Starting High Inertia Loads:
A Comparison of Starting Options

Rockwell Automation
Allen-Bradley

High Inertia Loads

Inertia is defined as the *resistance to acceleration*. Also, inertia is the characteristic of an object at rest to remain at rest, and when in motion, to remain in motion.

In terms of motor starting, a high inertia load is one that requires a relatively lengthy acceleration period before the motor achieves normal operating speed. Depending on the application, this acceleration period can often exceed two minutes.

High inertia loads are found in motor starter applications throughout industry. Typical examples include the following:

- Punch presses
- Grinders
- Shredders
- Centrifuges
- Induced draft fans
- Refiners
- Band mills
- Separators
- Chippers/ Debarkers

Choosing the best motor starting solution for a high inertia load application requires an understanding of the effects of torque, current, voltage, motor wiring schemes, and starting methods. The following sections cover these topics.

Torque

The starting of high inertial loads requires an understanding of how torque applied to the load is related to the starting time and total inertia of the system.

Equation 1

$$T_{accel} = WK^2\left(\frac{\Delta N}{308t}\right)$$

T_{accel} = Acceleration torque or the difference between the applied torque and the required torque
WK^2 = A measurement of system inertia
DN = The change in speed of the motor or system dependent on a point of reference
t = The acceleration time of the motor in seconds

The equation above shows that acceleration time is inversely proportional to acceleration torque. Therefore, as more torque is applied, the start time decreases. This equation also shows that a relatively small amount of acceleration torque will eventually accelerate the load to full speed, but over a much longer period of time.

Achieving a quick start is simple - just apply a very large motor to the load. This is of course is impractical because of the costs associated with a large motor and a drive train strong enough to withstand the strain of a high torque start-up. A more practical alternative is to size the motor for the final load. Unfortunately, a smaller motor would take much longer to achieve normal speed. This longer starting time would cause the motor to overheat and its thermal overload to trip.

To prevent unwanted tripping of a high inertia load at start-up, many manufacturers and users shunt out the motor's overload. This procedure is permissible provided it is done in accordance with N.E.C. Article 430-35. This does not mean that the motor does not experience heating during start-up. This fact must still be considered when sizing the motor and the starter.

Voltage and Current

A motor experiences heating during start-up due mainly to *I-R losses* (where I is the motor current and R is the resistance) in its rotor. These losses are expressed as an instantaneous value I^2R. For actual heating calculations I^2R must be considered over a finite period of time t. This allows for the motor's heating characteristics to be expressed as an I^2t curve. Heating is a square function of the current. Therefore, a small increase in current can cause a large increase in heating. A simple way to reduce current is to reduce the voltage. The following equation shows the relationship between current and voltage:

Equation 2

$$\frac{V_{app}}{V_{max}} \approx \frac{I_{drawn}}{I_{max}}$$

V_{app} = *Applied motor voltage*
V_{max} = *Line Voltage*
I_{drawn} = *Current drawn by motor*
I_{max} = *Locked rotor current*

Also, by reducing the voltage, there is a reduction in applied torque:

Equation 3

$$T_{dev} \propto \left(\frac{V_{app}}{V_{max}}\right)^2$$

T_{dev}= *Torque developed*

For example, to start a motor with 50% of maximum current, the voltage must be reduced by 50%. This will result in an applied torque of $(.5)^2$ or 25%. Additionally, a 50% current reduction would also cause the I^2R heating to be reduced to 25% of its original value.

