# Motor Control – Reduced Voltage Starters

by

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Motor Control – Reduced Voltage Starters
*A SunCam online continuing education course*

# Learning Objectives

1. Understanding the starting characteristics of AC induction motors
2. Problems that can be caused by full-voltage starters
3. Understanding the functions and benefits of 5 methods for reduced voltage starters

# Introduction

When it comes to starting an electric AC induction motor, using a full-voltage starter is the simplest method. A properly sized contactor and overload relay with a couple of push buttons and you are ready to go. Although this is a simple way to start the motor, it has the potential to create problems.

1. Applying full voltage to the motor terminals, immediately creates approximately 150% of the motor's rated torque. This immediate torque causes a shock to the driven equipment connected to the motor. The result can be high mechanical stress in conveyors, gear boxes and couplings and can cause belts and pulleys to slip.
2. When applying full voltage to the motor terminals the motor will draw more than 600% of the normal full load current. If the motor is large compared to the overall electrical service, this can cause the voltage to drop across the entire electrical system. The results of the lower system voltage can be lights dimming or the motor failing to start. Other results could be that other motors may slow down, electronic equipment may shut down or protective devices may operate.

One possible solution to avoid these problems is to use a reduced voltage starter. Reducing the voltage to the motor during starting reduces the starting torque because torque is proportional to the square of the voltage. The resulting lower starting torque will reduce the mechanical stress on the driven equipment.

$$T_{Reduced\,Voltage} \sim T_{Full\,Voltage} * (\frac{V_{Reduced\,Voltage}}{V_{Full\,Voltage}})^2 \qquad \text{eq 1}$$

Reducing the voltage during starting also reduces the starting current proportional to the reduction in voltage. Lower starting current will reduce the possibility of the overall system voltage being reduced and the associated potential problems.

$$I_{Reduced\ Voltage} \sim I_{Full\ Voltage} * \frac{V_{Reduced\ Voltage}}{V_{Full\ Voltage}} \qquad \text{eq 2}$$

This course will cover the starting characteristics of AC induction motors and the impact of using 5 methods for reduced voltage starters.

# Motor Starting Characteristics

The National Electrical Manufacturers Association (NEMA) defines different designs for AC induction motors, designated as design A, B, C and D. The designs provide a range of values that manufacturers must adhere to for locked rotor torque, pull-up torque, break-down torque, locked rotor current and slip. The design characteristics are shown in table 1.

*Table 1: NEMA Motor Design Characteristics as a Percentage of Rating*

| Characteristic | Locked Rotor Torque | Pull-Up Torque | Breakdown Torque | Locked Rotor Current | Slip |
|---|---|---|---|---|---|
| Design A | 70-275 | 65-190 | 175-300 | Not Defined | 0.5-5% |
| Design B | 70-275 | 65-190 | 175-300 | 600-700 | 0.5-5% |
| Design C | 200-285 | 140-195 | 190-225 | 600-700 | 1-5% |
| Design D | 275 | N/A | 275 | 600-700 | 5-8% |

NEMA design B is considered a typical motor when looking at manufacturers' catalogs. This design will be used as the basis for this training. The torque vs. speed curve for a design B motor is shown in figure 1.

This curve identifies some of the key torque characteristics.

1. Locked rotor torque – also called starting torque is the amount of torque produced at the moment that full voltage and frequency are applied to the terminals of a motor at rest.
2. Pull up torque – as the motor accelerates, the torque will decline slightly. The minimum value of torque during motor acceleration is the pull up torque.
3. Breakdown torque – the maximum torque produced during acceleration. This normally occurs at 70-85% of the rated speed.

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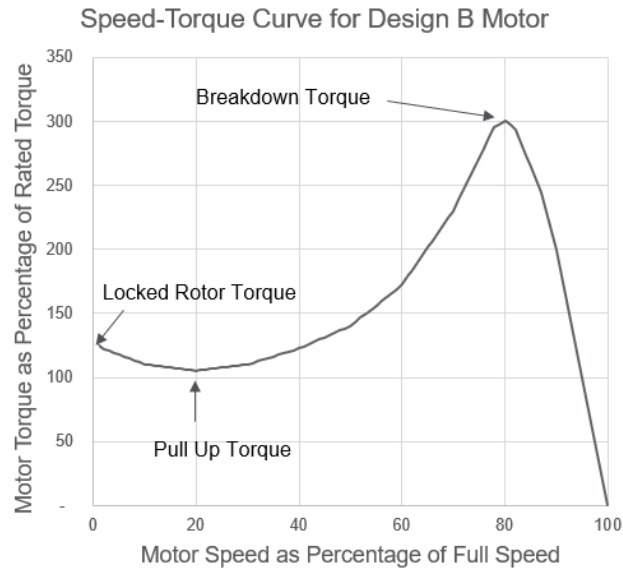*A SunCam online continuing education course*

