Electricity and New Energy

Three-Phase Induction Motor Starters

Courseware Sample

88197-F0

Order no.: 88197-10
Revision level: 11/2014

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Printed in Canada

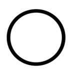
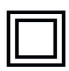
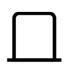
ISBN 978-2-89640-644-9 (Printed version)
ISBN 978-2-89640-645-6 (CD-ROM)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2013
Legal Deposit – Library and Archives Canada, 2013

Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
∼	Alternating current
$\overline{\sim}$	Both direct and alternating current
3∼	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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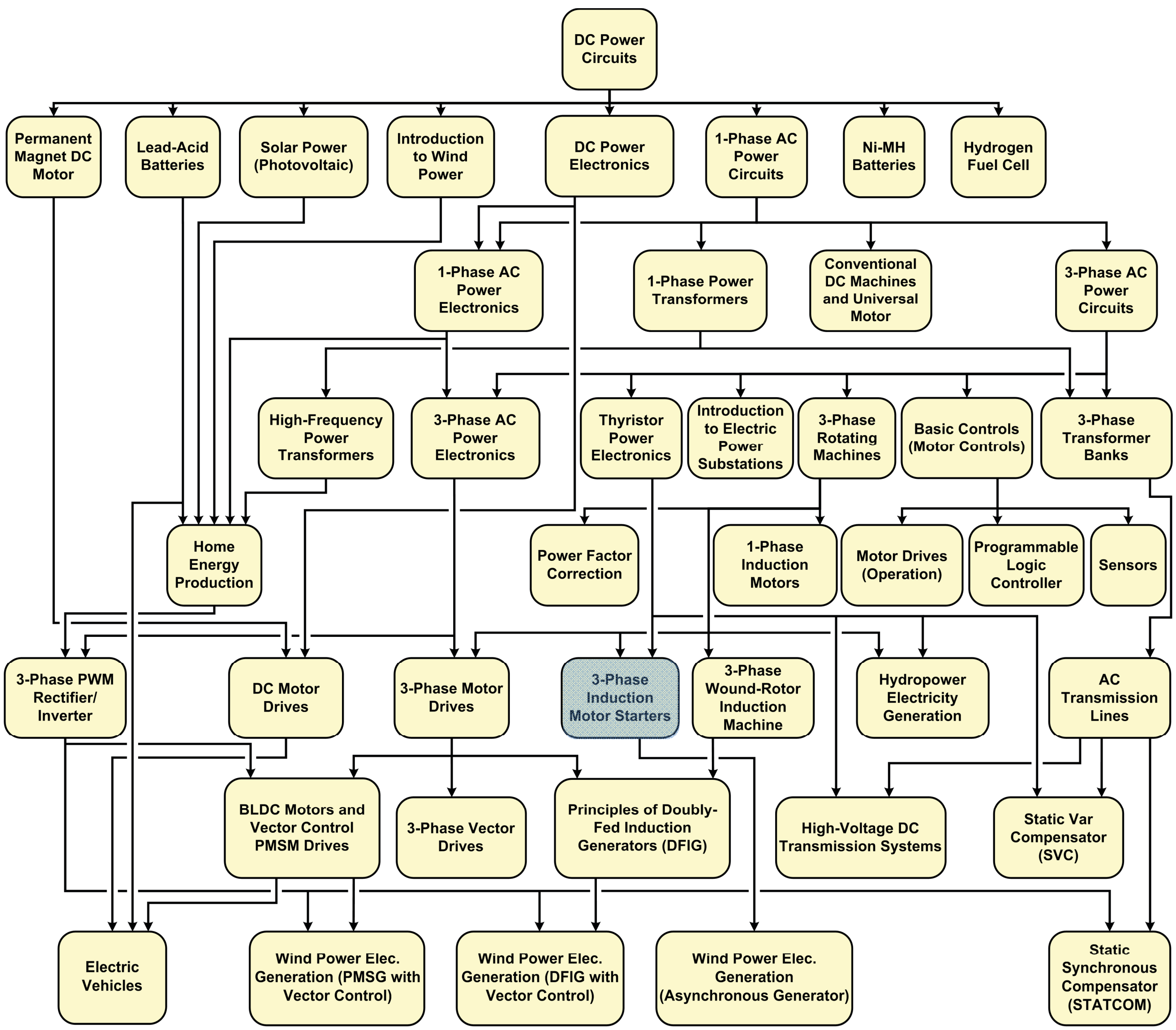
Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

An industrial motor can usually not be started by plugging its power cord directly into a wall outlet. For proper operation, it requires protections, such as an overload, and a starter. This course teaches the basic principles of three-phase induction motor starters.

Manual objectives

When you have completed this manual, you will be familiar with the basics of three-phase induction motor starters. More precisely, you will be familiar with the characteristics of direct-on-line starters and soft starters. You will understand the important phenomena that occur when you start a motor using either a direct-on-line starter or a soft starter. And finally, you will be familiar with the following advanced features of soft starters: the kick start, soft stop, and current limit start features.

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, part number 86350, *Single-Phase AC Power Circuits*, part number 86358, *Three-Phase AC Power Circuits*, part number 86360, Thyristor Power Electronics, part number 86363, and *Three-Phase Rotating Machines*, part number 86364.

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment, part number 38486-E.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

DOL Starters and Soft Starters

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with direct-on-line starters and soft starters. You will understand the important phenomena that occur when you start a motor using either one of these two types of starters.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction
- Direct-on-line starters
- Motor protections
  Overcurrent protection. Overload protection.
- Motor start-up phenomena
  Start up current. Consequences of extended large currents. Voltage sag. Start-up torque.
- Soft starters
  Voltage output of a soft starter. Effect of the soft starter on the motor current. Effect of the soft starter on the motor torque. Effect of the soft starter on the motor speed. How a soft starter controls voltage. Bypass circuit. Types of soft starters.

DISCUSSION

Introduction

Connecting a small electrical motor to a power source via a switch or by plugging the electrical cord into a wall outlet is correct in most situations. However, high power induction motors require a device called a starter to handle the connection to the ac power source. This exercise covers DOL starters and soft starters, which are two of the most popular types of starters for industrial induction motors.

Direct-on-line starters

Direct-on-line starters are the simplest type of starter. A DOL starter connects an induction motor directly to the power source via a three-phase contactor. A DOL starter usually includes **overcurrent protection** and overload protection. The overcurrent protection protects the starter circuitry from short circuits and usually takes the form of circuit breakers or fuses. The **overload protection** is usually an overload relay and prevents motor burn-out due to excessive overheat caused by high currents flowing through the motor windings. Both the overcurrent and overload protections connect in series with the contactor.

Figure 6 shows a typical DOL starter with overcurrent and overload protections. If anything goes wrong, either of the protections trips and cuts power to the motor. Aside from the protective devices, a DOL starter is just a switch (in the form of a three-phase contactor) inserted between the power source and the motor.

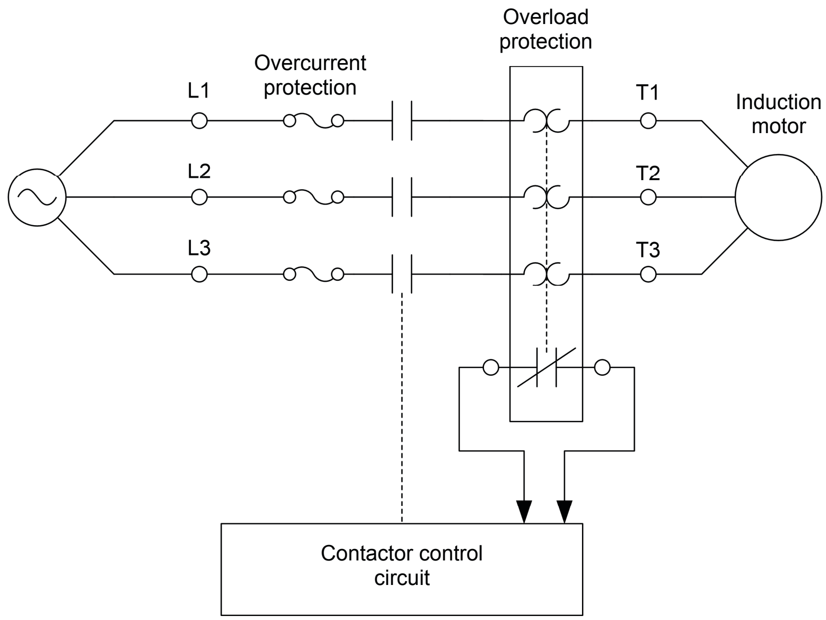


Figure 6. Typical DOL starter with overcurrent and overload protections.

Motor protections

A typical motor installation requires both overcurrent protection and overload protection. We briefly discuss these types of protection below since the overcurrent protection may be an issue for motor starting and some motor starters come with built-in overload protection.

Overcurrent protection

Short circuits and ground faults mainly cause overcurrent faults. If such a fault occurs, a large current can flow and cause material damage or fire, and put people's lives at risk. An overcurrent protection device, such as a fuse or a circuit breaker (Figure 7), reacts rapidly to a very large current. If the current is above the device rated current, the **fuse** or **circuit breaker** opens the circuit to avoid ill consequences. The current rating of the overcurrent protection must be selected with care; it must respect the local electrical code and offer adequate protection against high current. Yet, the rated current must be high enough to allow the current the motor requires to start, or to run under a heavy mechanical load, without causing the overcurrent protection to trip.

(a) Fuses

(b) Circuit breakers

Figure 7. Overcurrent protection devices.

Overload protection

At start-up, a motor requires a current higher than the nominal current until the rotation speed stabilizes. The motor overcurrent protection is selected so that its rated current is above the motor start-up current. Consequently, a current lower than the overcurrent protection rated-current, but higher than the motor nominal current can flow in the motor windings. A current of such value can cause overheating and eventually damage the motor if it circulates in the windings for an extended period, hence the need for overload protection in addition to overcurrent protection.

Overload protection, commonly implemented with an **overload relay**, protects a circuit from overheating due to a high current that flows for too long. Motor starters sometimes come with a built-in overload relay; otherwise, the overload protection must be installed separately.

Overload relays are mainly defined by their tripping class. By definition, the **tripping class** is the number of seconds it takes for the overload relay to trip if the current is six times its current setting. For example, a class 10 overload relay with a 1 A current setting trips after 10 seconds if a 6 A current goes through it. Class 10 overload relays are usually used with motors that heat rapidly, such as hermetic motors. Higher class overload relays are mostly used with motors driving high inertia loads that take time to accelerate.

The above definition is not sufficient to define the behavior of an overload relay in every situation. An additional requirement for an overload relay is that it should never trip if the current is equal or below its current setting. In between the current setting and six times the current setting, the relationship between the current and tripping time varies slightly depending on the overload design.

Figure 8 shows typical trip curves for different classes of overload relays.