This does not mean the total heating has been reduced. If we refer to *Equation 1* and assume that the WK^2 and the ΔN remain constant, we find the following:

$$t = \frac{K}{T_{accel}}$$

K = Constant
t = Time to accelerate

So, if we apply *Equation 1* to a real situation where the across-the-line starting time is 20 seconds, and we reduce the voltage by 50%, we get the following:

$$T_{dev} = (.5)^2 = .25 \text{ or } 25\% \ T_{max}$$

T_{max} = Locked rotor torque

Assuming T_{dev} is approximately T_{accel} (we assume no friction or windage) we get:

$$t_{aol} = \frac{K}{T_{accel}} = \frac{K}{T_{max}} = 20 \ \therefore \ T_{max} = \frac{K}{20}$$

t_{aol} = Across-the-line starting time
t_{rv} = Reduced voltage starting time

$$\text{if} \quad T_{dev} = (.25)T_{max} \quad \text{and} \quad t_{rv} = \frac{K}{T_{dev}}$$

$$\text{then} \quad T_{rv} = \frac{K}{(.25T_{max})} = \frac{K}{\left(.25\left(\frac{K}{20}\right)\right)} = 80 \text{ seconds}$$

A 50% reduction in voltage results in a start time that is four times as long. Heating is determined by the I^2t value. To determine if lowering the current reduces heating, we can compare the two current values:

600% current for 20 seconds

$(600)^2(20) = 7,200,000$

300% current for 80 seconds

$(300)^2(80) = 7,200,000$

The equations above show that even though the current has been reduced, the amount of heating has not. So, theoretically, if the motor is designed for an across-the-line start, it should be capable of a reduced voltage start.

Across-the-line starting

The simplest method of starting a high inertia load is to use an across--the-line motor starter. This, however, introduces a number of negative side effects.

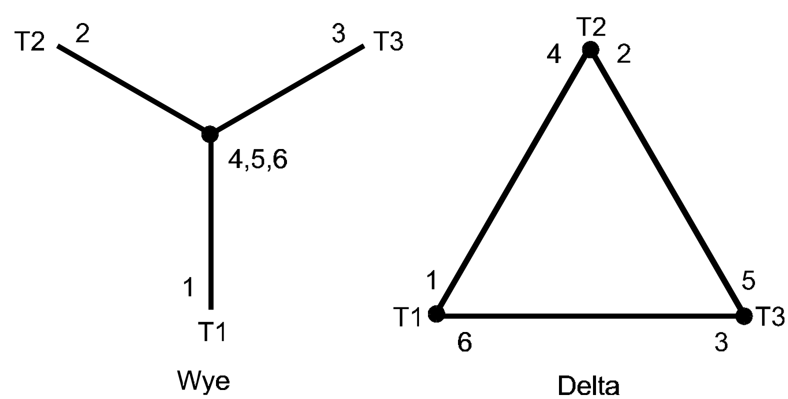
First, due to the relatively long starting time inherent in starting a high inertial load, the system (i.e., the wiring, motor, motor starter, and protective equipment) must be sized to handle the locked rotor current of typically 6-8 times full load current for the length of the acceleration time. This extended, high current draw, may exceed current consumption limits set by your power utility, or may require some load shedding during start-up.

Second, if the motor is a significant distance from the starter, heavier cable may be required to handle the additional time the motor is drawing locked rotor current.

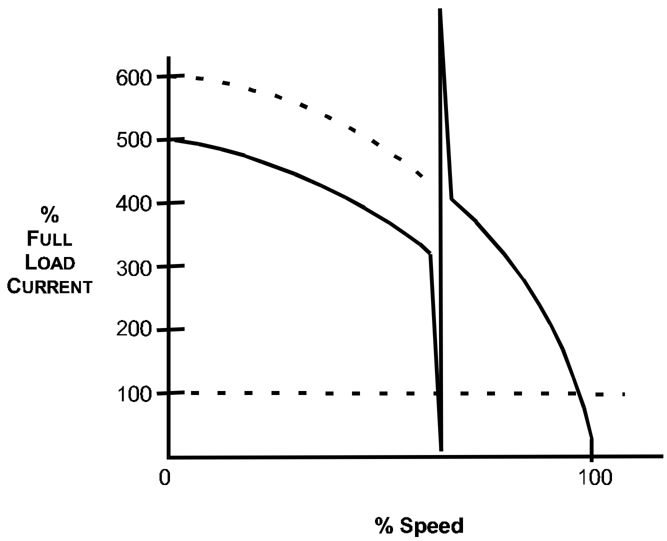
Third, if the application's drive train isn't designed for the across-the-line strategy, you may experience serious mechanical failures such as broken drive shafts and damaged gear boxes. These difficulties can be overcome with a reduced voltage starter.

