and the applied voltage.
- The start torque when the rotor is not turning, is the Locked Rotor Torque LRT and is commonly expressed in percent or NM
60% - 250% (wound rotor motors with rotor shorted 20% - 80%)
- The start torque peaks at almost full speed. (95% – 98% speed)

Full Voltage Start Torque



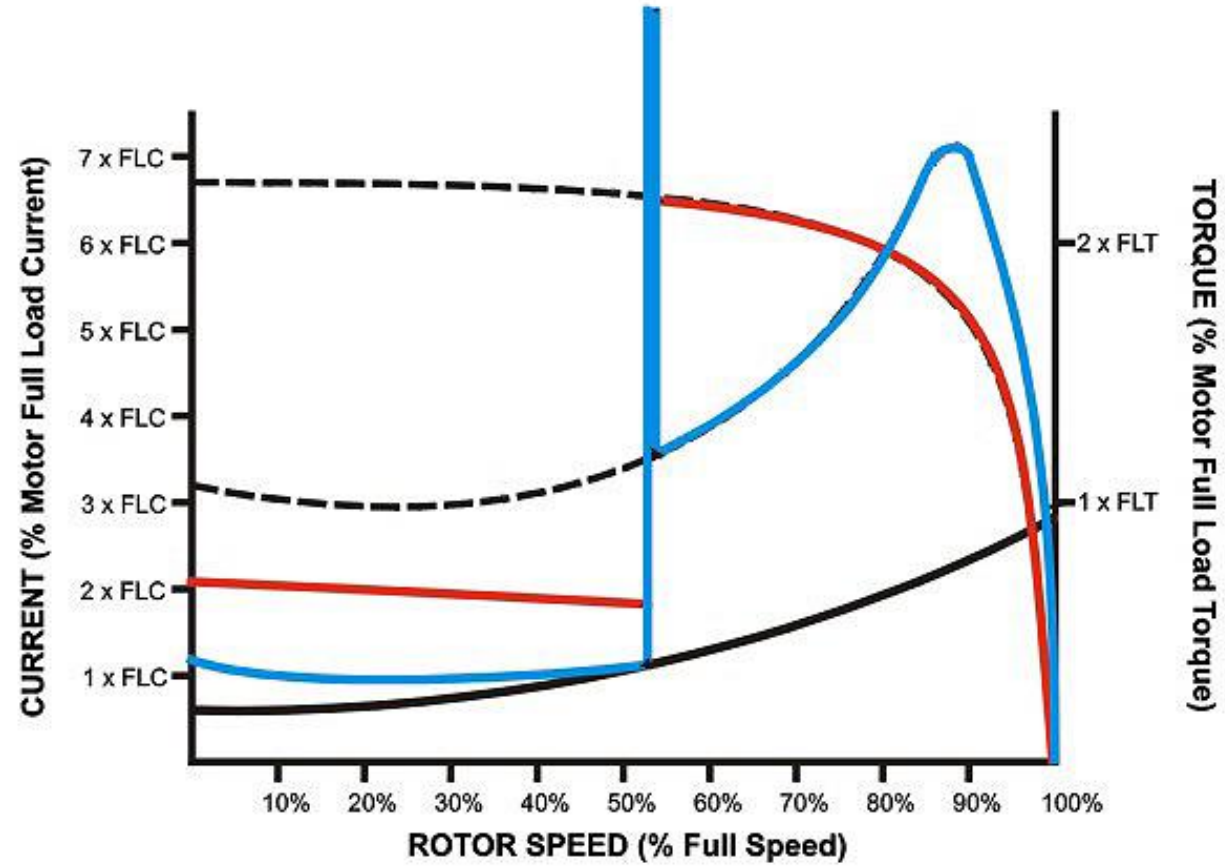
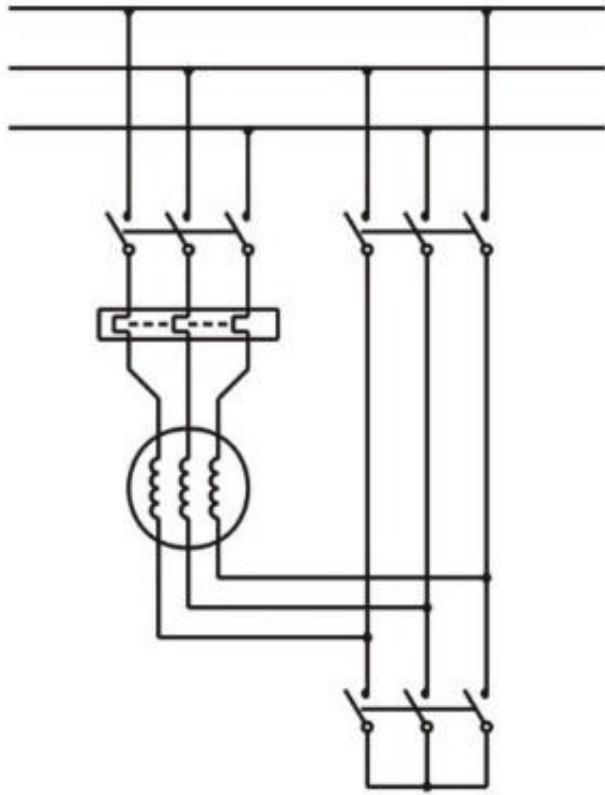
Reduced Voltage Starting

