

Power Factor Correction

FESTO

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Electricity and New Energy

LabVolt Series

Student Manual



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Student Manual

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General Safety Symbols and Procedures












The following table lists the safety and common symbols that may be used in this course and on the equipment. Before performing manipulations with the equipment, you should read all sections regarding safety in the Safety Instructions and Commissioning manual accompanying the equipment.

If applicable, following subsections give general procedures related to the tasks you will be asked to perform in this course. Additional safety procedures are given before any task requiring specific safety precautions.


Symbol	Description
	DANGER indicates a hazard with a high level of risk, which, if not avoided, will result in death or serious injury.
	WARNING indicates a hazard with a medium level of risk, which, if not avoided, could result in death or serious injury.
	CAUTION indicates a hazard with a low level of risk, which, if not avoided, could result in minor or moderate injury.
	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 danger. Consult the relevant user documentation.
	Caution, risk of electric shock.
	Caution, lifting hazard.
	Caution, hot surface.
	Caution, risk of fire.

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Symbol	Description
	Caution, risk of explosion.
	Caution, belt drive entanglement hazard.
	Caution, chain drive entanglement hazard.
	Caution, gear entanglement hazard.
	Caution, hand crushing hazard.
	Static sensitive contents. Observe precautions for handling electrostatic discharge sensitive devices.
	Notice, non-ionizing radiation.
	Consult the relevant user documentation.
	Radio Equipment Directive (RED) geographical restrictions – consult the relevant user documentation.
	Direct current.

Symbol	Description
	Alternating current.
	Both direct and alternating current.
	Three-phase alternating current.
	Earth (ground) terminal.
	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.

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Symbol	Description
	Out position of a bi-stable push control.

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.