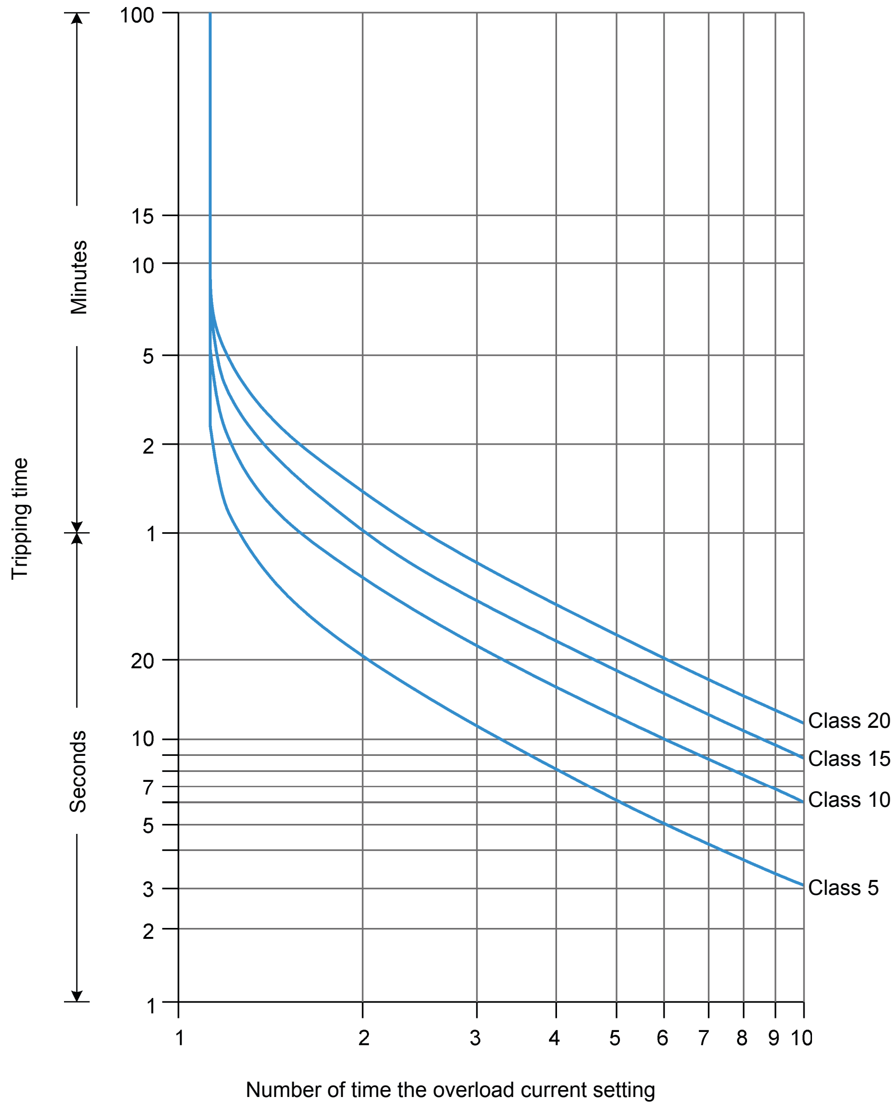


Figure 8. Overload relay trip curves.

The role of an overload relay is to prevent damages to a motor (or any other component in a circuit) due to overheat caused by excessive current. Electrical power, which is proportional to the square of the current ($P = RI^2$), is what causes the heating. The overload relay essentially "integrates" the square of the current over time to estimate heating. In a thermal overload relay, nature does this integration via a bimetal element that bends with heat, which causes the overload relay to trip if excessive current causes overheating. In an electronic overload relay, the square of the current is integrated over time electronically and the overload relay trips if the estimated heating is too high according to the current setting.

Motor start-up phenomena

A motor transforms electrical power into mechanical power. The time a motor takes to accelerate from still to full speed is called the start-up time. During this period, various electrical and mechanical phenomena take place. They eventually lead to the acceleration of the rotor up to full speed.

When power is applied to an induction motor, the three-phase currents in the stator windings produce a rotating magnetic field. This magnetic field induces an electromotive force (**emf**) in the rotor according to Faraday's law of electromagnetic induction. In turn, the emf induces large currents in the rotor, which is a squirrel cage in most instances. These currents create a magnetic field at the rotor that interacts with the rotating magnetic field at the stator to produce a torque, which drags the rotor in the same direction as the rotating magnetic field. Once the motor reaches full speed, the current stabilizes as well as the torque exerted on the rotor. However, before the motor reaches steady-state operating conditions, it is subject to transient conditions. These transient conditions cause much more stress on the system compared to the steady-state operating conditions. Some of them can cause problems to both the motor and power network. Taking a closer look at the start-up phenomena may hint at how undesired **transient conditions** can be controlled.

Start up current

An induction motor draws large currents at start-up to produce the magnetic field required to start the motor. The maximum value of these currents can be three to eight times the nominal full-load current of the motor (also known as full-load amps or **FLA**). The high **start-up current** of a motor is frequently referred to as **inrush current**. Figure 9 shows the inrush current for an induction motor started using a DOL starter. The maximum value of the inrush current for this particular motor is about six times the motor FLA.

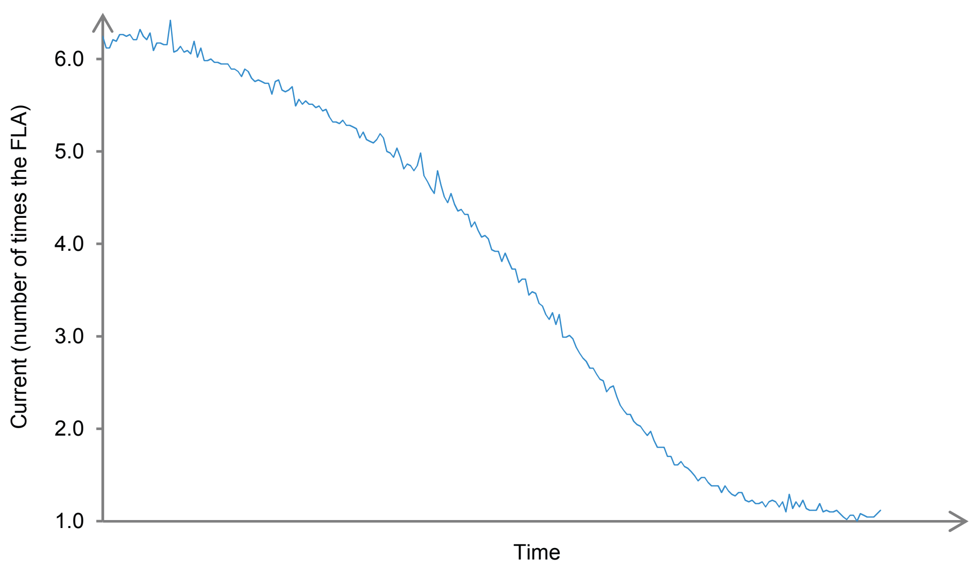


Figure 9. Inrush current for an induction motor started using a DOL starter.

Inrush current and other transient conditions can last from a fraction of a second to several seconds. For a given motor, the duration of the transient conditions depends mainly on the inertia of the mechanical load. This contrasts with the maximum value of the inrush current, which only depends on the motor design and not on the mechanical load.

Consequences of extended large currents

Duration is one of the main concerns regarding inrush current since a large current flowing for an extended period of time produces a lot of heat, which can lead to motor overheat. The heat generated by the current circulating in a motor is due, at the atomic scale, to the electrons colliding with the wire lattice. The more resistive a conductor is, the more heat that is generated for a given current.

Reducing a motor winding resistance could be one way to make it sustain a large inrush current without overheating. However, the **resistance** of a piece of wire is proportional to its length ℓ and inversely proportional to its cross-sectional area A, making it difficult to increase the current carrying capacity of a motor without drastically increasing its cost and size (see Figure 10 and Equation (1)).

Other ways to reduce heating at start-up is to shorten the length of time during which high currents circulate in the motor or to find a way to limit the maximum amplitude of the current surge. Those avenues cannot be taken when using a DOL starter; however, they can with other types of starters such as soft starters.

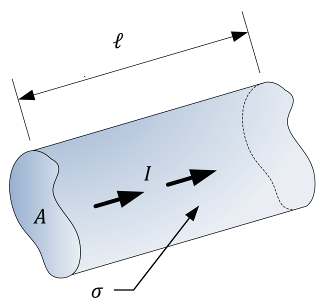


Figure 10. Parameters influencing the resistance (and cost) of a conductor.

$$R = \frac{\ell}{\sigma A} \tag{1}$$

where R is the resistance of the conductor

ℓ is the length of the conductor

σ is the conductivity of the conductor material

A is the (constant) cross-sectional area of the conductor

Voltage sag

The nominal value of a parameter is equal to 1.00 per unit (1.00 pu). For example, when the value of a parameter is twice the nominal value, the parameter value is equal to 2.00 pu. When the value of a parameter is half the nominal value, the parameter value is equal to 0.50 pu.

When starting a motor, especially using a DOL starter, the inrush current may not only have consequences for the motor itself, but also for the power network and the surrounding electrical equipment. If the motor inrush current is a significant fraction of the maximum current the power source can provide, the voltage drops momentarily across the source. This momentary reduction of the rms voltage is called **voltage sag** (or voltage dip). A typical voltage sag is shown in Figure 11 where the voltage is expressed in per unit or pu (see side note).

You are probably already familiar with voltage sags. Whenever the lights dim at the instant an electrical appliance is turned on, it is a voltage sag caused by the appliance inrush current. In a plant, a large voltage sag cannot only dim the lights, but also disrupt electronics and cause contactors to drop out. Needless to say that this situation is not welcome in most plants. Limiting the inrush current reduces the voltage sag at motor start-up. This can be achieved using a soft starter, for instance, and will be discussed later.

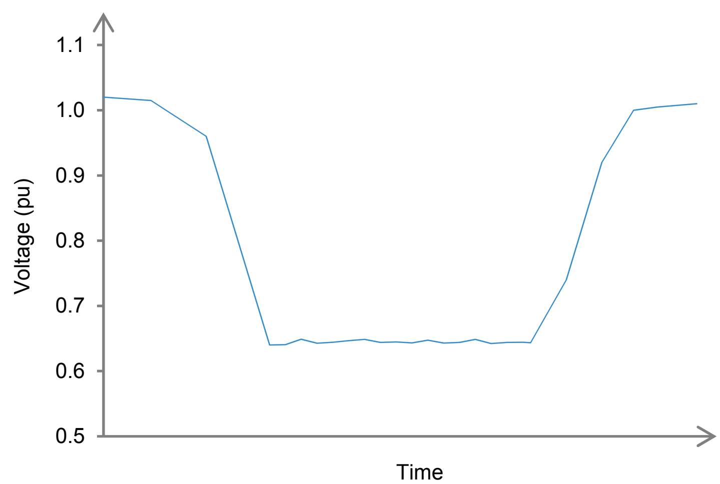


Figure 11. Example of a typical voltage sag.