Speed-Torque Curve for Design B Motor



*Figure 1- Torque vs. Speed for NEMA Design B Motor*

The generalized current vs speed curves for design B motors is shown in figure 2. This shows that the motor current will be 600% of its normal full load current when full voltage is applied to the motor terminals and decreases as the motor speed increases.
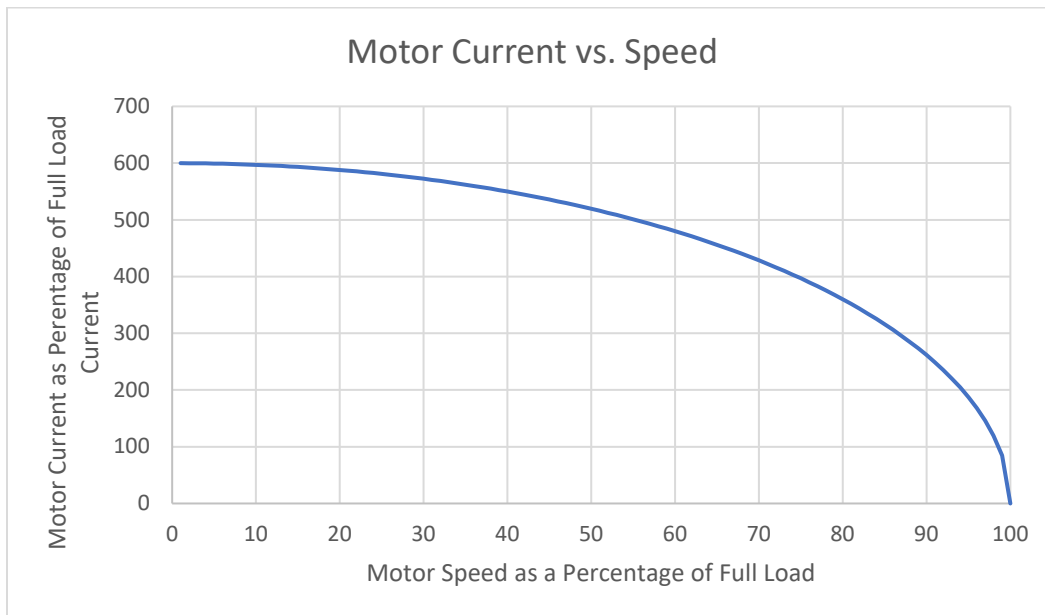


*Figure 2 - Motor Current vs Speed*

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There are five methods of reduced voltage motor starting that will be covered in this course. They are:

1. Primary resistor starting
2. Autotransformer starting
3. Part winding starting
4. Wye-delta starting
5. Solid state reduced voltage starting

The course will cover the starting characteristics, benefits and schematics for power and control of each of these methods.

# Primary Resistor Starting

Primary resistor starting is a simple method for reducing the voltage at the motor terminals during starting, although it is not a very energy-efficient method. The power circuit is shown in figure 3. The starter is constructed by inserting a resistor in line with the motor along with a bypass contactor in parallel with the resistor. When the motor is started, the bypass contactor is open so all current flows through the resistor. The current flowing through the resistor causes a voltage drop based on Ohm's Law ($V = IR$) so the voltage at the terminals ($V_{terminal}$) is less than the system voltage ($V_{line}$). The electrical power lost through the resistor is dissipated as heat. At the moment voltage is applied, the motor will draw 600% of the rated full load current. This high current causes a voltage drop across the resistor. As the motor accelerates and current decreases and the voltage drop across the resistor will decrease resulting in an increase in the voltage at the motor terminals. This creates a smooth acceleration up to the point that the bypass contactor is closed, which will cause the voltage at the motor terminals to increase to the system voltage.
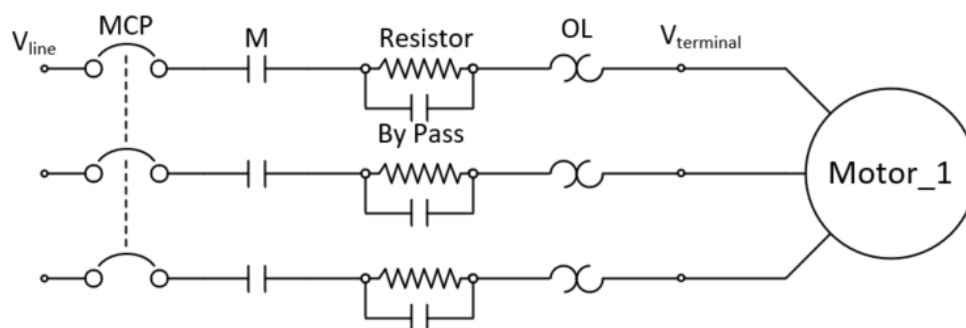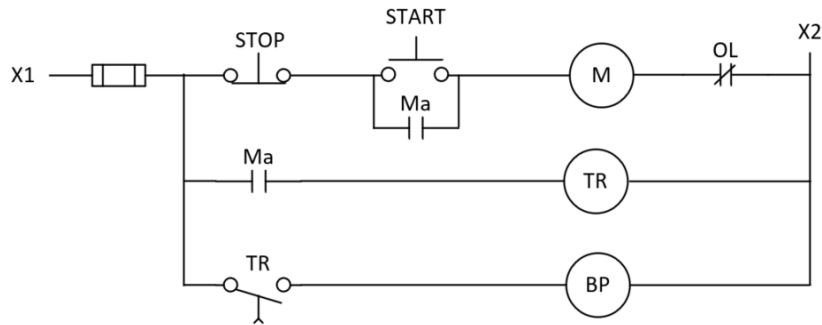


*Figure 3 - Primary Resistor Power Circuit*

The control circuit for primary resistor starting compared to full voltage starting requires the addition of a timing relay to control the resistor bypass contactor coil BP as shown in figure 4.

When the START button is closed, the motor contactor coil M is energized. This closes contactor M and energizes the timing relay TR. When the timing relay times out, it will energize the by-pass contactor BP, completing the starting sequence.



*Figure 4 - Primary Resistor Control Circuit*

This starter can achieve a lower starting current and lower starting torque, but because it wastes energy through heat dissipation in the resistor other reduced voltage starting methods are more common. Because heat builds up in the resistor, primary resistor starts will have a limited number of allowable starts per hour to prevent the resistor from over-heating.