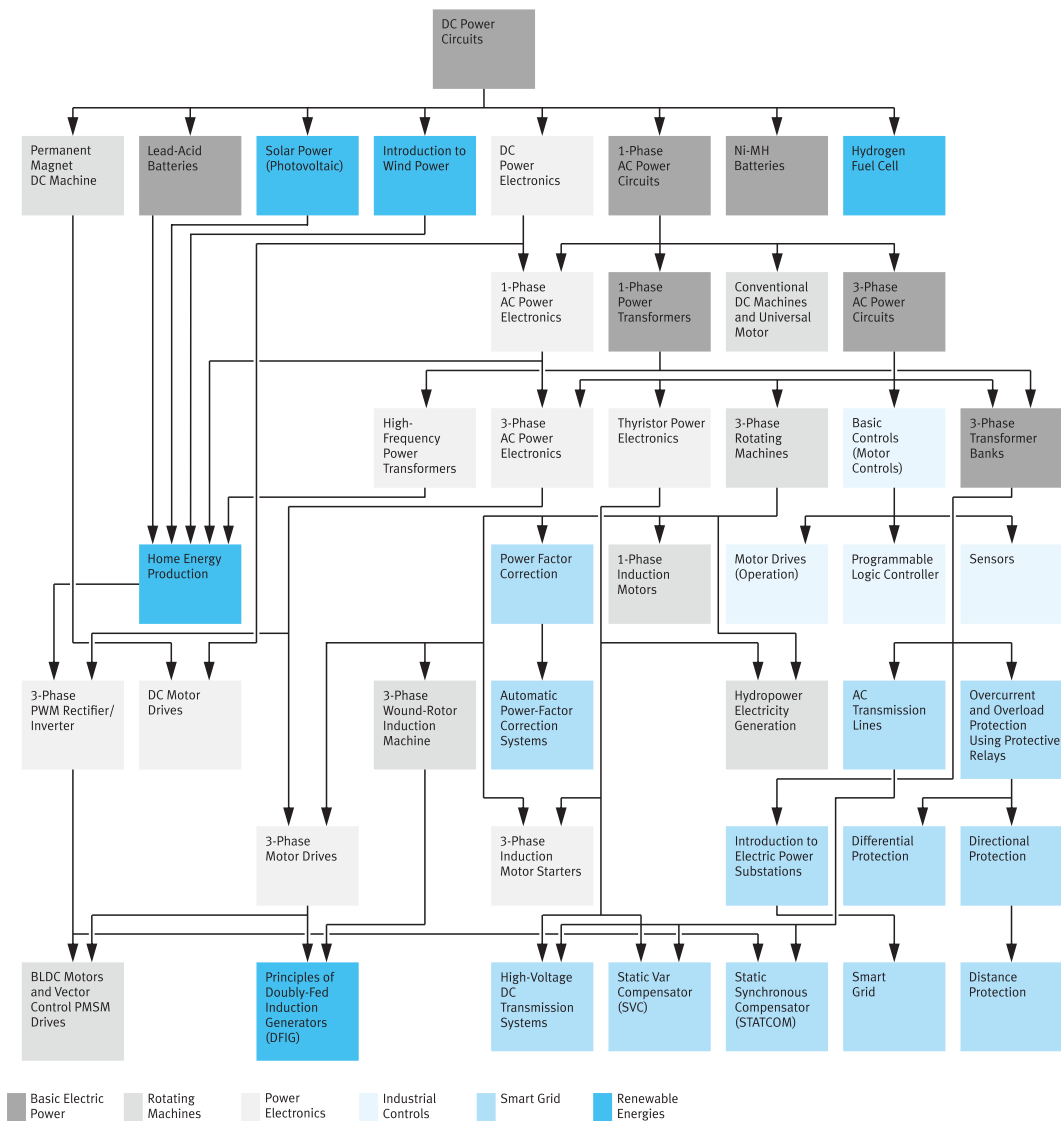


Figure 1: The Electric Power Technology Training Program.

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Electric Power Technology Training Program

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
- Drive systems for small electric vehicles and cars

Tips, feedback, and suggestions

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to:

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The authors and Festo Didactic look forward to your comments.

About This Course

Most large industrial applications nowadays have some means to implement power factor correction. This is because in almost any large industrial application, many loads and motors tend to absorb a substantial amount of reactive power from the ac power network, thus lowering the power factor of the application. This situation is undesirable as most electricity providers charge higher costs to customers having a power factor significantly lower than unity.

Therefore, to prevent their electricity bill from increasing due to a low power factor, it is common for managers of industrial applications with a high reactive power requirement to add some means to supply the reactive power required, thus increasing the power factor back to unity. This technique is called power factor correction. Power factor correction is usually achieved by adding capacitors to the industrial application. These capacitors are adjusted to supply the exact amount of reactive power required by the application to restore unity power factor.

This course teaches the basic principles of power factor correction. Students are introduced to the reasons for correcting the power factor of industrial applications. They learn how power factor correction is usually implemented in industrial applications with variable inductive loads (e.g., induction motors that start and stop). The course also introduces students to the two main types of power factor correction available: plant-wide and distributed. Finally, the principles of power factor correction are applied to both single-phase and three-phase ac power circuits. The theory presented in the course is then verified by performing various circuit measurements and observations.



Figure 2: Most industrial plants draw reactive power from the ac power network, thus lowering their power factor and increasing their energy cost. The use of power factor correction restores unity power factor, and thus, significantly reduces the energy costs.

Prerequisite

As a prerequisite to this course, you should have completed the following courses:

- DC Power Circuits
- Single-Phase AC Power Circuits
- Three-Phase AC Power Circuits
- Three-Phase Rotating Machines

System of units

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

Three-Phase Transformer Banks



The problem of a low power factor in an industrial application



It is generally accepted that inductive components absorb reactive power and capacitive components supply reactive power, although reactive components actually exchange reactive power and neither absorb nor supply reactive power.