Start-up torque

When a motor is started by connecting it directly to the grid, nothing other than the stator winding impedance limits the amount of electrical power that the motor draws. Consequently, the torque produced at start-up is significantly larger than the nominal torque of the motor. Figure 12 shows how the torque varies as a function of the rotation speed when a motor is started using a DOL starter. At the instant electric power is applied to the motor, the torque is quite large (up to 3 times the motor nominal torque). As the motor accelerates, the torque continues to increase and can generally reach 4 to 5 times the motor nominal torque. For small motors, the torque peaks at about 80 percent of the nominal speed, while for large motors, it peaks at about 98% of the motor nominal speed. Note that the maximal value of torque which any induction motor produces when started using a DOL starter only depends on the motor design and is not influenced by the mechanical load coupled to the motor.

The large start-up torque creates large stresses on the motor, belts and chains, and any other mechanical components connected to the motor. Mechanical stress reduces the lifespan of these parts and they tend to break more frequently, which increases the maintenance cost and the downtime a production line can endure.

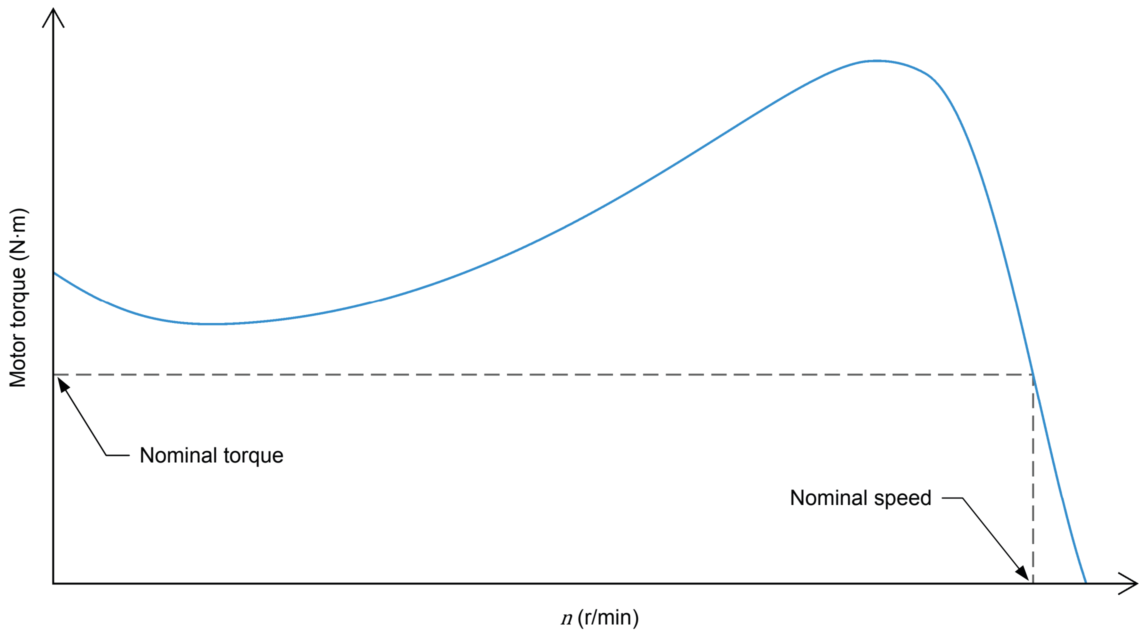


Figure 12. Variation of the torque as a function of the rotation speed when an induction motor is started using a DOL starter.

Soft starters

A common approach to lessen the undesired phenomena occurring during motor start-up is to use a soft starter instead of a DOL starter. A **soft starter** is a device that uses solid-state electronics to control the start-up voltage. A start-up voltage lower than the motor nominal voltage keeps the motor current and torque low and reduces the stress on the electrical and mechanical components. Figure 13 shows a simplified representation of an induction motor with a soft starter circuit. The soft starter connects in series with the motor and an external start or stop signal triggers it. Various parameters can usually be configured manually on the soft starter.

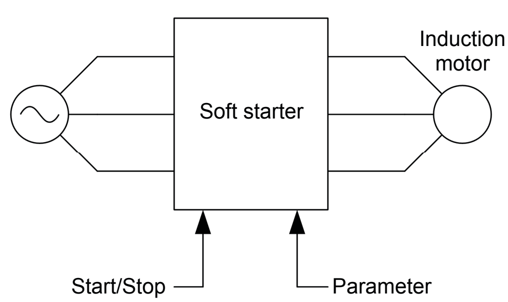


Figure 13. Simplified soft starter connection circuit.

Voltage output of a soft starter

Most soft starters can be configured to suit various applications and their design may vary depending on the manufacturer. Nevertheless, the voltage a soft starter applies to the motor windings generally varies, as shown in Figure 14. During motor start-up (region 1), the soft starter gradually increases the voltage it applies to the motor windings up to the motor nominal voltage. Since an induction motor needs a minimum voltage to produce enough torque to start rotating, the voltage ramp does not start at zero, but at a predetermined **initial voltage**. Most soft starters allow the user to adjust the initial voltage to meet the requirement of a specific application[1]. Once the full voltage is reached, the soft starter output voltage remains constant until the motor is stopped (region 2). The third region of the curve of Figure 14 shows the output of the soft starter when a soft-stop option is enabled. In soft-stop mode, the output voltage is gently reduced to zero to stop the motor smoothly. If the soft-stop option is disabled or unavailable, the output voltage goes directly from 100% to 0% when the user stops the motor and the motor coasts to rest. Note that the time intervals during which the output voltage of the soft starter increases at start-up or reduces when the motor is stopped are called ramp-up time and ramp-down time respectively.

The slopes of the **soft-start** and **soft-stop** ramps are two parameters that can be adjusted to suit different applications. For instance, a motor driving a high-inertia load will require a gentle slope, which means that the soft starter must be configured with a long ramp-up.

Before plunging into the inner working of soft starters, it is interesting to examine the effects a soft starter has on the motor current, torque, and acceleration during start-up. This is done in the next three subsections.

[1] Sometimes the user needs to specify the percentage of the locked rotor-torque he wants at start-up instead of the initial voltage in volts.

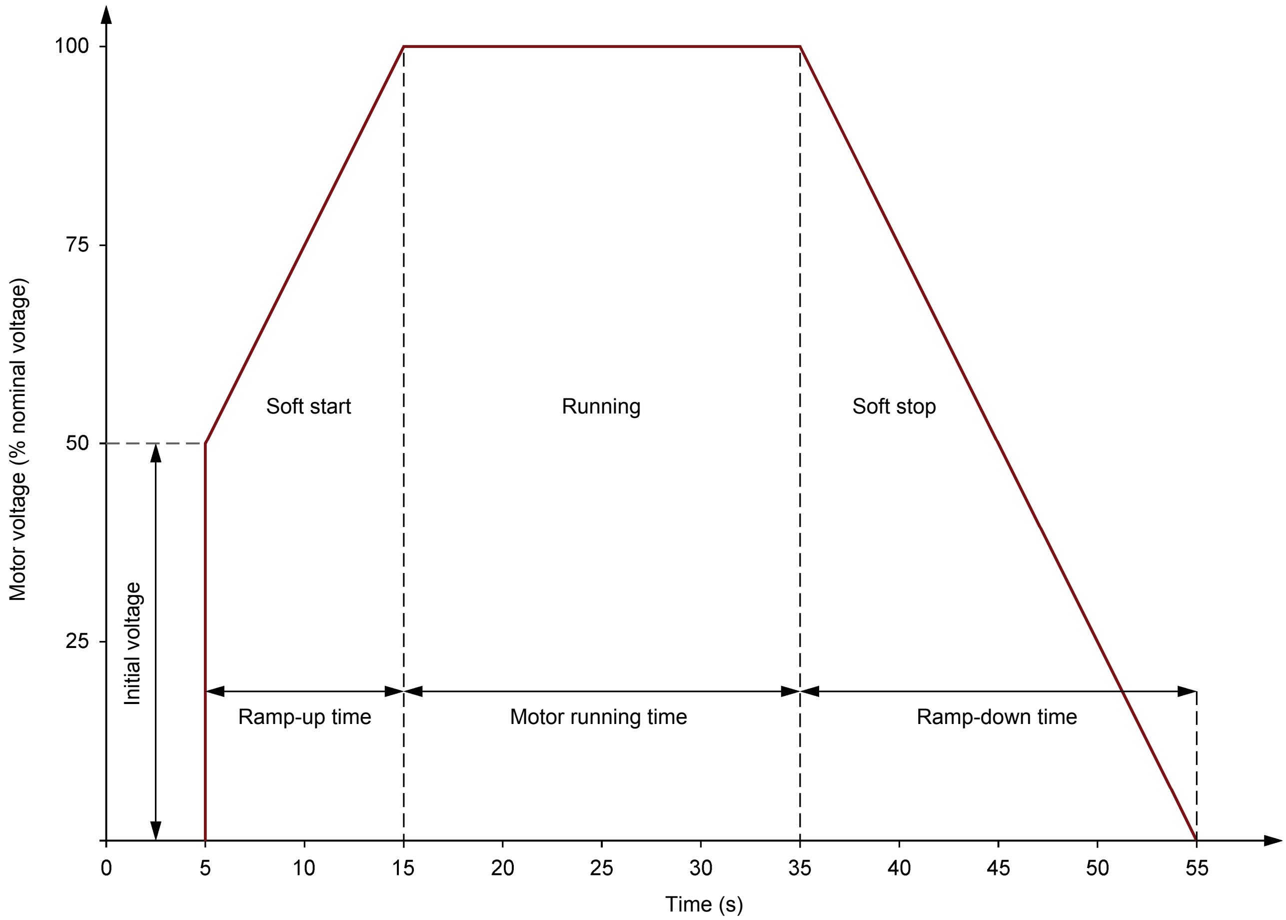


Figure 14. Soft starter ramp.

Effect of the soft starter on the motor current

The best way to observe the effect a soft starter has on the motor current is to compare the motor inrush current when a soft starter is used to the inrush current when a DOL starter is used. Figure 15 shows how the stator current varies as a function of the motor speed for both a soft starter (red curve) and a DOL starter (blue curve). The current scale is shown as a factor by which the motor FLA is multiplied.

With a DOL starter, the motor current is maximal at the instant the starter applies power to the motor winding and decreases gradually as the motor gains speed. As the motor approaches full speed, the current decreases more rapidly until it stabilizes at a steady-state value when the motor reaches full speed. The value at which the current stabilizes depends on the torque opposing rotation (mainly due to friction). The higher the inertia of the mechanical load coupled to the motor, the longer the current stays high since the motor takes more time to reach full speed. If the current stays high for too long, the motor windings are at risk of overheating and the overload protection trips (or the motor burns if it has no functional overload protection).