# Autotransformer Starting

In this type of starter, an autotransformer is placed in series with the motor to control the power input to the motor, rather than a resistor as in the primary resistor starter. The power circuit is shown in figure 5. The voltage at the motor terminals is connected to the autotransformer taps during starting. The available taps are typically 80%, 65% and 50% of the line voltage.
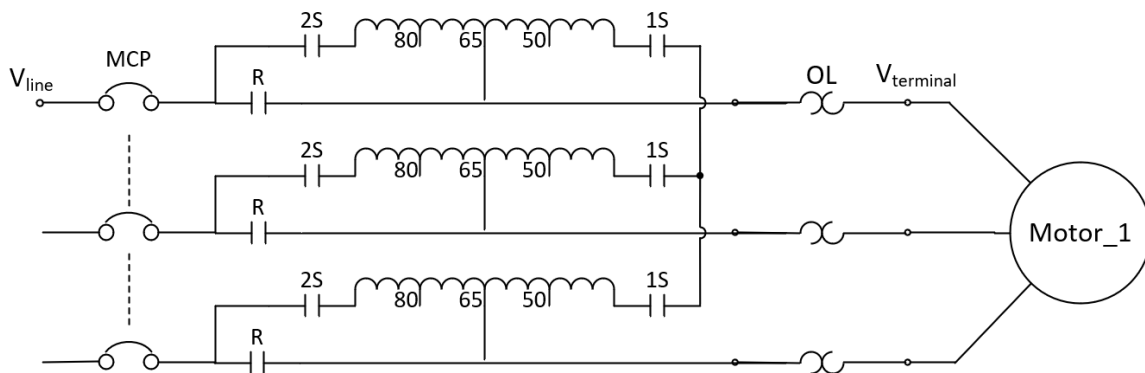


*Figure 5 - Autotransformer Power Circuit*

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The main characteristic of an autotransformer is that the power delivered into the line side of the autotransformer and the power delivered at the load side are equal. The line side voltage ($V_{line}$) is higher than the load side ($V_{terminal}$) and the line current is lower than the load current.
This provides the major benefit of this type of starter, which is developing the highest starting torque with the lowest starting line current compared to other starting methods.

When using an autotransformer, the voltage applied to the motor terminals ($V_{terminal}$) is defined by the tap setting times the line voltage ($V_{line}$).

$$V_{terminal} = tap * V_{line} \hspace{3cm} \text{eq 3}$$

The starting current at the motor terminals is proportional to the voltage at the motor terminals, thus the motor starting current is also reduced in proportion to the tap value compared to the current during full voltage starting.

$$I_{terminal} = tap * I_{full\ voltage\ starting} \hspace{3cm} \text{eq 4}$$

To calculate the current on the line side of the autotransformer, take the new starting current and reflect it to the line side of the autotransformer.

$$I_{line\ side\ of\ autotransformer} = tap * I_{terminals} \hspace{3cm} \text{eq 5}$$

By substituting $I_{terminal}$ from eq. 4 into eq. 5 results in the follow.

$$I_{line\ side\ of\ autotransformer} = tap * tap * I_{full\ voltage\ starting} \hspace{2cm} \text{eq 6}$$

This shows that the line current during starting is proportional to the tap setting squared. An example of the impact of using an autotransformer starter on the motor current and line current is shown in table 2.

*Table 2 Motor Current at Various Tap Settings*

| Tap | I (motor) | I (line) |
|---|---|---|
| Full Voltage | 444 | 444 |
| 80% | 355 | 284 |
| 65% | 289 | 288 |
| 50% | 222 | 111 |

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Since high starting line currents can cause the system voltage to drop, this type of starter can help alleviate large system voltage drops during starting.

The control circuit for autotransformer starting shown in figure 6 requires the following components in addition to the contactor and overload of a standard full-voltage non-reversing starter:

1. Two contactors
2. Timing relay



*Figure 6 - Auto Transformer Control Circuit*

When the START push button is pressed, the timing relay is energized which seals-in the START signal and energizes the coils for contactor 1S. The auxiliary contacts on contactor 1S are used to energize the coil for contactor 2S. Contactors 1S and 2S connect the autotransformer in the motor power circuit with power flowing to the motor through the tap that has been selected. This will apply 50%, 65% or 80% of the system voltage to the motor terminals. The motor will start with lower torque and lower motor current compared to using a full-voltage starter.

After a preset delay on the timing relay, the timing contacts on TR will open. This will cause coil 1S to be de-energized, coil R for the run contactor to be energized and the coil for 2S to be

deenergized. The auxiliary contacts on the RUN contactor should be a late-break type. Using a late-break contact will ensure that the 2S coil will not be de-energized until after the RUN contactor has closed. This arrangement ensures that there is a closed transition from the autotransformer starting to full voltage running condition.

Closed transition avoids the transients associated with an open transition. An open transition is a condition when the motor is briefly disconnected from the line voltage. During this brief time, the motor will act as a generator and its frequency will not be in synch with the line frequency. In this situation, when the RUN contactor closed, there will be torque impulse that will cause mechanical stress and there will be electrical transients that can cause problems for other equipment on the system.

The timing relay should be set with a time delay that causes the transition from the autotransformer to full voltage when the motor stops accelerating. This is typically at 80 – 85% of the motor's rated speed.

During the starting sequence, current flowing through the autotransformer will cause its temperature to rise. To prevent the autotransformer from overheating there will be a limitation on the maximum number of allowable starts per hour.

# Part Winding Starting

Part winding starters are used with motors that have two stator windings that are intended to be operated in parallel. These motors will have 6 leads brought to the connection box, 3 for each set of windings. Both windings will be connected to the full system voltage when the motor is running. During starting, only one of the motor windings will be connected to the voltage which will reduce the torque compared to typical full-voltage starting. The winding and motor lead configuration is shown in figure 7.