Managers of most industrial applications today have to deal with the problem of maintaining a high power factor. This is because almost all industrial applications contain several inductive loads. The most common examples of such inductive loads are conveyors, pumps, grinders, mills, mixers, and arc furnaces. All these loads use either a motor or a transformer that requires magnetizing current (and thus reactive power) to build up the magnetic field necessary for its operation, in addition to the active power required to produce actual work. The higher the amount of reactive power that a load requires in proportion to its active power requirement, the lower the power factor of the load. In any industrial application containing several inductive loads, the amount of reactive power absorbed by each load adds up at the main bus where the application draws electric power from the ac power network. When an industrial application requires a significant quantity of reactive power in comparison to its active power requirement, the power factor of the application is low.

Having a low power factor (i.e., generally less than 0.9) at the main bus has several drawbacks for any industrial application. The main drawback is that a low power factor significantly increases the intensity of the current flowing from the ac power network to the industrial application for a given amount of active power supplied to the application. This is because the ac power network has to supply to the industrial application both the amount of active power and the amount of reactive power that it requires. Consequently, the intensity of the current flowing in the distribution lines supplying electric power to the industrial application increases. A higher current flowing in these distribution lines increases the copper losses (RI^2 losses) in these lines, and in all equipment (transmission lines, power transformers, etc.) upstream in the ac power network. Furthermore, a higher current also requires the electricity provider to increase the size of the distribution lines bringing power to the application, and possibly the size of other equipment (transmission lines, power transformers, etc.) upstream in the ac power network, to supply the required power to the industrial application.

The additional power losses in the ac power network caused by the low power factor of an industrial application, as well as the larger size equipment required, both result in supplementary expenditures for the electricity provider. Because of this, most electricity providers charge extra costs to industrial customers that have a low power factor. The method used to calculate these extra costs varies from one electricity provider to the other, but generally, the lower the power factor of the industrial application, the higher the extra costs on the electricity bill. As a result, most large industrial customers use certain means to implement **power factor correction**. Power

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factor correction consists in increasing the power factor of an inductive load to as close as possible to unity. The load can be the electric devices in a whole industrial application or a specific electric device in an industrial application such as a three-phase induction motor. Power factor correction is achieved by connecting capacitors to the load in order to supply the exact amount of reactive power that it requires. When sized properly, the capacitors supply all the reactive power that the load requires and thus bring the power factor to unity. As you will see in Exercise 1, an industrial customer can greatly increase the power factor of its application and reduce its energy costs by supplying its own reactive power.



Figure 3: Large industrial plants containing motors and other reactive loads in constant or near constant operation (such as the large conveyors in the mining plant in the above figure) greatly benefit from power factor correction.

Three-Phase Transformer Configurations



Discussion outline

Learning outcomes

- Know how to correct the power factor of an industrial application whose reactive power demand is either fixed or variable.
- Be familiar with the two main types of power factor correction: plant-wide and distributed.
- Be familiar with the power factor correction of three-phase circuits.

The Discussion of this exercise covers the following points:

- Correcting the power factor of an industrial application
- Using banks of switched capacitors for variable power factor correction
- Types of power factor correction: plant-wide versus distributed
- Power factor correction in three-phase circuits

Correcting the power factor of an industrial application

As mentioned in the Introduction of this course, an industrial application with a low power factor has detrimental effects on the power transmission and distribution system of the electricity provider, as well as on the industrial application itself.

The main detrimental effects are listed here.

- The intensity of the current flowing in the distribution lines supplying electric power to the industrial application increases. This requires the electricity provider to increase the size of the distribution lines bringing power to the application, and possibly the size of other equipment (transmission lines, power transformers, etc.) upstream in the ac power network, to supply the required power to the industrial application.
- The amount of copper losses ($R I^2$ losses) in the distribution lines, as well as in the equipment (transmission lines, transformers, etc.) upstream in the ac power network, also increases.
- The voltage at the main power bus of the industrial application decreases.
- The amount of active power supplied to the industrial application decreases.

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To illustrate these effects, consider the circuit in Figure 4 which represents one phase of the distribution system of an electricity provider that supplies power to an industrial application. The resistor and the inductor connected in series with the power source in the distribution system represent the combined resistance and inductive reactance of the distribution lines and other equipment in the distribution system. In this example, the industrial application is a purely resistive load (represented by a resistor), which means that it draws no reactive power, only active power. The power factor of the industrial application is thus equal to 1.000.