- Reducing the voltage applied to the stator, reduces the start current. ($I = V / Z$) ohms law applies.
 - Reducing the stator current during start, reduces the rotor current during start.
 - Reducing the rotor current during start, reduces the rotor power and the rotor torque.
 - Start Torque reduces with the square of the voltage reduction, or the square of the current reduction.
- $P = I \times I \times R$

Star – Delta Starter

- Stator initially connected in Star, then switched to delta.
- In star, voltage across each winding reduced to 57.7% ($1/\sqrt{3}$) of line voltage. (400V – 230V)
- Torque in star reduced to one third full voltage torque.
- Winding Current in star reduced to 57.7% of Delta winding current.
 - Line Current is reduced to one third of line current in delta.
- Motor must be six terminal motor designed for 400V operation in Delta Connection.

Star Delta Starter



Star Delta Starter

- Stepped starter with no adjustment other than time.
- If insufficient torque in star to get motor and load to full speed, switching will occur at less than full speed and result in Full voltage current.
- Open transition starter, star contactor must be opened before delta closed, interrupting current flow through the motor windings.

Open Transition Switching

- A rotating induction motor, when connected to the supply, has a current flowing in the short circuited rotor winding.
- When the stator is disconnected from the supply, the motor continues to rotate, driven by the load inertia.
Current continues to flow in the rotor for a period of time.
- The motor acts as a generator, generating voltage at a frequency set by the rotational speed, and voltage related to the rotor flux.
- Re-connection to the supply causes a current and torque transient due to the sum of the generated voltage and supply voltage.
 - Torque transient can break shafts, chains, couplings, gearboxes etc.

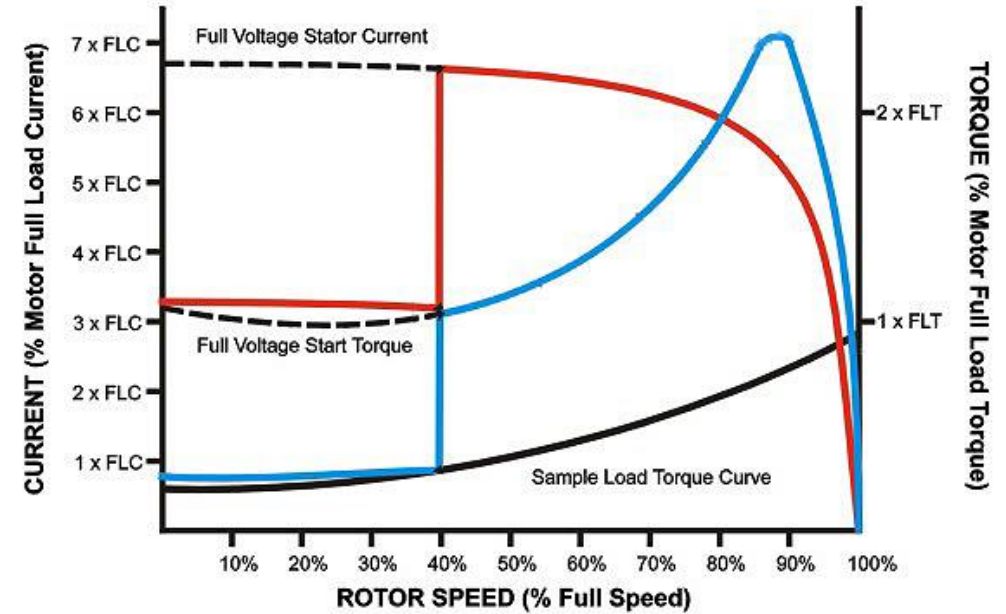
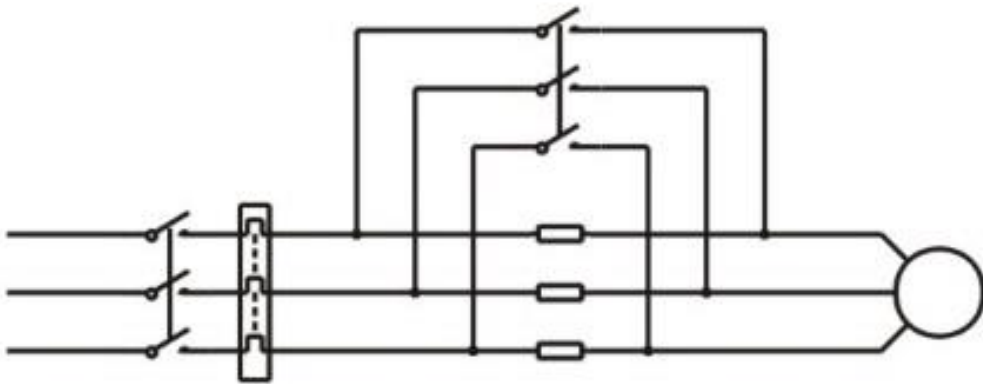
Closed Transition Star Delta Starter.