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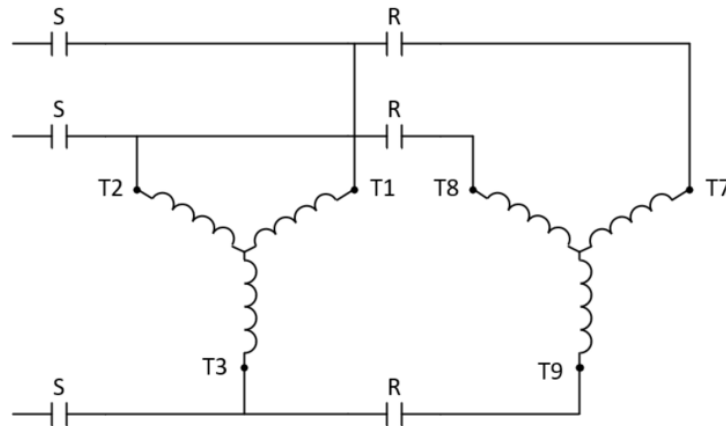*A SunCam online continuing education course*



*Figure 7 - Motor Winding Configuration for Part Winding Starting*

A part winding starter has two main contactors and two overload relays, one to control each set of windings as shown in figure 8. At the beginning of the start sequence, the first contactor S is energized. The second contactor R will be energized after a short time delay. The time delay is typically 2-3 seconds. The motor is then running with both contactors closed. This is considered a closed transition starter, since voltage is not disconnected from the motor during transition from start to run.
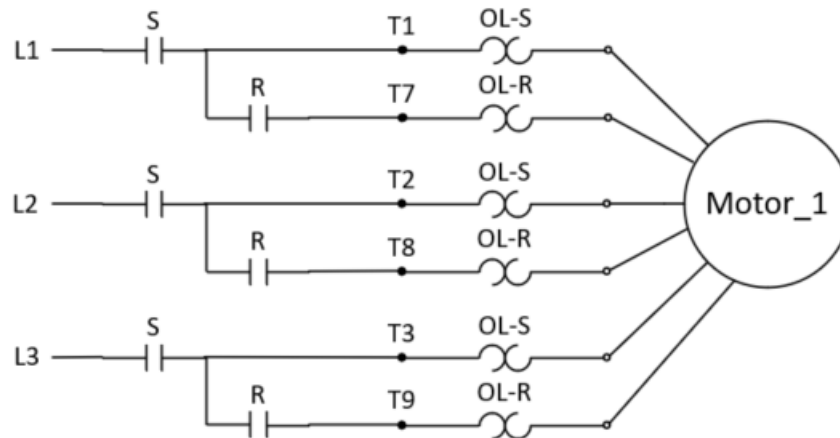


*Figure 8 - Part Winding Starter Power Circuit*

When the stator winding is split in half, the starting torque with one winding energized will be 50% of the torque produced with both windings energized. The part winding starting method is an incremental start. While the first contactor is closed, the torque will be approximately 50% and the current will rise to approximately 400% of the full load current. If the motor is not near

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full speed when the second contactor closes, the current will rise to approximately 600% of full load current, then decreasing to the running current as the speed increases to full speed.

Although technically this does not use reduced voltage, it does provide reduced torque during starting and an incremental rise in starting current. Due to the low starting torque, part winding starters are well suited for centrifugal loads, such as pumps.

The control schematic for the part winding starter is shown in figure 9. The operating sequence is straight forward. The START signal closes the timing relay TR and is sealed in with an instantaneous contact on the timing relay TR. A second instantaneous contact TR energizes the starting contactor S. The timed-closed contact on the timing relay is used to energize the run contactor R after the time delay. Contacts from the two thermal overload relays are wired in series in the control circuit to protect the motor from overheating.
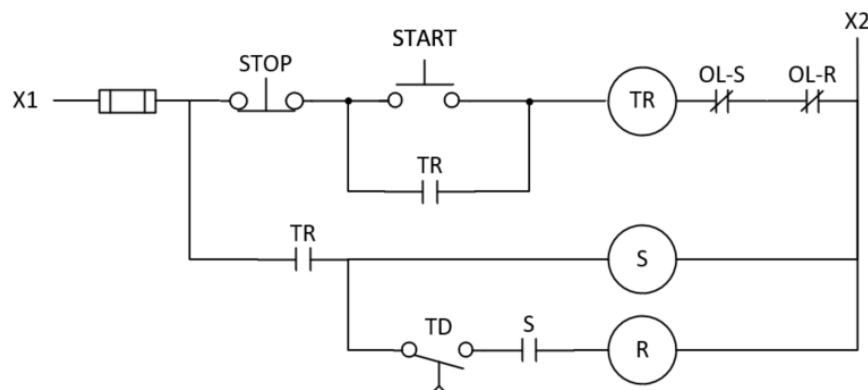


*Figure 9 - Part Winding Control Circuit*

# Wye-Delta Starting

Wye-delta starters can only be used with motors that are specifically designed for this type of starting. This type of starter requires that both ends of each stator winding be brought to the terminal box, therefore there will be 6 leads from the motor in the terminal box. As with part winding starters, wye-delta starters use the full system voltage, but the way the windings are connected affects the torque and current characteristics.