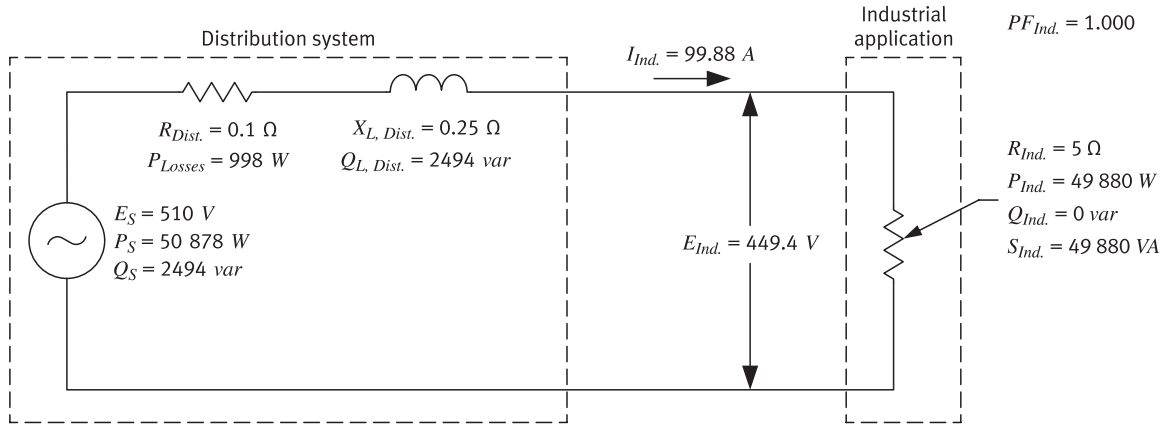


Figure 4: Distribution system supplying active power to an industrial application with a power factor of 1 (one phase shown).

As Figure 4 shows, the intensity of the current $I_{Ind.}$ flowing in the distribution lines supplying power to the industrial application is equal to 99.88 A, the amount of active power $P_{Ind.}$ supplied to the industrial application is 49 880 W, and the amount of power losses P_{Losses} in the distribution system is equal to 998 W. The circuit also shows that the voltage $E_{Ind.}$ at the main power bus of the industrial application is slightly lower than the distribution system source voltage E_S (499.4 V in comparison to 510 V).

Now consider the circuit in Figure 5, which represents the same distribution system as in Figure 4, but this time supplying power to an industrial application drawing as much reactive power as active power (represented by a resistor and an inductor connected in parallel).

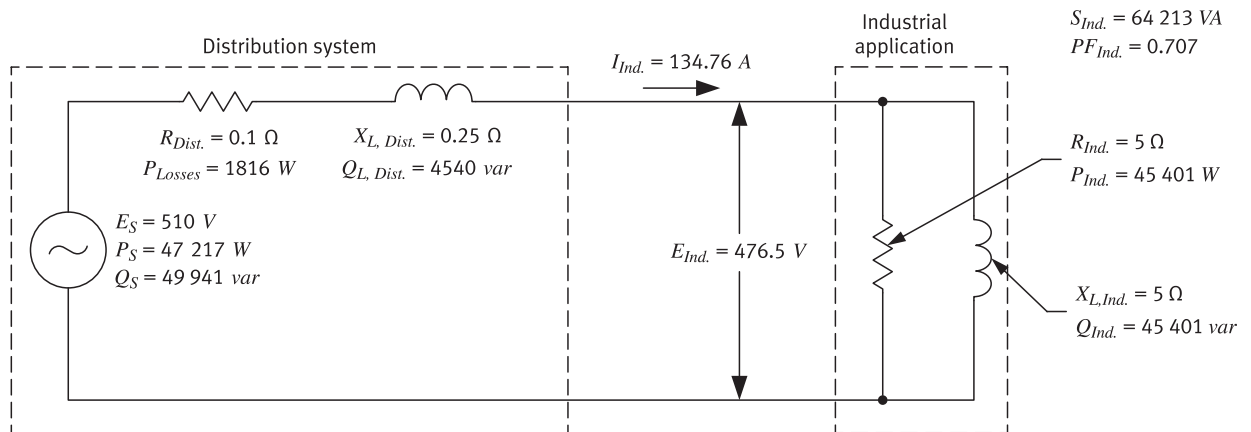


Figure 5: Distribution system supplying active power and reactive power to an industrial application with a power factor of 0.707 (one phase shown).