- The open transition star delta starter can be converted to a closed transition star delta starter by adding an extra contactor and large resistors.
- Operation:
 - Close line contactor and star contactor.
 - Close Aux star contactor in series with resistors across star contactor
 - Open star contactor
 - Close delta contactor.

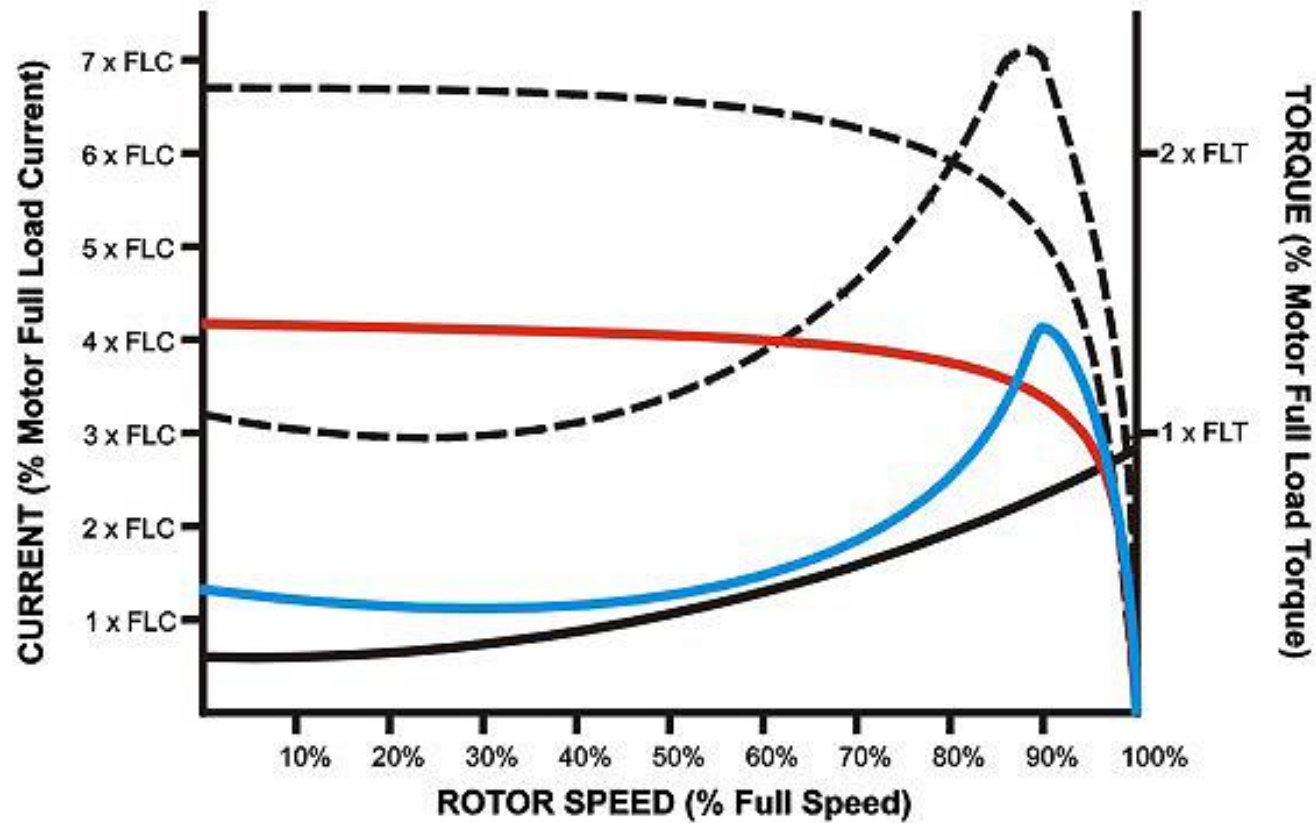
Primary Resistance Starter.