By contrast, a soft starter does not apply the full voltage to the motor windings at start-up. Instead, the voltage is gently ramped-up to full voltage, as shown in Figure 14. This reduces the current that the motor draws and keeps it significantly lower than when a DOL starter is used. As the motor speed increases, the current increases slightly but remains much lower than when a DOL starter is used. The motor current decreases rapidly as the motor approaches full speed in somewhat the same way as when a DOL starter is used. Finally, the current stabilizes at a steady-state value as when a DOL starter is used.

Since the power dissipated as heat by the motor windings is proportional to the square of the current, reducing the starting current using a soft starter significantly reduces the motor heating. Furthermore, the lower maximal current drawn at start-up when using a soft starter helps reduce the undesired effects of voltage sags.

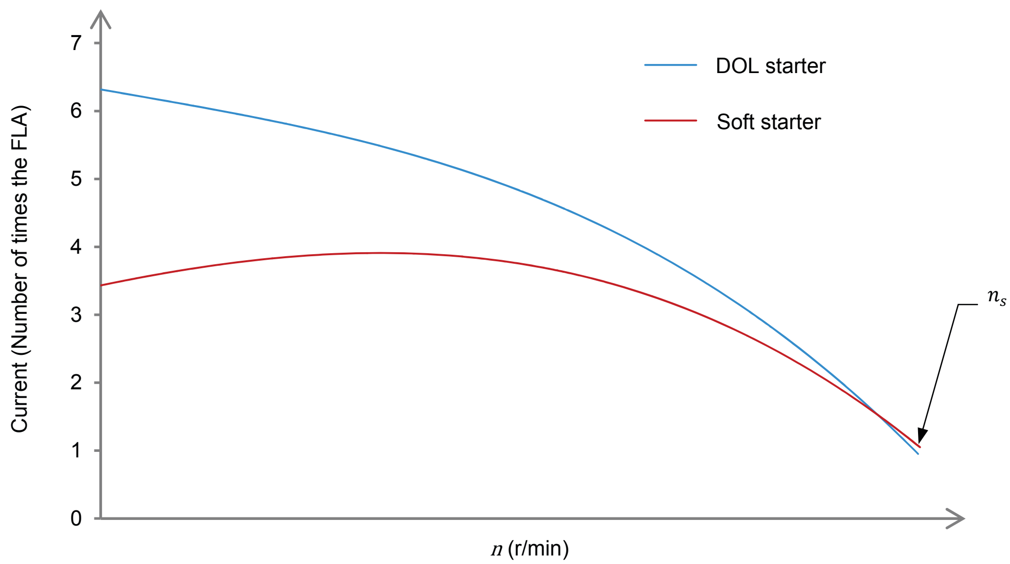


Figure 15. Variation of the stator current as a function of the rotation speed.

Effect of the soft starter on the motor torque

With a DOL starter, the full voltage of the power source is applied to the motor at start-up and a large torque is exerted on the rotor. This torque is transmitted to the mechanical components connected to the rotor with the aforementioned consequences. Figure 16 shows curves of the motor torque as a function of the motor rotation speed for both a DOL starter (blue curve) and a soft starter (red curve). Comparing both curves, it is clear that the motor produces a much lower torque when a soft starter is used than when a DOL starter is used.

To understand why, one must remember that the **torque** an induction motor produces is proportional to the square of the voltage applied to the stator windings. Therefore, starting the motor at a reduced voltage using a soft starter also reduces the torque. For example, applying half the nominal voltage of the motor reduces the torque by four. Reducing the motor torque at start-up is one of the most useful features of soft starters since it reduces the frequency of mechanical breakdowns and, consequently, the down time and maintenance cost of the equipment.

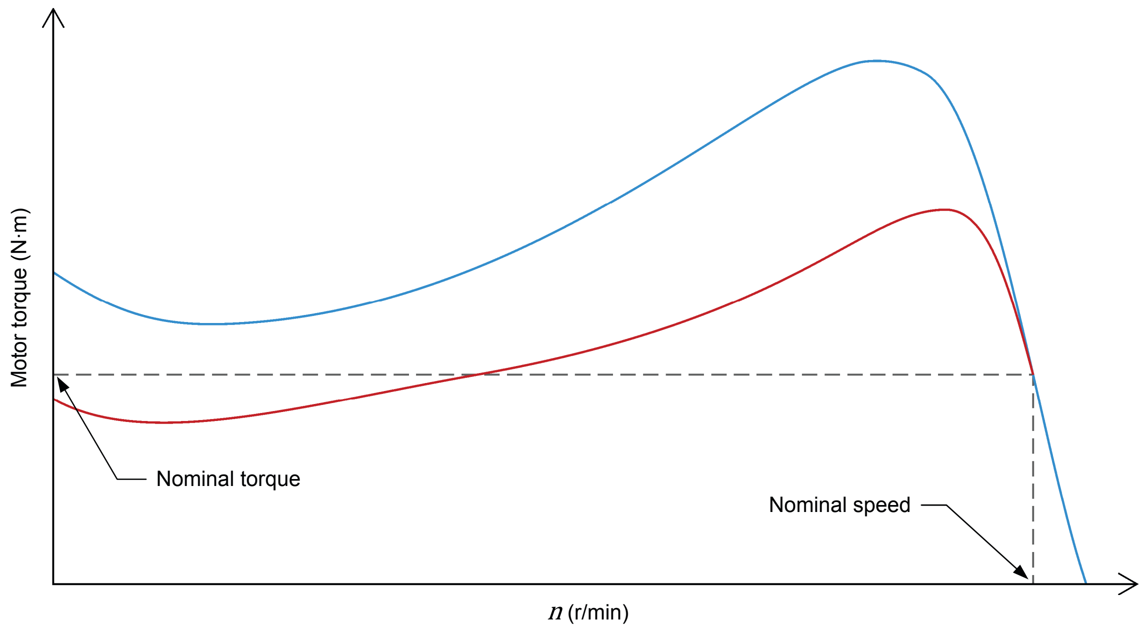


Figure 16. Variation of the torque as a function of the rotation speed when an induction motor is started with either a DOL starter or a soft starter.

Effect of the soft starter on the motor speed

Starting a motor at reduced voltage using a soft starter has another interesting effect. Less voltage applied to the stator windings means the motor produces less torque to accelerate the rotor. Hence, it takes more time for the motor to reach full speed when a soft starter is used.

Figure 17 shows how the rotation speed increases as a function of time when an induction motor is started with either a DOL starter (blue curve) or a soft starter (red curve). The first thing to note is that the slopes of the two curves are different. Remember that the slope of a speed as a function of time curve corresponds to acceleration. Hence, the gentle slope of the soft starter speed as a function of time curve indicates that the motor accelerates more slowly with a soft starter than with a DOL starter. This is to be expected since the torque exerted on the rotor is lower because of the reduced start-up voltage.

One may say that the price to pay for using a soft starter is a degradation of the dynamic performances since the motor takes more time to reach full speed. This is true in some situations, but as we will see later in this manual, this drawback can be turned into an advantage when fragile goods or containers filled with liquid must be moved on a conveyor belt, for example.

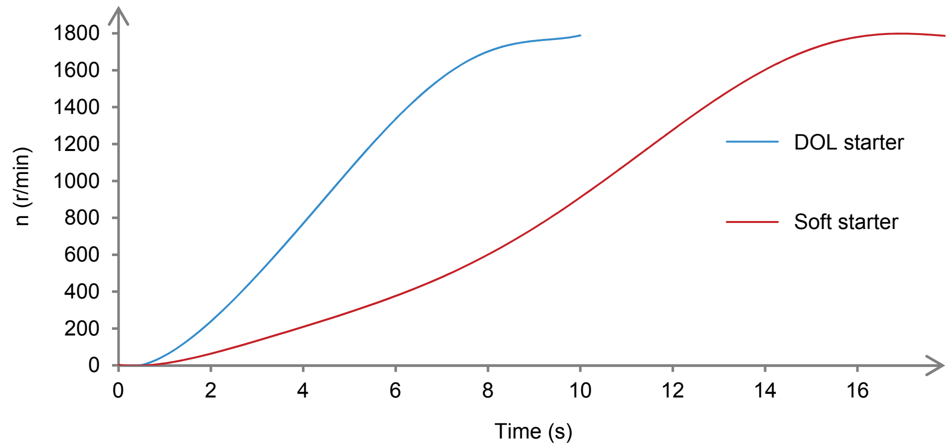


Figure 17. Variation of the rotation speed as a function of time when an induction motor is started with either a DOL starter or a soft starter.

How a soft starter controls voltage

A soft starter uses solid-state semiconductor devices called **thyristors** to control the voltage it applies to the motor windings. Figure 18 shows a simplified block diagram of a soft starter. Although overcurrent and overload protections are frequently built-in for soft starters, they have been omitted on the diagram for the sake of simplicity.

As this figure shows, a soft starter is a three-phase ac control circuit with two antiparallel thyristors in each branch of the wye-connected circuit. A control circuit sends firing signals to the thyristors gates to vary the starter output voltage as desired. The control circuit uses a thyristor firing control technique called phase angle modulation to produce the appropriate voltage output. For example, to limit the voltage on each branch, the control circuit times the moment it “fires” each thyristor, such as the thyristor starts to conduct when the voltage phase-angle is greater than the **firing angle**.

To start the motor smoothly, the soft-starter control circuit varies the firing angle so as to gradually increase the voltages at the motor windings. The user has access to different parameters that influence the minimal voltage the starter applies to the motor windings and the start time, for example.