As Figure 5 shows, the reactive power $Q_{Ind.}$ (45 401 var) which the industrial application draws from the distribution system causes the apparent power $S_{Ind.}$ supplied to the application to increase significantly (from 49 880 VA to 64 213 VA). This, in turn, makes the intensity of the current $I_{Ind.}$ flowing in the distribution lines supplying power to the industrial application pass from 99.88 A to 134.76 A (an increase of 34.9%). The increase of current $I_{Ind.}$ causes the amount of power losses P_{Losses} in the distribution system to almost double (they pass from 998 W to 1816 W). The increase of current $I_{Ind.}$ also causes the voltage $E_{Ind.}$ at the main power bus of the industrial application to pass from 499.4 V to 476.5 V (a decrease of 4.5%) which, in turn, makes the amount of active power $P_{Ind.}$ supplied to the industrial application decrease slightly (from 49 880 W to 45 401 W). Finally, this results in a significant decrease (from 1.000 to 0.707) of the power factor $PF_{Ind.}$ of the industrial application.

The values of the various parameters in the above example show all the detrimental effects listed at the beginning of this section caused by an industrial application with a low power factor. These undesirable effects can be negated by implementing power factor correction (PFC). This can be done by adding a source of reactive power at the main bus of the industrial application in order to supply the reactive power required by the inductive loads in the application. This source of reactive power generally consists of one or more capacitors connected in parallel to the main power bus of the industrial application, as shown in Figure 6.

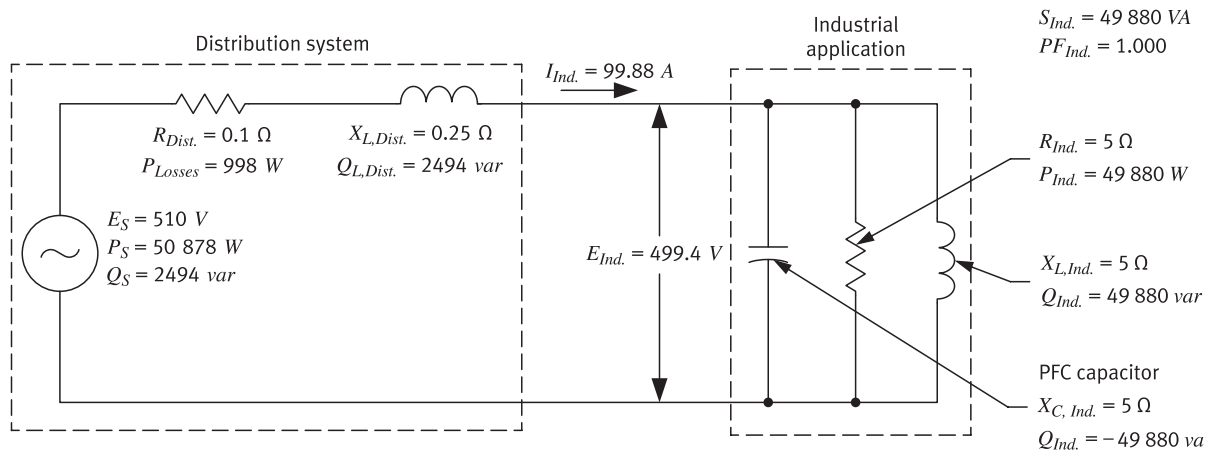


Figure 6: Distribution system supplying active power to an industrial application whose power factor of 0.707 is corrected to 1.000 using a capacitor connected in parallel at the main power bus of the application (one phase shown).