- Large resistors in series with motor during start. Resistors limit current, reducing the torque developed by the motor.
- Resistors bridged when the motor reaches full speed.
- Very high power dissipated in resistors.
 - Lots of heat.
 - Long cool down period.
 - Resistance changes with temperature.
 - Resistors metallic, or liquid.

Primary Resistance Starter.



Primary Resistance Starter

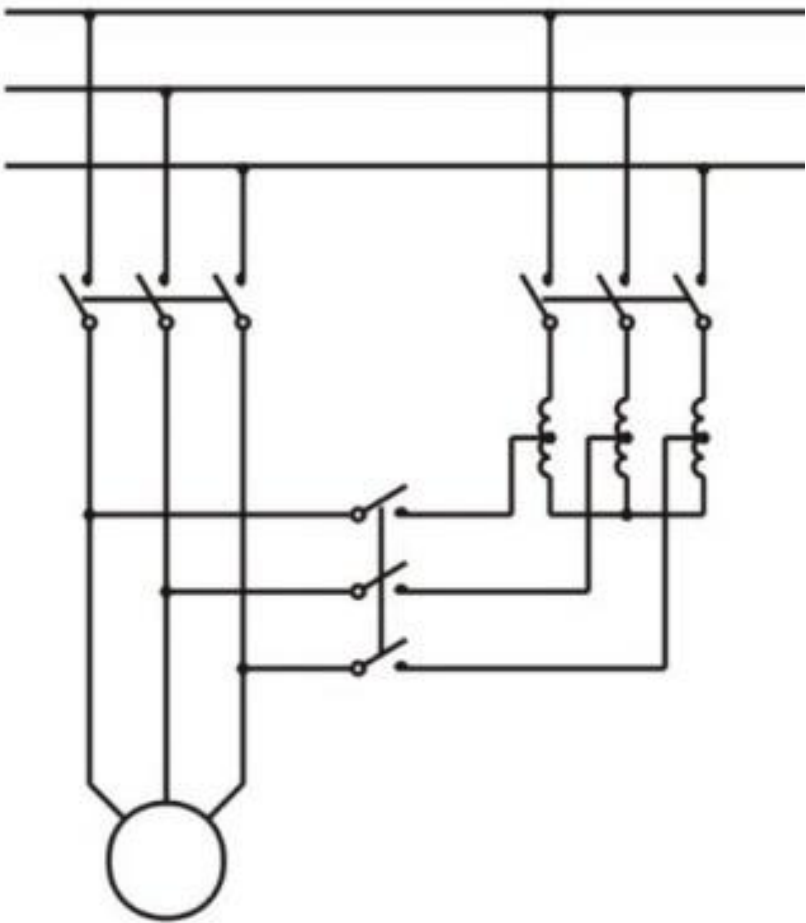


Auto Transformer Starter

- Voltage Reduced by action of a three phase (or two phase) auto transformer.
- Usually multi-tap, 50%, 67% 80%
- Can be multistage – additional control equipment.