Wye-Delta starting

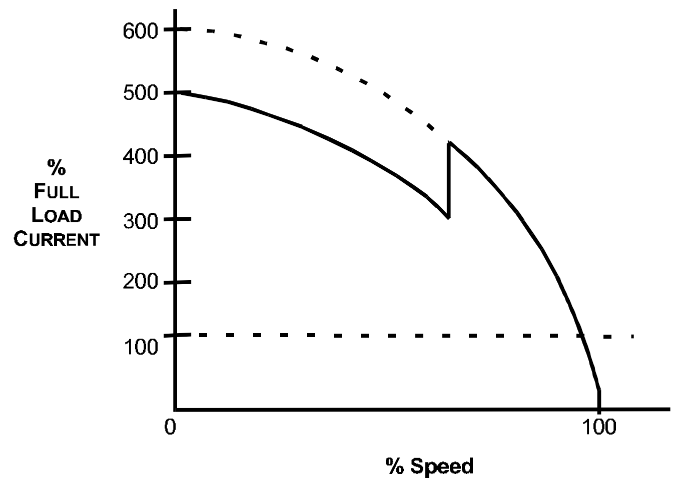
This reduced voltage starting method is particularly suitable for applications involving long acceleration times and is the most commonly used method for starting high inertia loads. Wye-Delta starters are used with Delta-wound motors that have all six leads brought out to facilitate a Wye connection for reduced voltage starting. Wye-Delta starters provide reduced voltage starting by first connecting the motor's leads into a Wye configuration for starting and then switch the connection to a Delta configuration for running.



Typical Wye-Delta starters are made up of magnetic contactors that switch from the Wye to Delta connections, and a timing unit that controls the switching. When the operator presses the start button, the line and Wye contactors close and the motor starts. Full voltage is not applied across the winding, but rather it is applied between the “Y” points. The voltage across the winding is then reduced by the square root of three. Consequently, starting torque and starting current are approximately 1/3 normal. After the starting period, which is determined by a timer setting, the Wye contactor opens and a brief time later, the Delta contactor closes. This means that the circuit is opened from the motor for brief period time before switching to the Delta configuration. This “open transition” can cause voltage spikes, which may be detrimental to other devices on the power grid.

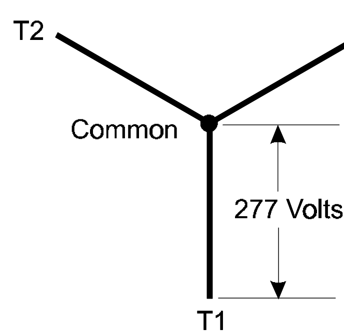


Open Circuit Transition



Closed Circuit Transition

In a three phase system, when the motor’s internal leads are connected in a Y configuration, the voltage applied across the stator windings is from line to common.



Wye

This connection reduces the voltage by the square root of three. For example:

$$\frac{480V}{\sqrt{3}} = 277V$$

This results in a reduced torque. (Refer to *Equation 3*).

$$\frac{277V^2}{480V^2} = .333$$

This also results in a reduced current, assuming the locked rotor current to be 600% of full load current. (Refer to *Equation 2*).

$$\left(\frac{277}{480}\right)600\% = 346\% \text{ full load current}$$

But this current value must also be reduced by the square root of three:

$$\frac{346\%}{1.73} = 200\%$$

An appeal of Wye-delta starting is that it doesn’t need accessory voltage reducing equipment such as resistors or transformers. Also, there is very little noise or vibration associated with this method.