Figure 6 shows that all the reactive power absorbed by the inductive load of the industrial application (49 880 var) is supplied by the power factor correction (PFC) capacitor, which means that the application does not draw any reactive power from the distribution system. Because of this, the net power factor measured at the main power bus of the industrial application is equal to 1.000, just as when the industrial application is purely resistive as shown in Figure 4. Similarly, the values of all other parameters of the industrial application in the circuit of Figure 6 are equal to those calculated in the circuit of Figure 4. This means that an industrial application containing both resistive and inductive loads whose power factor is corrected to 1.000 operates exactly like an ideal industrial application that only contains purely resistive loads.

Using banks of switched capacitors for variable power factor correction

Figure 6 showed an example of power factor correction in which the inductive load of the industrial application is fixed. In this case, the reactance of the capacitor required to correct the power factor of the industrial application is equal to the reactance of the inductive load in the application. However, in most cases, the inductive reactance of the load in an industrial application varies continuously. For example, this happens when motors, mills, compressors, or arc furnaces are turned on or off. Consequently, the resulting reactive power demand variation can be great or small, rapid or slow, predictable or unpredictable, depending on the type of application.

Correcting the power factor in an industrial application whose reactive power demand varies over time thus requires a capacitor whose reactance is variable. However, high-voltage, high-power variable capacitors are not available commercially. As a substitute, a bank of switched capacitors of different capacitance values is connected in parallel with the variable inductive load in the industrial application, as shown in Figure 7.

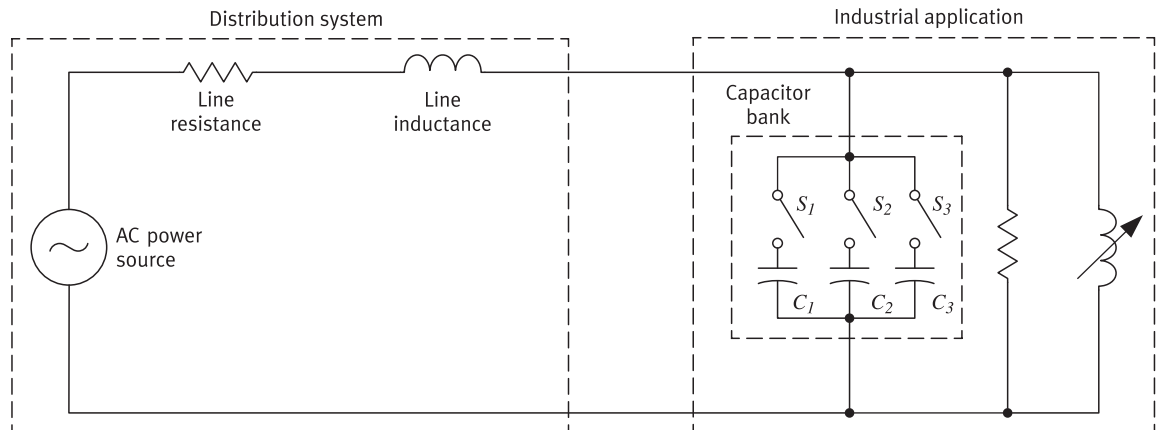


Figure 7: A bank of switched capacitors of different capacitance values allows the power factor of an industrial application to be corrected even when the inductive reactance of the load varies (single-phase diagram shown).

Depending on the current reactive power demand of the industrial application, capacitors are switched in or out to meet the reactive power demand of the application as closely as possible and maintain the power factor as close as possible to unity. For example, if the reactive power demand of the industrial application is equal to 25 kvar, capacitors are switched on or off so that the amount of reactive power supplied by the capacitors is as close as possible to 25 kvar. This ensures that most of the reactive power required by the industrial application is supplied by the power factor correction capacitors and that virtually no reactive power is supplied by the distribution system. Consequently, the power factor of the industrial application as seen from the distribution system seems to be very close to unity.



Figure 8: Bank of capacitors used for power factor correction.