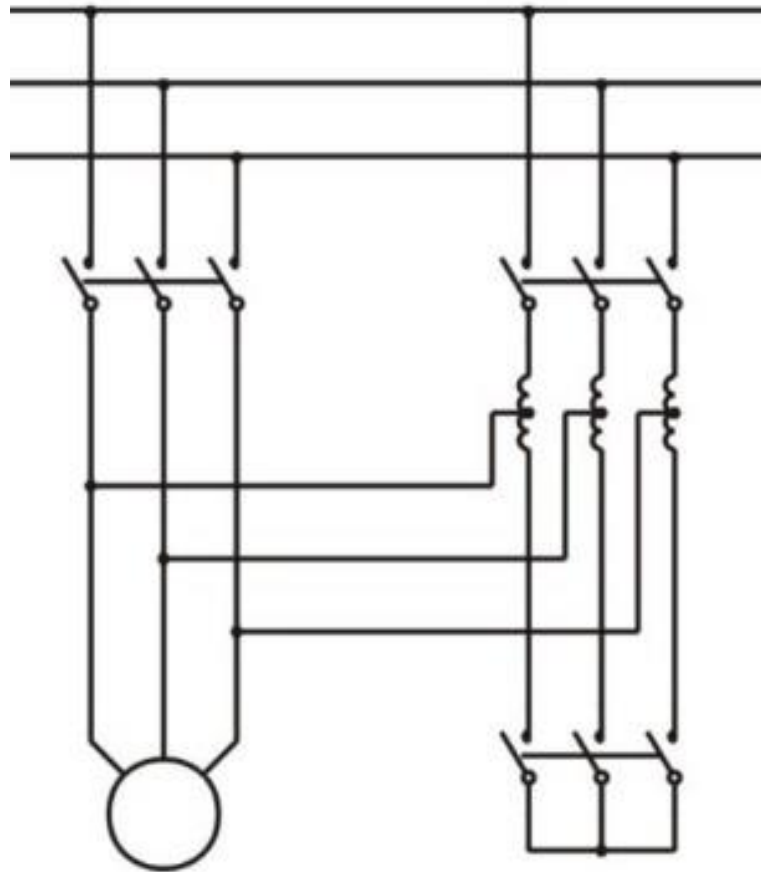
Autotransformer Starter

Open Transition

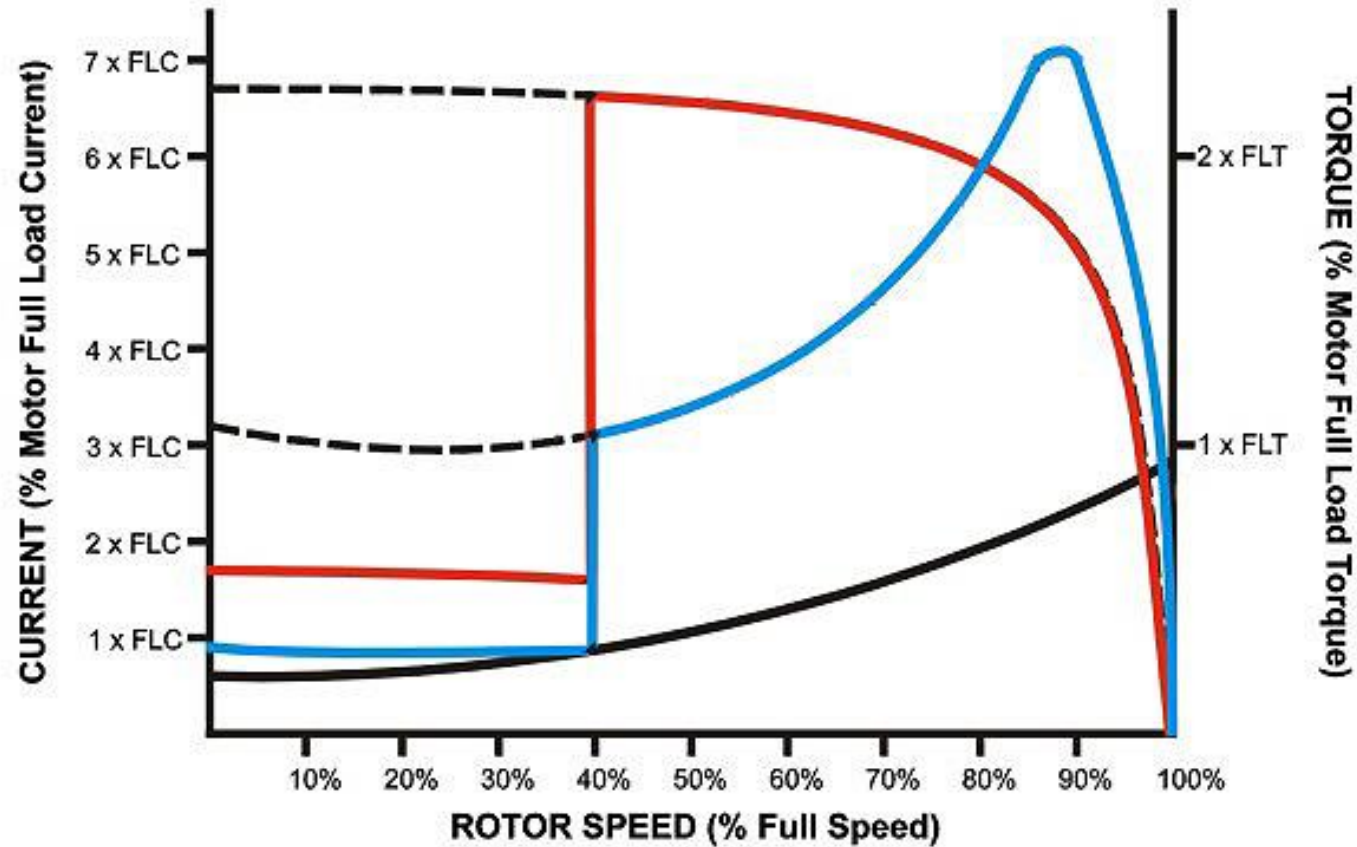