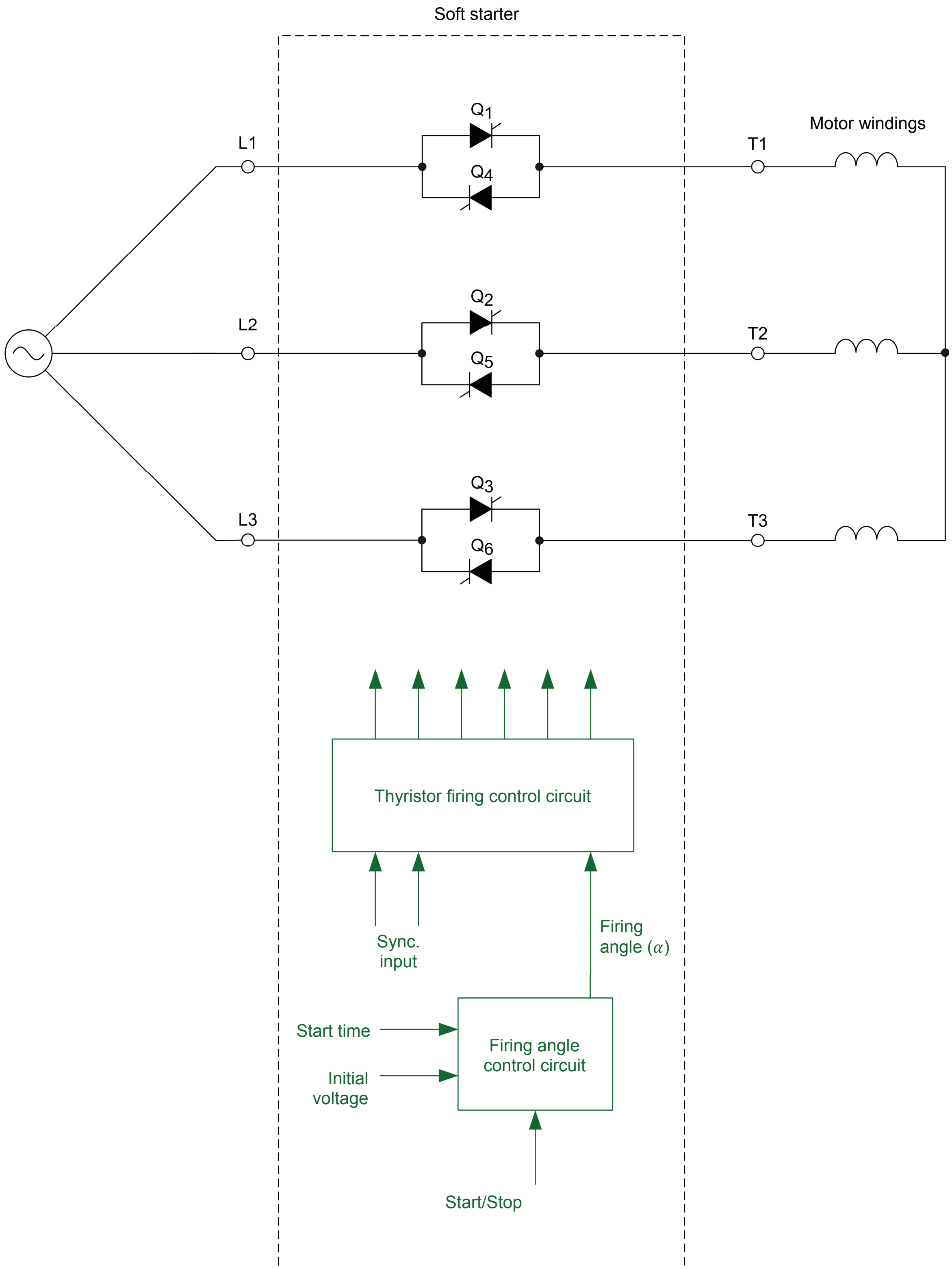


Figure 18. Simplified block diagram of a soft starter implemented using thyristors in all three branches of the circuit.

Bypass circuit

Thyristors, just as any other solid-state device, dissipate energy in the form of heat when they conduct current. The energy the thyristors dissipate during motor start-up is not significant since the start time for most soft starters is under one minute. However, running a motor for an extended period of time with the thyristors fully conducting is not energy efficient. To reduce power losses, soft starters come either with a built-in **bypass contactor**, or an external one is connected in parallel with the soft starter. This bypass contactor closes automatically once the soft start is completed. This greatly reduces the power lost in the soft starter since a contactor is not a solid-state device and dissipates a negligible amount of power (as heat) across its contacts. Figure 19 shows how the contacts of the bypass contactor are wired in a soft-starter circuit.

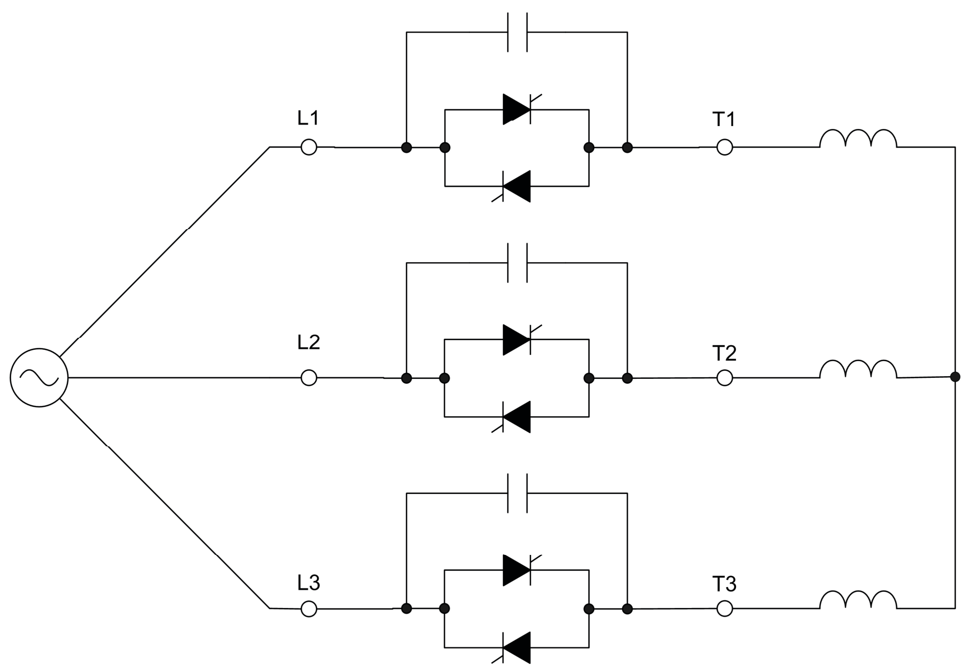


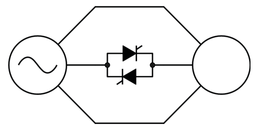
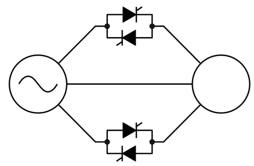
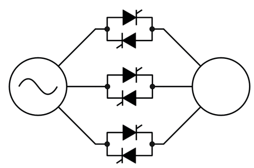
Figure 19. Wiring of the contacts of the bypass contactor in a typical soft starter.

Types of soft starters

When it comes to soft-starter design, there are many variations on the same theme. The topology presented above, with two antiparallel thyristors in each branch of the circuit, is not the only option. In order to reduce cost, manufacturers sometimes implement ac power control using thyristors in only two out of the three branches of the circuit. This reduces the number of thyristors from six to four and reduces the associated electronics. Some manufacturers even use thyristors in only one branch, leaving only two thyristors in the circuit.

Soft starters that use thyristors in one phase, two phases or all three phases are not equivalent. The benefits and limitations of each topology must be weighed out when selecting a soft starter for a given application. Table 1 lists the advantages and limitations commonly associated with each of these types of soft starters. Note that some manufacturers try to compensate for some of the limitations by adding sophisticated control of the phase angle.

Table 1. Topology, advantages, and limitations of various types of soft starter.

Type of soft starter	Topology	Advantage(s)	Limitation(s)
Single-phase soft starter (torque controller)		• Inexpensive • Reduces starting torque	• Do not reduce starting current • Requires the use of a DOL starter
Two-phase soft starter		• Less expensive than a three-phase soft starter • Reduces starting torque • Reduces starting current	• Starting current in the uncontrolled phase is higher than in the other two phases • Not suitable for heavy loads
Three-phase soft starter		• Reduces starting torque • Reduces starting current • All three phases are controlled (the rms current is the same on all three phases) • Ideal for applications where current must be strictly controlled at start-up or for heavy loads	• More expensive than the other two types of soft starters

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Starting an induction motor using a DOL starter
- Soft starter setup and settings
- Starting an induction motor using a soft starter
- DOL starter versus soft starter

PROCEDURE

⚠ WARNING

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Setup and connections

In this part of the exercise, you will connect your equipment as a DOL starter, configure parameters in LVDAC-EMS so that the Four-Quadrant Dynamometer/Power Supply emulates a flywheel, and set the Oscilloscope to observe the motor start-up current, torque, and speed.

1. Refer to the Equipment Utilization Chart in Appendix A for a list of the equipment required for this exercise.

   Install the equipment in the Workstation.

   ⚠ WARNING

   Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

   Mechanically couple the Four-Pole Squirrel Cage Induction Motor to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

2. Make sure that the ac and dc power switches on the Power Supply are set to the O (off) position and then connect the Power Supply to a three-phase ac power outlet.

   Make sure that the main power switch on the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position and then connect the *Power Input* to an ac power outlet.

   Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to a 24 V ac power supply.

   Connect the *Low Power Input* of the Power Thyristors module to the *Power Input* of the Data Acquisition and Control Interface. Turn the 24 V ac power supply on.

3. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

   Connect the USB port of the Four-Quadrant Dynamometer/ Power Supply to a USB port of the host computer.

4. Turn the Four-Quadrant Dynamometer/Power Supply on and then set the *Operating Mode* switch to *Dynamometer*.

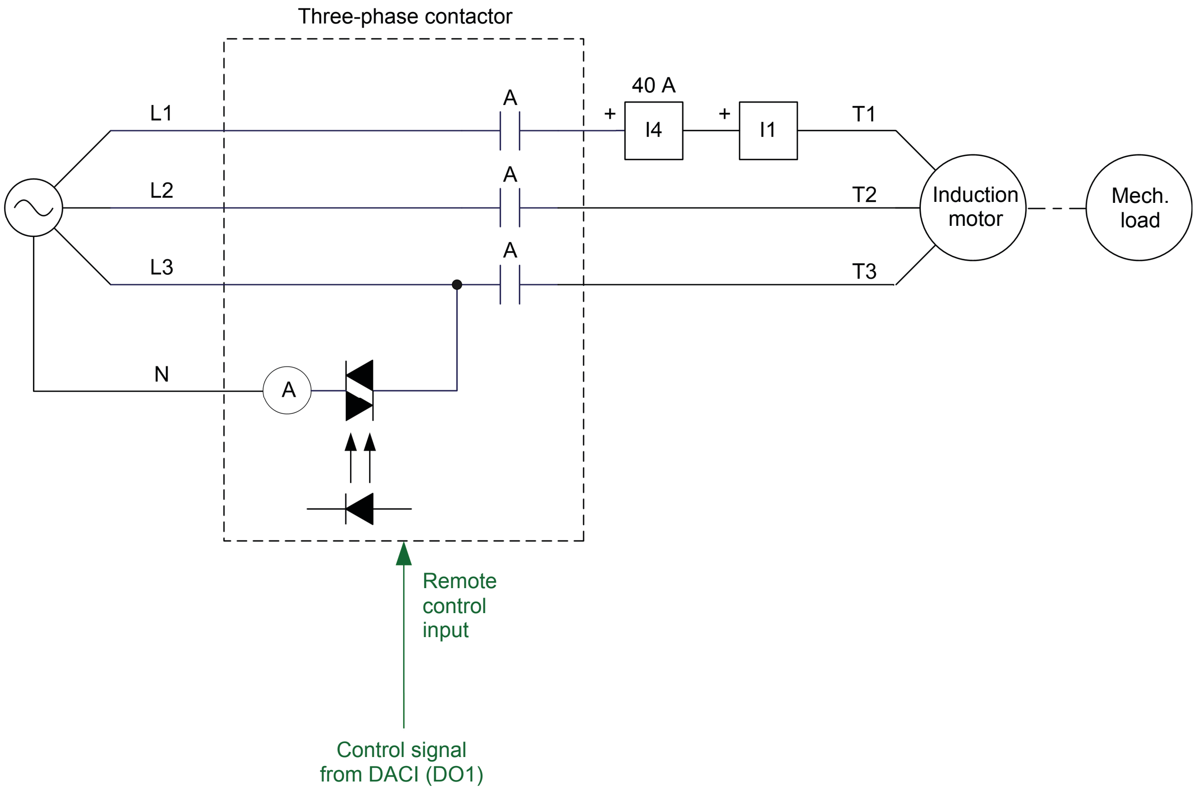
5. Turn the host computer on and start the LVDAC-EMS software.