The Wye-Delta starting method seems like an ideal solution until one examines the following points:

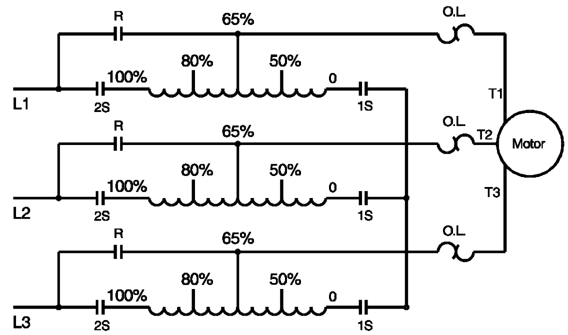
- To accomplish Wye-Delta starting, a special (typically more expensive) motor is required. This motor has the ends of its windings drawn out into six leads that are routed to the termination box for connection.
- On a typical three-phase motor, three leads are required to be run from the motor starter to the motor. With a Wye-Delta system, six leads are needed between the motor and the and the starter, adding expense.
- If the starting method used is open transition, a significant spike can be generated on the power system that could cause damage elsewhere.
- Closed circuit transition Wye-Delta starting requires an additional contactor and therefore adds additional expense.
- Only two choices of starting torque - 600% or 33% torque.

Autotransformer starting

Autotransformer starting is another method of reduced voltage starting, which offers the flexibility of different voltage taps so that the applied torque can be varied for different starting times.

An autotransformer starter offers maximum starting torque per ampere of incoming *line* current. It is effective in applications that require the inrush current to be held to a minimum value, while providing the highest possible starting torque, thus making it an acceptable choice for starting a high inertia load.

Typical autotransformers have three taps which allow you to start the motor at 50%, 65% or 80% of the incoming line voltage. (For most applications, 65% is sufficient for successfully starting a motor.)



Typical Autotransformer Starter Power Wiring Diagram

Autotransformer starters step down the voltage at the motor, which in turn increases current on the load side of the transformer, providing the maximum amount of starting torque. For example, a motor has a full voltage starting torque of 180% and a full voltage starting current of 600%. The power company has set a limitation of 400% incoming line current at start. With autotransformer starting, the current inside the motor need not be limited to 400%, only the incoming *line* current must meet this limitation. This is possible because of the autotransformer's turns ratio advantage, which results in the incoming line current being different from the motor current. This is further explained in the example below.

assuming no losses $VI_{in} \cong VI_{drawn}$

V = *Voltage*
I_{in} = *Incoming line current*
I_{drawn} = *Current drawn by the motor*

$$\therefore \quad 480 I_{in} = V_{tap} I_{drawn}$$

V_{tap} = *Voltage at the transformer tap to which the motor is connected*

$@50\%V \quad I_{drawn}$ = *50% of 600% or 300%*

$$\therefore \quad I_{in} = \frac{(240 \times 300)}{480} = 150\%$$

So, the autotransformer can provide 300% current to the motor with 150% incoming line current.

Autotransformer starters must make the transition from reduced voltage to full voltage at some point in the starting cycle. When the transition is made, there is normally a line current surge. The amount of surge depends on the type of transition being made and the speed of the motor at the transition point. There are two methods for transition from reduced to full voltage - open circuit transition and closed circuit transition. Open circuit transition means that the motor is actually disconnected from the line for a brief period of time while the transition from reduced to full voltage takes place. With closed transition, the motor remains connected to the line during transition. Open transition produces a higher surge of current because the motor is momentarily disconnected from the line. These surges are considered undesirable because they may exceed incoming line current limitations. Motor speed determines the amount of current surge that occurs at transition. Transition should occur as close as possible to full speed, minimizing the amount of surge on the line.

Many autotransformer manufacturers have adopted closed transition as the preferred method for switching from reduced to full voltage starting. This method is slightly more expensive, but eliminates undesirable transient line surges of current.