Auto Transformer

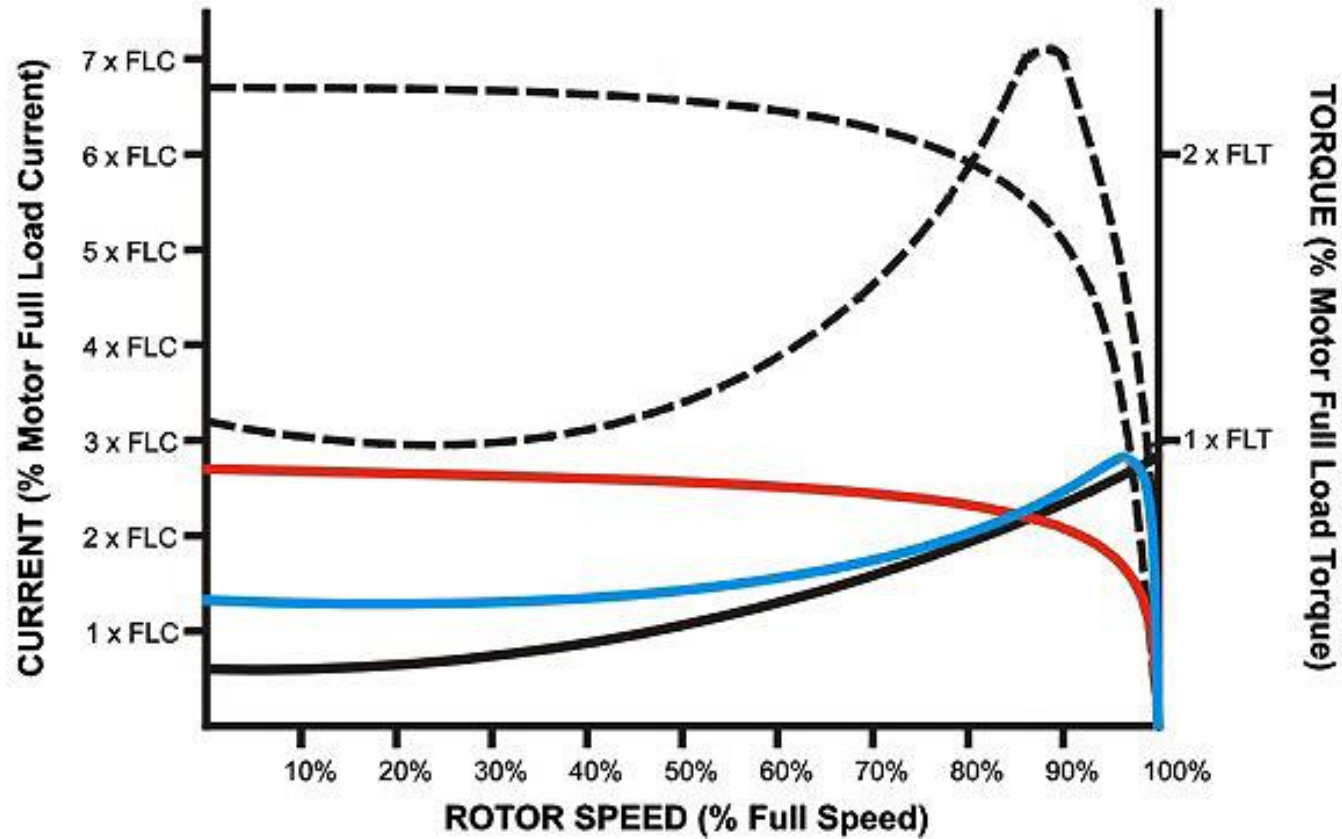
- Closed Transition
- Korndorffer.
 - No additional cost