   In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure the *Computer-Based Instrumentation* and *Thyristor Control* functions are available for the Data Acquisition and Control Interface module. Also, select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

6. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window. In the *Tools* menu of this window, select *Friction Compensation Calibration*, which will bring up the Friction Compensation Calibration dialog box. Click *OK* in this box to start the calibration process. Observe that the prime mover starts to rotate at high speed, thereby driving the shaft of the Four-Pole Squirrel Cage Induction Motor. The prime mover speed is then automatically decreased by steps to perform the calibration process. Once the calibration process is completed (which takes about two minutes), the prime mover stops rotating, then the Friction Compensation Calibration dialog box indicates that the calibration process is finished. Click *OK* in the Friction Compensation Calibration dialog box to close this box. Restart the Four-Quadrant Dynamometer/Power Supply to apply the changes (i.e., the newly calibrated friction compensation curve) by setting the main power switch of this module to *O* (off), and then *I* (on).

7. Connect the equipment as shown in Figure 20. In this circuit, the mechanical load is implemented using the Four-Quadrant Dynamometer/Power Supply coupled to the Four-Pole Squirrel Cage Induction Motor. The range of current input *I1* to be used on the Data Acquisition and Control Interface depends on your local ac power network (see table in Figure 20).

   Current input I4 of the Data Acquisition and Control Interface is used to monitor the motor current in order to protect the motor from overheating if excessive currents flow through the stator windings. The range of current to be used for current input I4 is 40 A.



Local ac power network		Range of Input *I1* (A)
Voltage (V)	**Frequency (Hz)**	
120	60	40
220	50	4
240	50	4
220	60	4

Figure 20. Direct-on-line starter.

8. In the Data Acquisition and Control Settings window of LVDAC-EMS, set the Range of current input *I1* as indicated in the table of Figure 20 for your local ac power network.

9. On the Synchronizing Module/Three-Phase Contactor module, set the *Sync.* switch to the O (off) position.

10. Connect *Digital Output 1* (*DO1*) and a digital (*D*) common (white terminal) of the Data Acquisition and Control Interface to the + and *– Remote Control* terminals of the Synchronizing Module/Three-Phase Contactor module, respectively, using two miniature banana plug leads. These connections allow the three-phase contactor to be controlled using the Direct-On-Line Starter control function in LVDAC-EMS (via the Data Acquisition and Control Interface).

11. Connect *Analog Outputs T* and *n* of the Four-Quadrant Dynamometer/Power Supply to *Analog Inputs* 7/*T* and 8/*n* of the Data Acquisition and Control Interface, respectively, using two miniature banana plug leads. Connect the common (white terminal) of the *Analog Outputs* on the Four-Quadrant Dynamometer/Power Supply to an analog (*A*) common (white terminal) of the Data Acquisition and Control Interface. These connections are required to observe the induction motor speed and torque using the Oscilloscope.

12. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *Mechanical Load*. This makes the Four-Quadrant Dynamometer/Power Supply operate like a configurable mechanical load.

– Set the *Load Type* parameter to *Flywheel*. This makes the mechanical load emulate a flywheel.

– Set the *Inertia* parameter to 0.09 kg·m^2 (2.14 lb·ft^2). This sets the moment of inertia of the emulated flywheel.

– Set the *Friction Torque* parameter to 0.1 N·m (0.88 lbf·in). This sets the torque that opposes rotation of the emulated flywheel.

– Set the *Pulley Ratio* parameter to 24:24.

Note that the pulley ratio between the Four-Quadrant Power Supply/Dynamometer and the Four-Pole Squirrel Cage Induction Motor is 24:24.

13. In LVDAC-EMS, open the Thyristor Control window, then make the following settings:

– Set the *Function* parameter to *Direct On-Line Starter*.

– Set the *Motor Full Load Current [FLA]* parameter to the value of the motor rated current. The motor rated current is indicated on the motor front panel; it depends on the frequency and voltage of the local ac power network.

– Set the *Overload* parameter to *On*.

– Set the *Overload Class* parameter to 10.

14. In LVDAC-EMS, open the Oscilloscope window. Make the appropriate settings to display one of the motor currents (measured via input *I1)*, the motor torque (measured via *Analog Input 7/T*) and the motor speed (measured via *Analog Input 8/n*) using channels 1, 2, and 3, respectively. Set the vertical sensitivity of channel 1 to 2 A/div if your ac power network voltage is 120 V. Otherwise set the sensitivity of channel 1 to 1 A/div. Set the vertical sensitivity of channel 2 to 1 N·m/div (10 lbf·in/div). Set the vertical sensitivity of channel 3 to 500 (r/min)/div. Set the time base to 2 s/div. Finally, set the acquisition mode to *Peak Detect*.

Starting an induction motor using a DOL starter

In this part of the exercise, you will start the motor using a DOL starter. You will record the motor current, torque, and speed at start-up and analyze the results.

15. On the Power Supply, turn the three-phase ac power source on.

16. In the Four-Quadrant Dynamometer/Power Supply window, start the mechanical load by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button. The induction motor is now coupled to a flywheel emulated by the mechanical load.

17. In the Oscilloscope window, click the *Single Refresh* button, then immediately press the *Start* button of the DOL starter in the Thyristor Control window to start the motor.

The above manipulation must be performed rapidly to ensure that the Oscilloscope records the entire evolution of the various parameters during motor start-up.

18. Wait until the Oscilloscope displays the evolution of the motor current, torque, and speed, then press the *Stop* button of the DOL starter to stop the motor.

Since the Oscilloscope operates in peak detect mode and a slow time base is used, it displays the envelope of the motor current rather than its waveform.

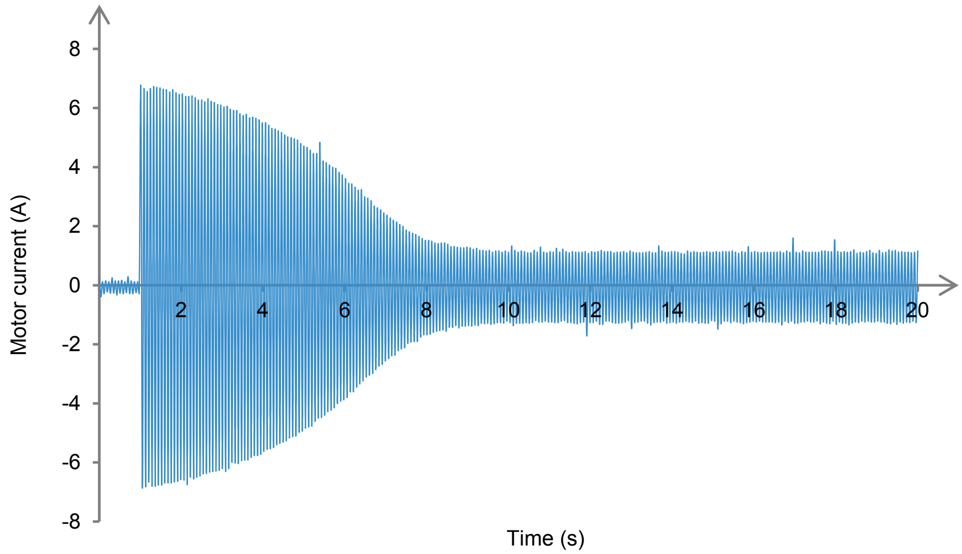
19. In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load by setting the *Status* parameter to *Stopped* or by clicking the *Start/Stop* button.

On the Power Supply, turn the three-phase ac power source off.

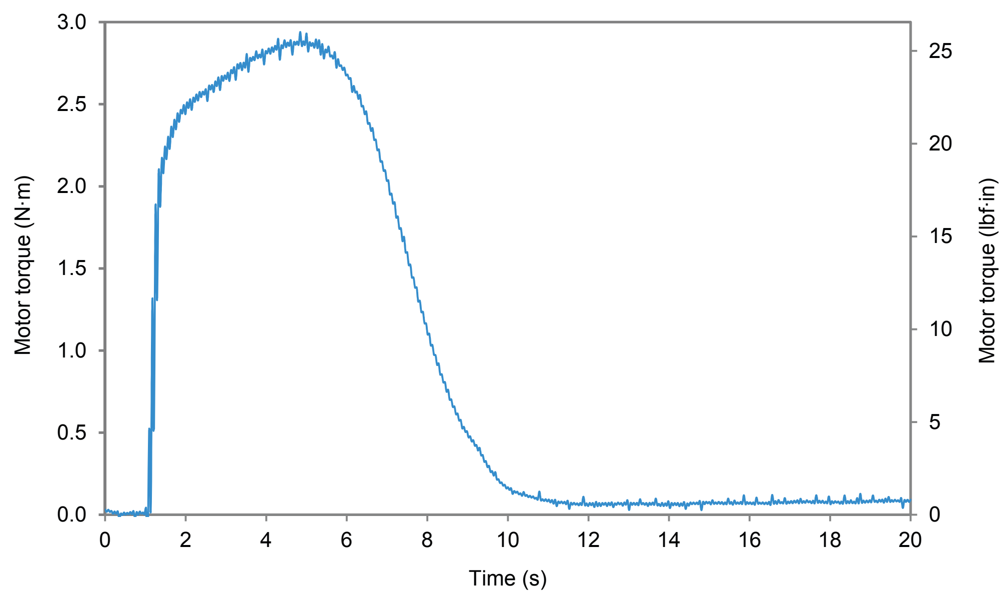
20. From the File menu of the Oscilloscope window, save to a text file (export) the data related to the motor current, torque, and speed displayed on the Oscilloscope screen.