Types of power factor correction: plant-wide versus distributed

There are two primary types of power factor correction, differentiated by the location of the capacitors in the industrial application: **plant-wide power factor correction** and **distributed power factor correction**. Both types of power factor correction are covered in the following subsections.

Plant-wide power factor correction

In plant-wide power factor correction, the switched-capacitor bank is connected in parallel to the main power bus of the industrial application, as shown in Figure 9. In the industrial application of Figure 9, the reactive power demand of the application is due to several resistive-inductive loads representing different devices such as motors and power transformers. Each load can be switched in or out using switches S_{M1} , S_{M2} , and S_{M3} .

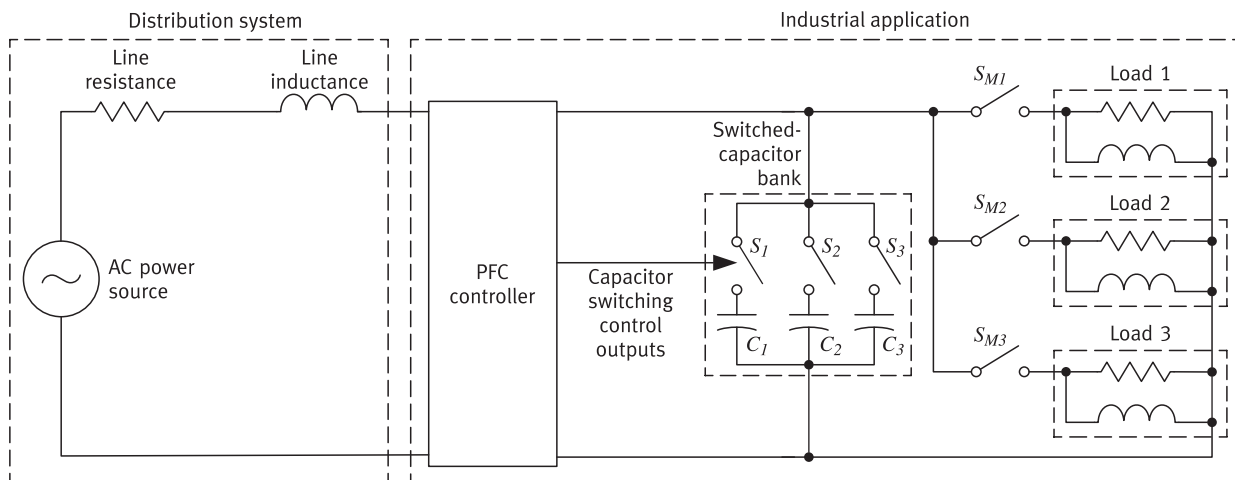


Figure 9: In plant-wide power factor correction, the switched-capacitor bank is connected in parallel to the main power bus of the industrial application (single-phase diagram shown).

When using plant-wide power factor correction, the switched-capacitor bank needs to be sized so that it can supply enough reactive power to meet the maximal reactive power demand occurring when all resistive-inductive loads in the industrial application are switched in. Furthermore, the capacitance values of the various capacitors in the bank must be carefully selected so as to allow any intermediate value of reactive power demand (occurring when not all resistive-inductive loads are switched in) to be met closely. Since the total inductive load in an entire industrial application can vary often and rapidly, plant-wide power factor correction is generally achieved using a power factor correction controller. This controller constantly monitors the reactive power demand of the industrial application and switches capacitors in and out in order to supply the proper amount of reactive power required. Such a controller enables the power factor of the industrial application to be maintained as close as possible to unity despite important variations in the reactive power demand. The controller also ensures that the power factor transients that occur during sudden variations of the reactive power demand are kept as short and unnoticeable as possible.

Distributed power factor correction

In distributed power factor correction, the capacitors are connected in parallel to each significant resistive-inductive load in the industrial application, as shown in Figure 10. Typically, a single fixed capacitor is used to supply reactive power to each load requiring power factor correction.