The windings are shown in figure 10. During starting, the windings are connected in a wye configuration (shown on the left). If the line to line voltage (L1 – L2) is 480VAC then the

voltage across the coil T1-T4 will be 277VAC.  In the running condition, the windings are connected in a delta configuration (shown on the right). In this case, the voltage across coil T1-T4 will be 480VAC. The effective voltage across the windings is changed by how the stator windings are connected.
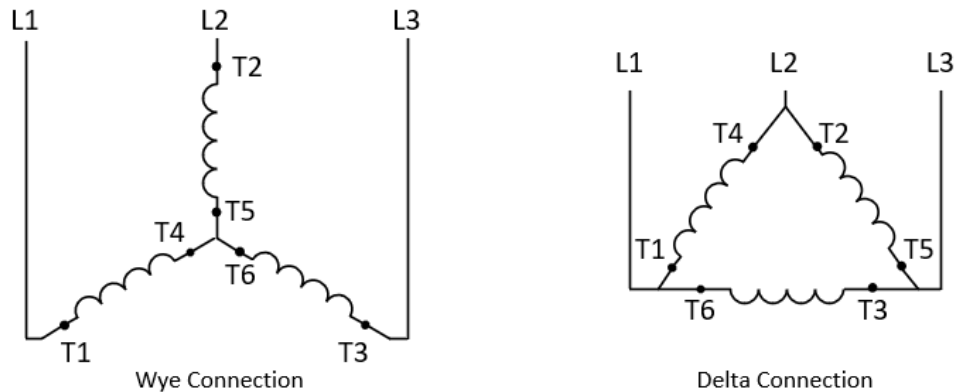


*Figure 10 - Wye-Delta Motor Winding Connections*

By connecting the windings in a wye configuration during starting, the line voltage is connected across 2 windings. This results in  58% of the line voltage across each coil. While connected in a wye, the reduced voltage results in a reduction in the current and starting torque. During this starting method, the starting torque will be 33% as compared to full voltage starting. After a time-delay, the windings are reconnected in the delta arrangement, allowing the motor to produce full torque.

Because there are no limiting devices such as resistors or autotransformers which produce heat, these starters can be used with accelerating loads that have a long starting time. Long starting times are typical for high inertia loads such as centrifuges, grinders, induced draft fans and shredders.

Wye-delta starters are available in either open transition or closed transition.

## Open Transition Wye-Delta Starters

The power circuit for an open transition wye-delta starter is shown in figure 11.

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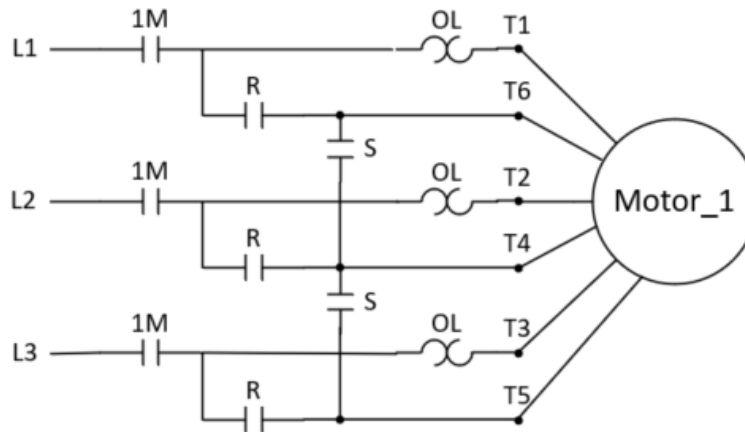*A SunCam online continuing education course*



*Figure 11 - Wye-Delta Open Transition Motor Starter Power Circuit*

The open transition wye-delta starter control circuit shown in figure 12 consists of two mechanically interlocked contactors, a magnetic starter and a timing relay.
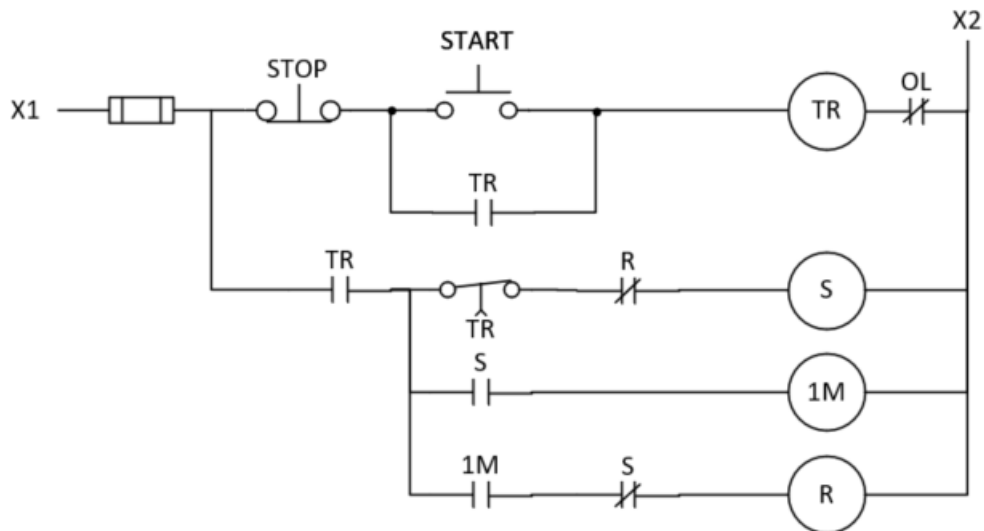


*Figure 12 - Wye-Delta Open Transition Motor Starter Control Circuit*

1. Pressing the START button energizes the timing relay TR.
    a. Two normally open TR instantaneous contacts are used to seal in the start signal around the START button and to energize the shorting contactor S. The shorting contactor creates the center point of the wye-connected stator coils.
    b. A normally open S contact is used to energize the magnetic starting contactor 1M. At this point the motor has the line voltage connected across the wye-connected

stator windings and accelerates the motor with 58% of the line voltage across each winding.

2.  After the timing relay time delay, the normally closed timed-open contact of TR opens, deenergizing the shorting contactor S.