21. Using a spreadsheet software, plot the evolution of the motor current, torque, and speed as a function of time on three separate graphs:

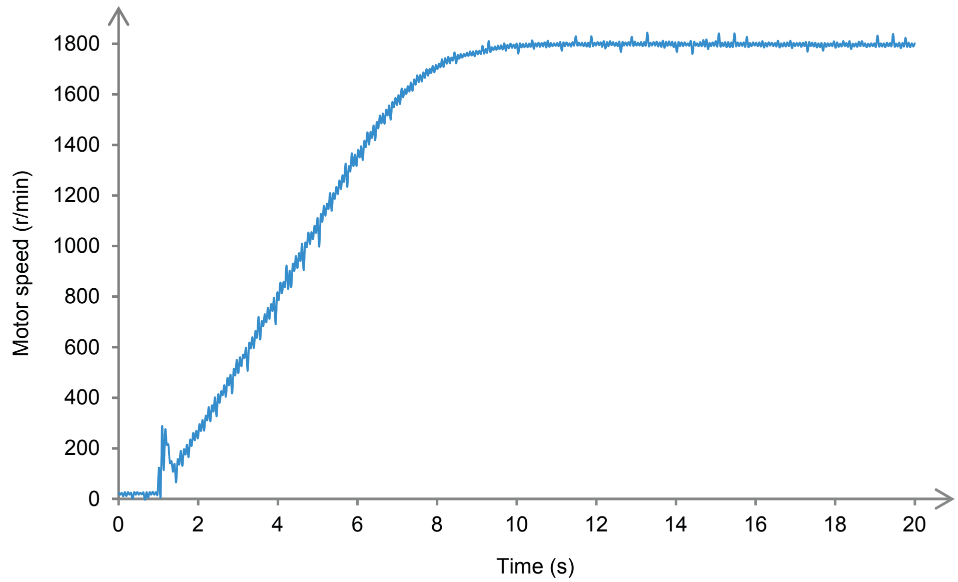
The following graphs show the evolution of the motor current, torque, and speed as a function of time.



Motor current (peak value) envelope as a function of time.



Motor torque as a function of time.



Motor speed as a function of time.

22. From the motor current graph you plotted in the previous step, determine the maximal value that the motor current reached during motor start-up.

The maximal value which the motor current reached during motor start-up is about 7.0 A (peak value).

23. Compare the maximal current from step 22 to the motor FLA.

The maximal current obtained in step 22 is a peak value. Convert this peak value to an rms value before making the comparison.

The maximal current is 4.3 times the motor FLA.

24. From the motor speed graph you plotted in step 21, is the maximal speed reached by the motor higher than the motor synchronous speed (n_s)?

❑ Yes ❑ No

No. For an induction motor, the speed is always lower than the synchronous speed.

25. From the motor torque graph you plotted in step 21, determine the maximal torque that the motor produced during start-up.

The maximal torque the motor produced during start-up is about 2.8 N·m (24.8 lbf·in).

26. Compare the maximal torque from step 25 to the motor nominal torque. The value of the motor nominal torque depends on the voltage and frequency of your local ac power network (see table below.)

Table 2. Nominal torque of the Four-Pole Squirrel Cage Induction Motor.

Local ac power network		Motor nominal torque T
Voltage (V)	Frequency (Hz)	
120	60	1.13 N·m (10.00 lbf·in)
220	50	1.42 N·m (12.56 lbf·in)
240	50	1.40 N·m (12.39 lbf·in)
220	60	1.15 N·m (10.18 lbf·in)

The maximal torque is 2.5 times the motor nominal torque.

27. Would doubling the inertia of the mechanical load double the maximal torque produced during motor start-up? Why?

No, because the maximal torque produced by an induction motor started using a DOL starter only depends on the motor design.

28. How would doubling the inertia of the mechanical load affect the start-up time?

Doubling the inertia of the mechanical load coupled to the induction motor would increase (approximately double) the start-up time.

29. From the motor speed graph you plotted in step 21, how long does it take for the motor to accelerate up to full speed?

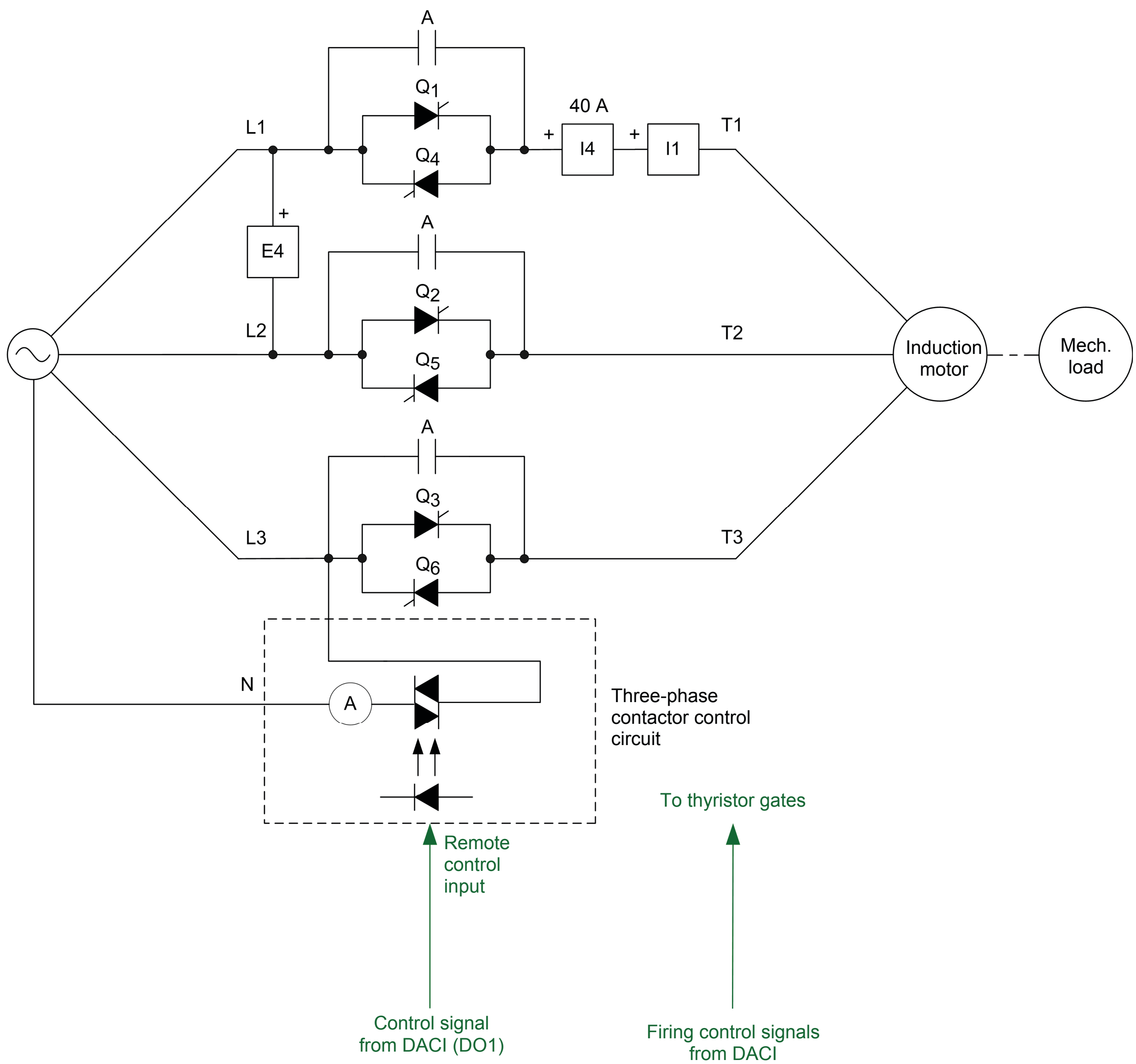
Approximately 9 s

Soft starter setup and settings

In this section, you will modify the equipment connections so as to replace the DOL starter with a soft starter.

30. Make sure that the three-phase ac power source is off.

31. Modify the equipment connections so as to obtain the circuit shown in Figure 21. The range of current input *I1* to be used on the Data Acquisition and Control Interface depends on your local ac power network (see table in Figure 21).



Local ac power network		Range of Input *I1* (A)
Voltage (V)	Frequency (Hz)	
120	60	40
220	50	4
240	50	4
220	60	4

Figure 21. Soft starter setup.

32. On the Synchronizing Module/Three-Phase Contactor module, make sure the *Sync.* switch is still set to the O (off) position.

33. Make sure that *Digital Output 1* of the Data Acquisition and Control Interface is still connected to the *Remote Control* input of the Synchronizing Module/Three-Phase Contactor module.

34. Make sure that the *T and n Analog Outputs* of the Four-Quadrant Dynamometer/Power Supply are still connected to *Analog Inputs 7/T* and *8/n* of the Data Acquisition and Control Interface.

35. Connect the *Digital Outputs* of the Data Acquisition and Control Interface to the *Firing Control Inputs* of the Power Thyristors module, using the provided cable with DB9 connectors.

36. In the Data Acquisition and Control Settings window of LVDAC-EMS, make sure that the *Range* of current input *I1* is set as indicated in the table of Figure 21 for your local ac power network.

In the Four-Quadrant Dynamometer/Power Supply window, keep the settings of the Mechanical Load unchanged (i.e., as indicated in step 12).

In the Thyristor Control window, make the following settings:

– Set the *Function* parameter to *Soft Starter*.

– Set the *Mode* parameter to *Soft Start*.

– Set the *Motor Full Load Current [FLA]* parameter to the value of the motor rated current. The motor rated current is indicated on the motor front panel; it depends on the frequency and voltage of the local ac power network.

– Set the *Initial Torque* parameter to 35%. The soft starter function uses this parameter to determine the voltage it must apply to the motor winding in order to obtain the desired initial torque.

– Set the *Start Time* parameter to 15 s. The start time is the period of time during which the *Soft Starter* function varies the voltage from an initial voltage (determined by the *Initial Torque* parameter) to the full voltage.

– Set the *Kick Start Time* parameter to 0.0 s to disable the kick start function.

– Set the *Soft Stop* parameter to 0 to disable the soft stop function.

– Set the *Overload* parameter to *On*.

– Set the *Overload Class* parameter to 10.

Starting an induction motor using a soft starter

In this part of the exercise, you will start the motor, still coupled to the same mechanical load used earlier in the exercise, using a soft starter. You will record the motor current, torque, and speed at start-up and analyze the results.

37. On the Power Supply, turn the three-phase ac power source on.

38. In the Four-Quadrant Dynamometer/Power Supply window, start the mechanical load.

39. In the Oscilloscope window, click the *Single Refresh* button, then immediately switch to the Thyristor Control window and press the *Start* button of the soft starter to start the motor.