Auto Transformer

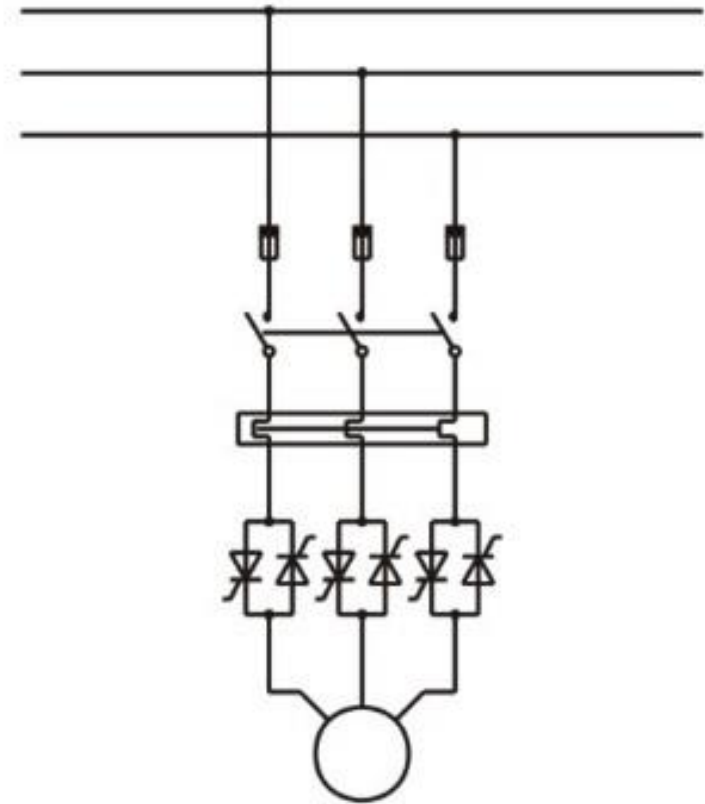


Auto Transformer



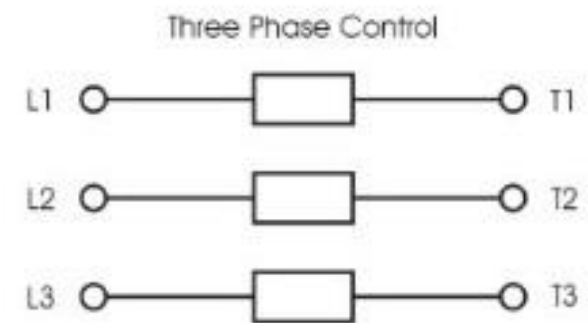
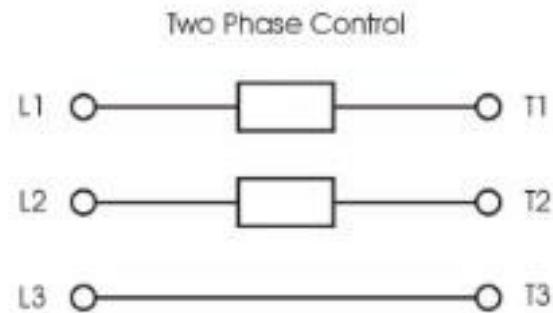
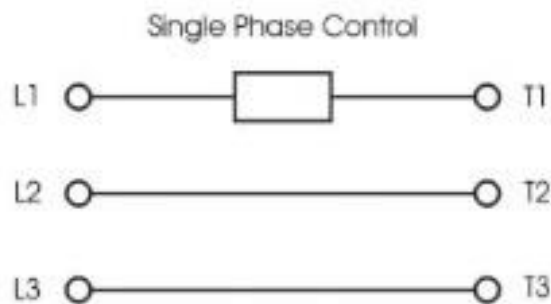
Solid State Soft Starters

- Solid State Soft Starters are similar to the Primary Resistance Starter where the Resistors are replaced by phase controlled Solid State Switches in series with the supply to the motor.



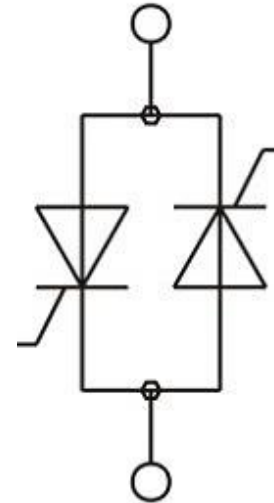
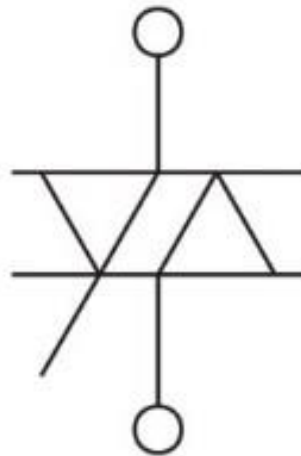
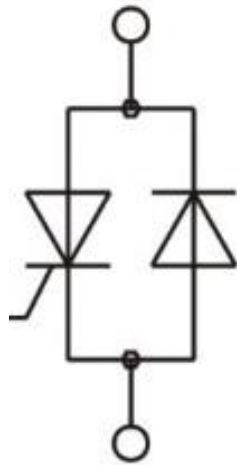
Solid State Soft Starters

- Soft starters are available with solid state elements controlling one phase, two phases and three phases.
- Three phase control is best and should be used on high inertia and heavy duty starts.
- Single phase control reduces torque, but not current.



Solid State Soft Starters

- Switching elements can be SCR/Diodes, Triacs or SCR/SCR.
- SCR/Diodes are not common now and cause even harmonics and undue motor heating.
- Triacs are not as rugged as SCR/SCR and tend to be limited in voltage rating.