The major advantages of starting high inertia loads with an autotransformer are that it:

- Works with any style motor - a Wye-Delta starting scheme requires a special motor.
- Provides the most torque per incoming line ampere of current.

The major points of consideration when starting high inertia loads using an autotransformer are that:

- It is more expensive when compared to other methods of reduced voltage starting.
- The physical size of the starter is significantly larger when compared with other starting solutions. The autotransformer requires a great deal of valuable floor space.
- “Oversizing” the autotransformer starter is frequently required to prevent the starter’s transformer from being thermally damaged during the long acceleration times of a high inertia load start-up.

Solid-state starting

Solid-state controllers (also referred to as softstarters) provide soft start or stepless reduced voltage starting of AC motors. The same principles of current and torque that apply to electromechanical reduced voltage starters also apply to solid-state controllers.

Solid-state controllers are able to closely control voltage applied to the motor - even when the motor is up to speed - because of semiconductors used in the power circuit. These semiconductors, known as silicon-controlled rectifiers (or SCRs) have no contacts to wear out, are rugged, and are small in size. Solid-state controllers also offer protection to the motor and controller and diagnostics to aid in set-up and troubleshooting. Protection typically provided includes indication and shutdown when the controller senses the following:

- an overload condition
- phase loss or imbalance
- stalled motor
- motor jam
- open load line condition
- SCR overtemperature
- under voltage conditions
- a shorted SCR

Typical solid-state controllers offer the choice of three starting modes in the same device:

- Soft start
- Current limit start
- Full voltage start

For the purpose of our discussion, we will only mention the current limit start mode.

Current limit start

When using a solid-state starter, the primary method of starting a high inertia load is by limiting the amount of current going to the motor. The softstarter’s current limit starting mode can be adjusted over a wide range. A current limit of 350% will provide similar starting performance of a Wye-Delta type starter. A 200% current limit could also be used. However, the load would take longer to accelerate at this setting. Fortunately, applying longer acceleration times is an acceptable practice in most high inertia load applications. This allows OEMs to offer a more sophisticated and flexible alternative to their customers.

Solid-state starters added benefits

An advantage of solid-state starters when compared to standard electromechanical starters (i.e., Wye-Delta and Autotransformer starters) is that many solid-state devices offer phase loss and stall protection as well as energy saving features.

When a single phase of three-phase line power is lost, the current at the motor increases in the other two phases and may overheat the motor’s windings. A solid-state starter with built-in phase loss protection can sense this condition (at start-up and while running) and shut down the motor before damage occurs. Conversely, a traditional electro-mechanical overload relay may detect phase loss, but may not be able to react because its trip setting would be set to accommodate higher current levels required at start-up and not the relatively light current load required once the motor is at running speed.

When a motor stalls, it is subjected to locked rotor current. A solid-state device with built-in stall protection can sense this condition and shut down the motor before damage occurs.

Very little current is needed once a high inertia load application reaches its rated speed. This may allow you to use the solid-state starter's energy saver feature, which monitors load and adjust voltage as necessary.

The major advantages of starting high inertia loads with a solid-state motor starter are:

- You can use the solid-state controller's current limit starting where power line limitations or restrictions require a specific current load.
- Solid-state controllers eliminate the current transition point found in reduced voltage electro-mechanical starters (i.e., Autotransformer and Wye-Delta starters).
- When compared with reduced voltage electro-mechanical starters, these devices work with standard motors and do not require additional wiring in retrofits and new applications.
- In many cases, the price of solid-state starters is comparable with Wye-Delta starters and is much less than the Autotransformer type. This is especially true in higher horsepower applications.
- Solid-state devices can retrofit an existing application where Wye-Delta or Autotransformer starters are used. For Wye-Delta, the motor should be wired in the Delta configuration and treated as a standard squirrel cage motor. The Autotransformer is even simpler, as it is normally used with a standard motor.