The above manipulation must be performed rapidly to ensure the Oscilloscope records the entire evolution of the various parameters during motor start-up.

40. Wait until the Oscilloscope displays the evolution of the motor current, torque, and speed, and then press the *Stop* button of the soft starter to stop the motor.

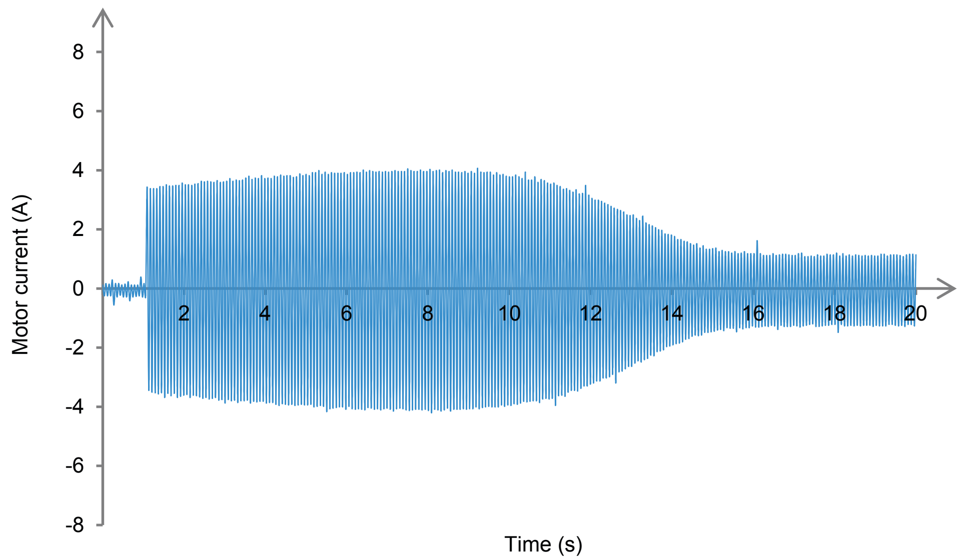
41. In the Four-Quadrant Dynamometer/Power Supply window, stop the mechanical load.

42. On the Power Supply, turn the three-phase ac power source off.

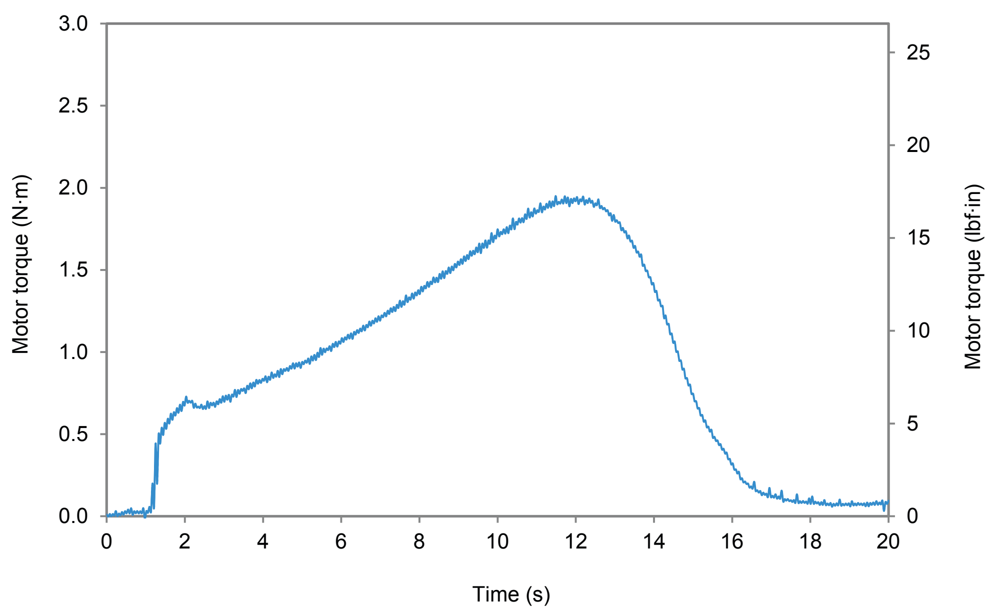
43. From the File menu of the Oscilloscope window, save to a text file (export) the data related to the motor current, torque, and speed displayed on the Oscilloscope screen.

44. Using a spreadsheet software, plot the evolution of the motor current, torque, and speed as a function of time on three separate graphs:

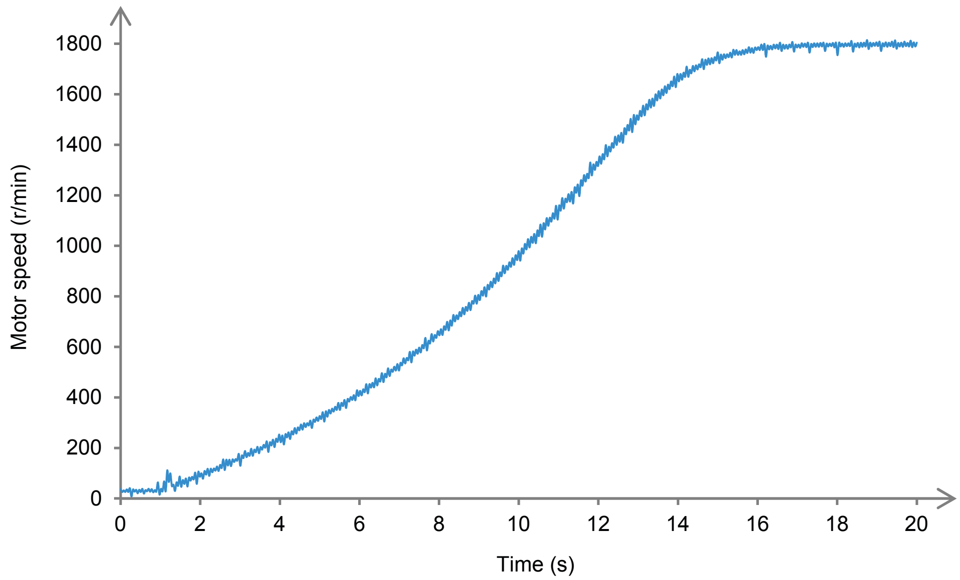
The following graphs show the evolution of the motor current, torque, and speed as a function of time.



Motor current (peak value) envelope as a function of time.



Motor torque as a function of time.



Motor speed as a function of time.

45. From the motor current graph you plotted in step 44, determine the maximal value that the motor current reached during motor start-up.

The maximal value which the motor current reached during start-up is about 4.1 A (peak value).

46. From the motor torque graph you plotted in step 44, determine the maximal torque that the motor produced during start-up.

The maximal torque the motor produced during start-up is about 1.9 N·m (16.8 lbf·in).

47. Compare the maximal torque from step 46 to the motor nominal torque. The value of the motor nominal torque depends on the voltage and frequency of your local ac power network (see Table 2).

The maximal torque is about 1.7 times the motor nominal torque.

48. From the motor speed graph you plotted in step 44, how long does it take for the motor to accelerate up to full speed?

Approximately 15 s

DOL starter versus soft starter

In this part of the exercise, you will compare the results you obtained with the DOL starter and the soft starter (for the same mechanical load) and try to deduce what the advantages and limitations of each one are.

49. Compare the current-versus-time curves obtained with both starters. Does using a soft starter significantly reduce the value of the current that the motor draws from the power source during start-up?

Yes. The peak value of the current drawn by the motor is between 3 A and 7 A during most of the start-up interval when the DOL starter is used, while it is between 3.0 A and 4.1 A when the soft starter is used.

50. Compare the torque-versus-time curves obtained with both starters. Does using a soft starter significantly reduce the amount of torque that the motor produces during start-up?

Yes. The torque produced by the motor largely exceeds 2.0 N·m (17.7 lbf·in) during most of the start-up interval when the DOL starter is used, while it is between 0.5 N·m (4.4 lbf·in) and 1.9 N·m (16.8 lbf·in) when the soft starter is used.

51. Which motor starter makes the mechanical load accelerate more rapidly?

The DOL starter. The mechanical load reaches full speed in about 9 s with the DOL starter compared to about 15 s with the soft starter.

52. Summarize your results by checking the appropriate box:

The starter resulting in the lowest starting current is

❑ the DOL starter ❑ the soft starter

The starter resulting in the lowest starting torque is

❑ the DOL starter ❑ the soft starter

The starter providing the best acceleration is

❑ the DOL starter ❑ the soft starter

The starter resulting in the lowest starting current is the soft starter.
The starter resulting in the lowest starting torque is the soft starter.
The starter providing the best acceleration is the DOL starter.

53. In the *Tools* menu of the Four-Quadrant Dynamometer/Power Supply window, select *Reset to Default Friction Compensation*. This will bring up the Reset Friction Compensation dialog box. Click *Yes* in this window to reset the friction compensation to the factory default compensation.

54. Close LVDAC-EMS and then turn off all the equipment. Disconnect all leads and return them to their storage location.

CONCLUSION

In this exercise, you learned fundamental notions of motor starting. Namely, you learned about various phenomena occurring during motor start-up, motor protections, direct-on-line starters, and soft starters. In the exercise procedure, you wired two types of motor starters (a DOL starter and a soft starter) from basic components like a contactor and thyristors. You analyzed the start-up phenomena for both your DOL starter setup and soft starter setup. At the end of this exercise, you should have acquired a general understanding of DOL starters and soft starters and be able to point out the main differences between these two types of starter.

REVIEW QUESTIONS

1. Identify the type(s) of motor starters that require an overload protection and explain why.

   All types of motor starters usually require an overload protection to protect the motor from overheating due to large current flowing through the stator windings for an extended period.

2. Explain what an inrush current is, as related to an induction motor.

   The inrush current is the large current that circulates through the stator windings of an induction motor at start-up. The amplitude of the inrush current can be up to 8 times the motor nominal current (FLA).

3. How does using a soft starter instead of a DOL starter to start an induction motor affect the motor starting current and torque, and the motor acceleration?

   Using a soft starter instead of a DOL starter to start an induction motor significantly reduces the motor starting current and torque. Consequently, this also reduces the motor acceleration.

4. Explain how a soft starter can help reduce voltage sags.

   Voltage sags are caused by electrical devices producing large inrush currents. Starting an induction motor using a soft starter reduces the inrush current significantly, and thus, helps reducing voltage sagging.

5. An induction motor drives a conveyor belt via a chain and pulleys. A DOL starter is used to start the motor. The chain breaks frequently when the conveyor is started and the maintenance costs are high. Identify a possible cause for this problem and devise a solution to address this issue.

   The problem is probably due to the large starting torque produced by the motor that creates too much stress on the chain and reduces its lifespan. Installing a soft starter can help reduce the starting torque significantly, thereby reducing the stress the chain endures. This ultimately results in less frequent chain failures.

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