3.  When shorting contactor S is deenergized, the normally closed interlock contact S energizing the coil for the running contactor R which connects the stator coils in a delta configuration.

At the point of transition when the shorting contactor S is opened, disconnecting the power circuit before the running contactor R is closed. During the open transition, the current will decay toward zero and then rise to the full voltage current for that speed.

## Closed Transition Wye-Delta Starters

There is a design for a closed transition wye-delta starter. However, it requires more changes to the open transition starter than just closing contactor R before opening contactor S. Simply overlapping the timing of these contactors, will create a phase to phase short circuit. This shown in figure 13 by the red lines which would create the short circuit.
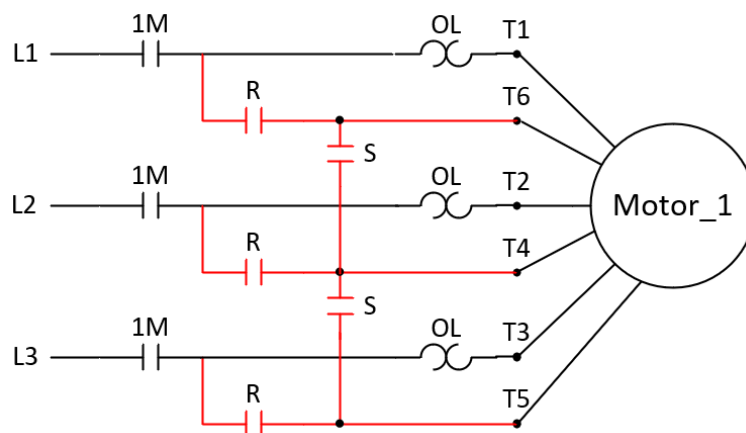


*Figure 13 - Wye-Delta starter with overlapping contactors*

Changes to the open transition wye-delta starter circuit require an additional contactor and resistors as shown in figure 14. The resistors are used for only a short time during the transition

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from wye to delta configuration. Since the resistors are used for a very short time, they are sized for intermittent duty.
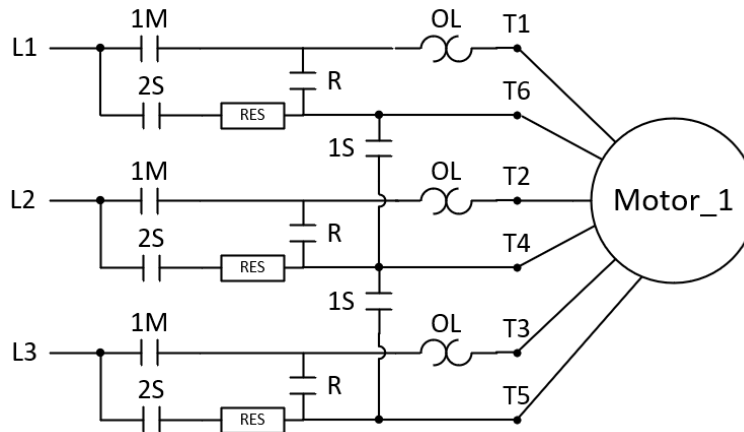


*Figure 14 - Closed Transition Wye-Delta starter power circuit*

The starting sequence is described below with references to the control circuit in figure 15.

1. START (WYE) - Pressing the START button energizes the timing relay TR. Two normally open TR instantaneous contacts are used to seal-in the start signal around the START button and to energize the shorting contactor 1S. The shoring contactor creates the center point of the wye-connected stator coils. A normally open S contact is used to energize the magnetic starting contactor 1M. At this point the motor has the line voltage connected across the wye-connected stator windings and accelerates the motor with 58% of the line voltage across each winding.

2. TRANSITION 1 – Before opening the shorting contactor 1S as in the open-transition sequence, a normally-open timed-closed contact on timing relay TR closes. This energizes shorting contact 2S. Shorting contactor 2S connects the stator windings in a delta configuration with a resistor in series with each winding. The resistors prevent a phase to phase short circuit through the wye-connection of shorting contactor 1S.

3. TRANSITION 2 – When contactor 2S is energized, a normally closed contact 2S will open in the circuit and de-energize coil 1S. This removed the center point of the wye-connection. The stator windings are now connected in a delta configuration with a resistor in series with each stator winding.

4.  RUN (DELTA) – When contactor 1S is de-energized, the normally-closed contact 1S will close, energizing contactor 2M. This effectively creates a short circuit around the resistors in the 2S circuit.



*Figure 15 - Wye-Delta Starter control schematic*

The contactor operating sequence chart will help understand the status of the power components.

Contactor Operating Sequence

| Operation | Contactor | | | |
|---|---|---|---|---|
| | 1S | 2S | 1M | 2M |
| Start (wye) | X | | X | |
| Transition 1 | X | X | X | |
| Transition 2 | | X | X | |
| Run (delta) | | | X | X |

# Solid State Reduced Voltage Starting

The four starters up to this point have been electro-mechanical methods to provide reduced voltage starting. Solid state reduced voltage (SSRV) starters use electronics to create reduced voltage. This is a more advanced controller which allows for greater control of both starting and stopping a motor.

The main power component of an SSRV starter is the silicon controller rectifier (SCR). An SCR is an electronic switch that turns power on and off. The schematic symbol for an SCR is shown in figure 16.