The major points of consideration when starting high inertia loads using a solid-state starter are:

- That solid-state starter you choose must be designed for long starting times.
- Heat build up at the junction of the SCR and the heat sink may result is some thermal limitations. Occasionally, oversizing or derating of the devices is required (Determining the derating factor should be done by the manufacturer).
- Solid-state starters require more line current to produce torque equivalent to that produced in a Wye-Delta starter or Autotransformer starter.

Variable frequency drives

Discussing in detail the application of Variable Frequency AC Drives (VFDs) goes beyond the scope of this document. However, we can mention a few points concerning their application in starting high inertia loads.

Variable Frequency Drives control AC current frequency, resulting in the control of acceleration and torque. The major advantages of starting high inertia loads with a VFD are:

- They provide greater flexibility and performance in torque control than any form of reduced voltage starting.
- Compared to other reduced voltage starting options, VFDs precisely control acceleration.
- The line current is less than a solid-state motor starter for equivalent torque output.
- Derating of VFDs is usually not required.

The major points of consideration when starting high inertia loads using a VFD are:

- Some drives create harmonics that may exceed harmonic limitations on the power system.
- VFDs are often more expensive than reduced voltage starting options.
- VFDs using IGBT technology may generate high frequencies that may be detrimental to older motors and may require extra consideration for long motor cables.

Solid-state vs. Electro-mechanical - which is the right choice?

Ask yourself these questions when deciding which type of starter to use in your high inertia load application:

- Are there any utility company line current restrictions?
- Will increasing acceleration time adversely affect the application?
- Is cost a major factor?
- Is floor space limited?
- Are there any in-plant bus current limits?
- Can belts, gears, or chains be damaged by across-the-line starting?
- What is the minimum torque required to start the load?
- Can higher technology products provide additional benefits?
- What are the cost trade-offs involved when comparing higher starter cost to reduced maintenance or damaged installation?

Overview of options

Proper selection of a starting method is critical to achieving maximum productivity on a high inertia load application. Consider the installation of each method when matching the requirements of your specific application.

	Full Voltage	**Autotransformer**	**Wye–Delta**	**Solid–state Controllers**
Smooth Start	Full Torque	Discrete Steps	Discrete Steps	Stepless
Starting Torque Control	None	Limited (1 step)	Limited (1 step)	Stepless Transition
Typical Starting Torque Characteristics (% of Full Load Torque)	180❶	Choice of 115, 76, 45❶	60❶	0-180❶
Limit Starting Current	None	Three Settings	Single Setting	Wide Range
Typical Starting Current (% of Full Load Current)	600❷	Choice of 480, 390, 300❷	198❷	0-600❷
Starting Mode				
Full Voltage	X			X
Reduced Voltage		X	X	
Soft Start				X
Current Limit				X
Diagnostics	None	None	None	Yes
Technology	Electro-mechanical	Electro-mechanical	Electro-mechanical	Solid–state
Shock and Vibration	Electro-mechanical Standards	Electro-mechanical Standards	Electro-mechanical Standards	Electro-mechanical Standards
Energy Saver Function	None	None	None	Yes

❶ Assuming 180% of full load torque at locked rotor condition.

❷ Assuming 600% locked rotor current.

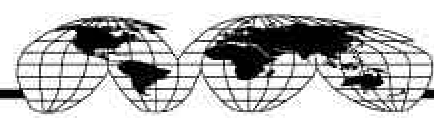
What is Motor Management?

Motor Management allows users to predict, avoid and remedy potential adverse effects of today's motors. It refers to using a complete, lowest long term cost solution set to maximize the production process, provide for extended motor life, improve plant efficiencies and protect in-process materials, equipment and personnel.

Rockwell Automation

Rockwell Automation helps its customers receive a superior return on their investment by bringing together leading brands in industrial automation, creating a broad spectrum of easy-to-integrate products. These are supported by local technical resources available worldwide, a global network of system solutions providers, and the advanced technology resources of Rockwell.

Worldwide representation.



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