Starting Induction Motors

- The minimum start current that can be applied to an induction motor, is the current that will develop sufficient torque to accelerate the driven load to full speed. If insufficient current is applied, the motor will reach part speed and remain at that speed until the motor burns out, or the protection operates.
- The minimum start current is a function of the load speed torque curve and the motor characteristics.

Starting Induction Motors

- The start characteristics of induction motors vary tremendously.

Motor	FLC	LRC	LRT	T 300%I	I 50%T
1	191	600	260	65	260
2	184	600	190	48	310
3	191	570	150	42	330
4	187	660	190	39	340
5	185	550	120	36	360
6	191	670	150	30	390
7	190	780	200	30	390
8	182	850	220	27	410
9	190	670	120	24	430
10	174	720	240	41	328

Starting Induction Motors

- High Inertia loads require a high start current for an extended time.
- High inertia loads are heavy duty starts and require motors with a high thermal inertial.
 - Motor Thermal inertia is indicated by “Max Start time” “Max Locked Rotor Time” or “Max Load Inertia”
- Incorrect motor selection can result in motor damage during start and/or excessive start currents.
- High Efficiency Motors tend to give low efficiency starts

Start Efficiency

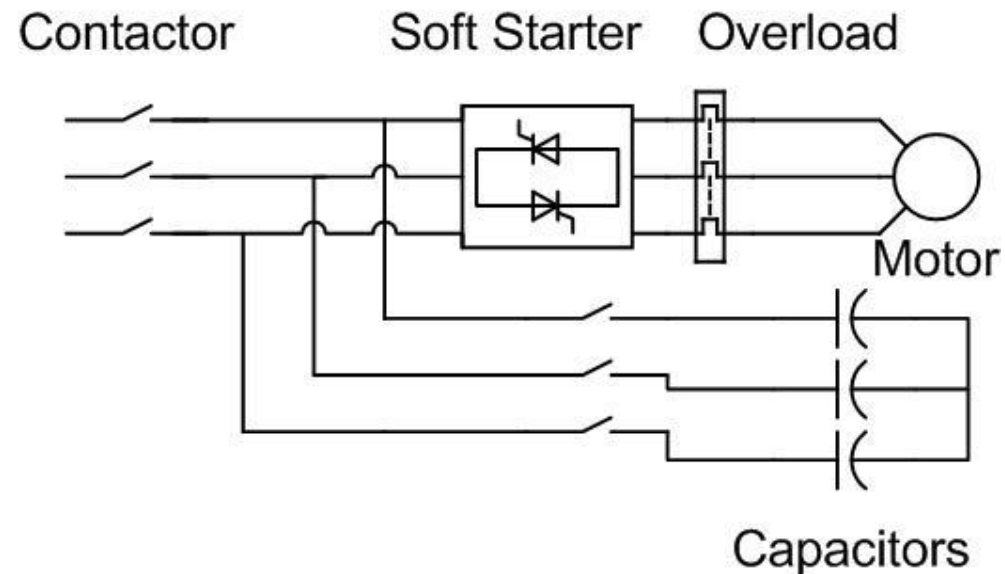
- Modern high efficiency motors are designed to operate at a high efficiency, but the reduction in slip losses that improves the operating efficiency, results in an increase in the LRC. This reduces the torque available for a given start current.
- A measure of the effectiveness of a motor during start, (converting Amps to NM) is given by LRT / LRC where both LRT and LRC are quoted in percent. This comparison is under Full Voltage conditions and becomes worse when reduced voltage starting is employed.

Selecting Soft starters

- High inertia loads require high start currents for long times. This requires a heavy duty rated soft starter, commonly as high as 500% current for 40 + seconds. Selecting lower duty soft starters will not usually cause immediate failure, but can significantly shorten the life of the SCRs.
- Soft starter losses are typically 0.5% and can be reduced by the use of bypass contactors. (Built in to some starters)

Power Factor Correction

- Power Factor Correction **MUST NOT** be connected to the output of the soft starter. This will damage SCRs.
- Power Factor Correction must be controlled by a dedicated contactor that is closed after the starter reaches full voltage.



Summary

- There is a very wide diversity in the starting performance of induction motors.
- The best starting characteristics are achieved when the best motor is selected for the application.
- Reduced voltage starting reduces start current and start torque. The reduction is limited by the torque requirement of the load. If there is a start current limitation (e.g. Genset) the motor must be selected for high start torque per amp start current. Target low LRC and high LRT. A bad motor can not be fixed by the application of a reduced voltage starter.

Summary

- High inertia loads require a high start current for a period of time to get them to full speed. The rotor can fail due to excess load inertia.