*Figure 16 - SCR Circuit Symbol*

SCRs have a feature like a diode in that current will only flow when there is positive voltage across the SCR. An electronic signal is used to turn the SCR on at a specific time in the voltage cycle.  If there is positive voltage across the SCR when it is turned on, it will conduct current. When the voltage goes to zero in the AC voltage cycle, the SCR will automatically turn off. This is shown graphically in figure 17. The voltage waveform in shown in blue. The current waveform is shown in yellow.  When the SCR is turned on at 45° of the voltage cycle current flows because of the positive voltage across the SCR. The current stops flowing when the voltage changes from positive to negative.
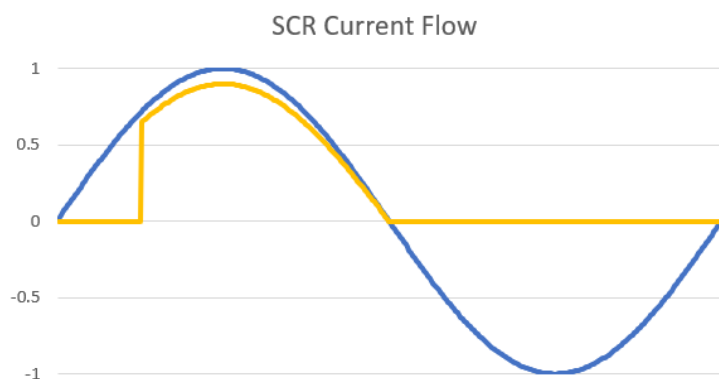


*Figure 17 - SCR Current Flow vs Voltage with Turn-on at 45 degrees*

By using two SCRs back-to-back, the electronics can control current flow in both the positive and negative portion of the voltage waveform cycle. This is shown schematically in figure 18.

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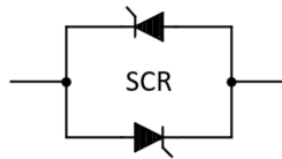*A SunCam online continuing education course*



*Figure 18 – Back-to-Back SCR Circuit Symbol*

Current flow is shown in figure 19 with the current in one SCR shown in yellow and the current in the other SCR in blue. By controlling when the SCR is turned on, the SSRV microprocessor controls the amount of voltage and current delivered to the motor during the starting sequence.
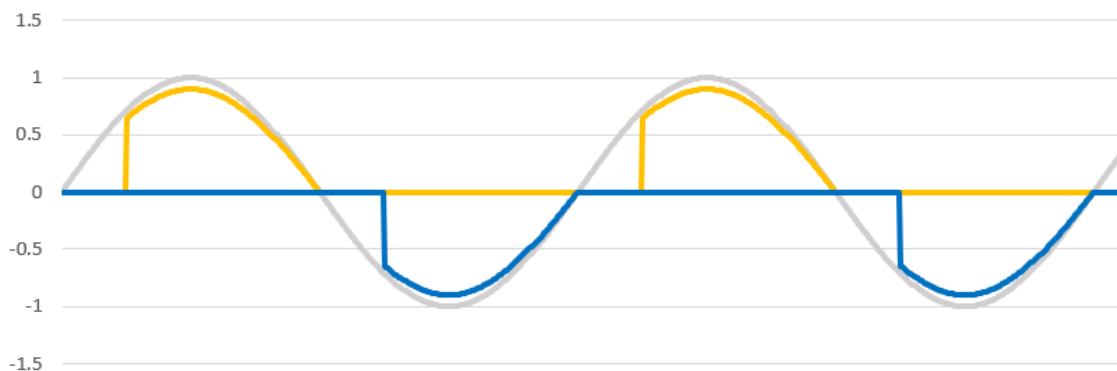


Back-to-Back SCR Current Flow

*Figure 79 - Back-to-Back SCR Current Flow vs Voltage with Turn-on at 45 degrees*

The power circuit for an SSRV starter is shown in figure 20. When a START signal is received, the SSRV uses electronic control of the SCRs to start at in initial voltage and then smoothly increase the voltage until it reaches the system voltage. When system voltage is reached, there is typically a RUN contactor that closes. The RUN contactor by-passes the SCR, allowing the SCRs to be turned OFF. This eliminates the heat generated by the SCRs and the small energy loss of the SCR. Typical energy loss in an SCR is 0.5%.

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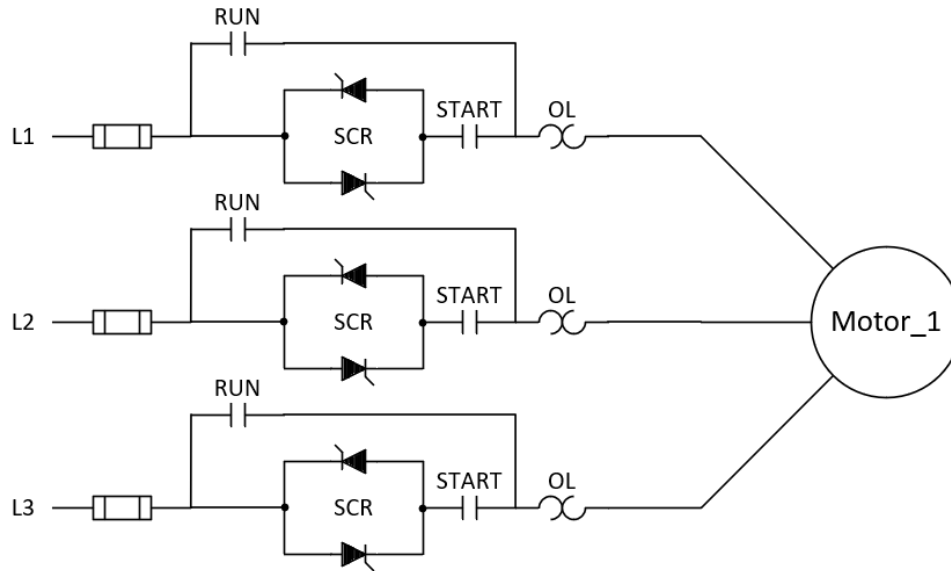


*Figure 20 - SSRV Power Circuit*

When SSRV starters were first introduced, the RUN contactor was an external contactor. Modern SSRV designs have the RUN contactor as an integral part of the SSRV. This RUN contactor is rated to carry the running motor current. It is not rated to handle the 600% current that is experienced during full voltage starting.

In some literature, this RUN contactor will be described as a "by-pass" contactor because it by-passes the SCR. This can occasionally cause confusion because some specifications are written requiring a solid-state reduced voltage starter with a full voltage by-pass starter. In this case the intent is that there is an SSRV with an external by-pass starter that is rated for full voltage starting and the associated 600% starting current. This type of specification is intended to have the ability to use the full-voltage starter when the SSRV may be out of service.

When using electronic control of the SCRs in an SSRV, there are several options for the type of control that can be implemented. Basic control is via a voltage ramp with current limit. If during starting, the load is not accelerating as fast as the voltage is increasing, the current will increase. If the current reaches the programmable current limit, the electronic controller will decrease the rate of voltage increase to maintain current at the current limit setting. This type of control can create a non-linear speed-torque curve during starting.

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A more advanced type of control is torque control. Using torque control, the SSRV starter can provide constant, linear torque output from the motor during the starting process. The amount of torque is typically programmable up to 100% of the motor rated torque.

For hard to start loads, some SSRV have a programmable start-up pulse. This is a feature that provides a voltage pulse for a few cycles when the START command is received. The voltage profile is shown in figure 21. This pulse provides higher torque to overcome a higher static inertia to get the load moving. After the pulse, the electronics will control the SCRs based on the voltage ramp with current limit or torque control programming.
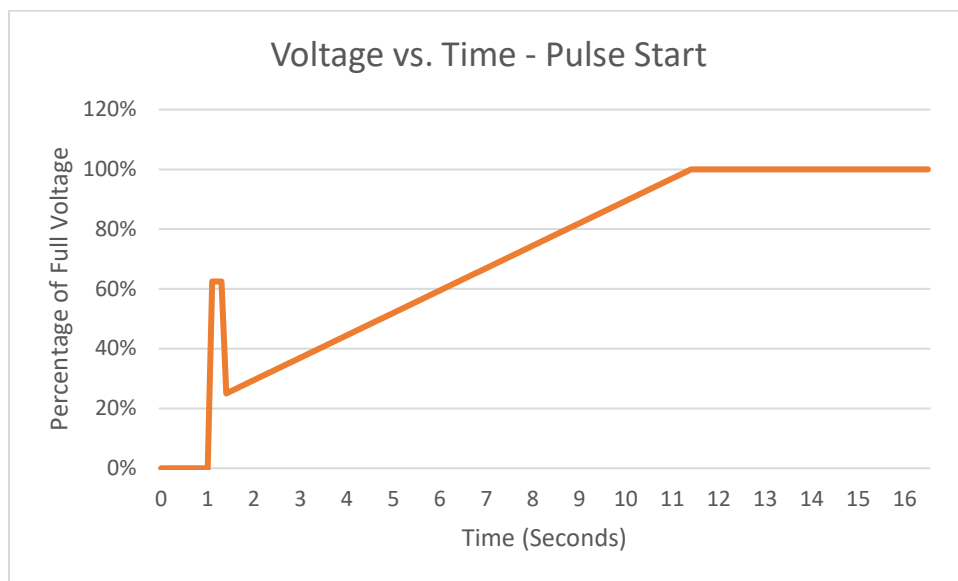


*Figure 21 - SSRV Pulse Start voltage profile*

The electronics of the SSRV can also be used to provide a ramp control when stopping the motor. This feature is useful for control of pumps with a check valve. If power is removed from a pump with a check valve, the back pressure from the liquid will cause the check valve to slam shut creating stress on the valve and create water hammer. Both stresses can cause premature failures in the pumping and piping system. Using a ramped stop, the motor voltage is reduced slowly. This will allow the valve to partially close before the backpressure pushes the valve closed. This will reduce the possibility of the valve closing too fast resulting in water hammer which can cause high mechanical stresses on the pipes and pumping system.

# Bringing it Together

Full voltage starting is used for most industrial applications. However, if the current or torque needs to be limited while starting, reduced voltage starting should be used. Selection of the reduced voltage starting method should be based on the application requirements and consideration of their advantages and disadvantages.

| Type | Advantages | Disadvantages |
|---|---|---|
| Primary Resistor Starters | 1. Closed transition starting<br>2. Smooth acceleration<br>3. No need for special motors | 1. Voltage reduction is achieved by power loss through a resistor<br>2. Adjusting the starting voltage and torque is difficult |
| Autotransformer Starter | 1. Produced maximum torque per amp of line current<br>2. Maximum reduction of starting current<br>3. Autotransformer taps permit easy adjustments to starting voltage<br>4. No need for special motors | 1. More expensive than other starters at low horsepower |
| Part Winding Starter | 1. Least expensive type<br>2. Closed transition starting<br>3. No heat producing devices in the starting circuit | 1. Special motors are required<br>2. Motors will not accelerate to full speed on a single winding |
| Wye-Delta Starter | 1. Produces high torque per amp of line current<br>2. Inexpensive - For most horsepower ranges has a lower cost than primary resistor or part winding starters | 1. Special motors are required<br>2. Starting torque is fixed at 1/3 of the delta connection (full voltage)<br>3. Most are open transition |
| Solid State Starter | 1. Provides smoothest acceleration<br>2. Adjustable current and torque during starting for highest degree of flexibility | 1. Heat is given off by the SCRs when conducting current |