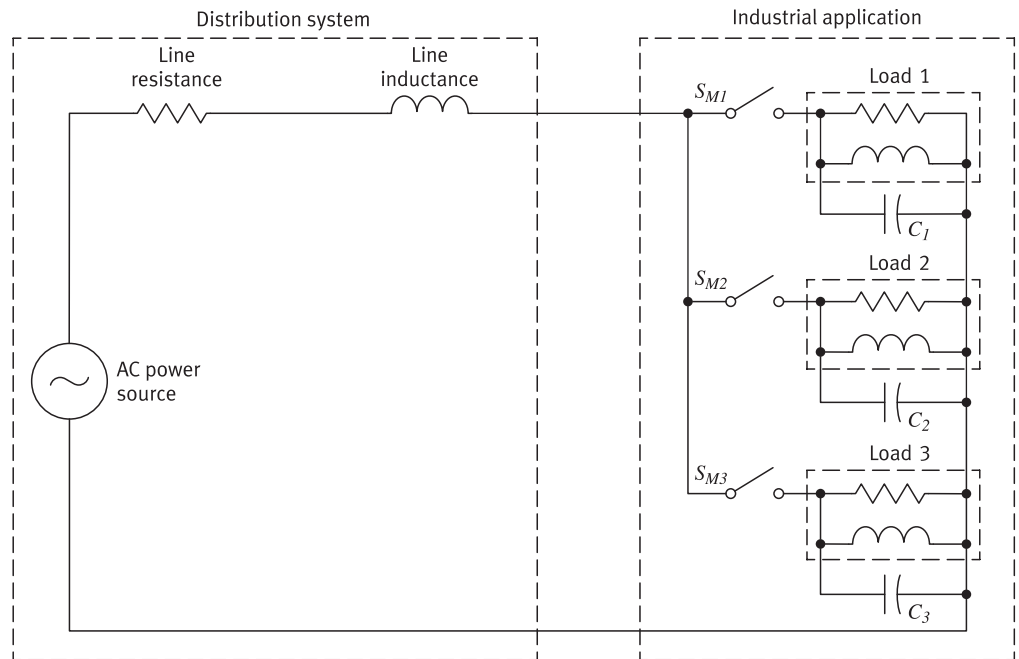


Figure 10: In distributed power factor correction, a capacitor is connected in parallel with each significant resistive-inductive load in the industrial application (single-phase diagram shown).

When using distributed power factor correction, each capacitor needs to be sized so that it supplies the exact amount of reactive power required by the inductive load to which it is connected. This type of power factor correction can only be used when the reactive power demand of each inductive load does not vary much over time. Because of this, distributed power factor correction is especially suited for induction motors, whose reactive power demand is almost constant no matter the mechanical load applied to the motor.



An induction motor can be represented by a variable resistor in parallel with a fixed inductor, as shown below. The resistance decreases when the mechanical load applied to the motor increases but the inductive reactance varies very little.

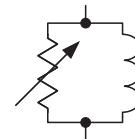


Figure 11: Equivalent electrical representation of an induction motor.

In distributed power factor correction, the capacitor connected to any given load is switched in or out at the same time as the load. This way, as soon as the load is

switched in and begins drawing reactive power, the capacitor is also switched in and begins supplying reactive power. This ensures that the power factor of each resistive-inductive load is individually corrected at all times.



Figure 12: Any induction motor driving a large load such as the ball mill shown above requires a substantial amount of reactive power to operate. Using distributed power factor correction prevents the large reactive power requirement of the motor from affecting the power factor of the industrial application.

Power factor correction comparison: plant-wide versus distributed

Both types of power factor correction described above present advantages that can be more appropriate for certain types of industrial applications than others. Plant-wide power factor correction is usually cheaper than distributed power factor correction because it requires a smaller number of capacitors to achieve a similar level of power factor correction. Plant-wide power factor correction also ensures that the power factor of the whole industrial application is corrected whereas distributed power factor correction corrects the power factor of each individual load, which does not necessarily ensure that the power factor of the whole industrial application is corrected.

On the other hand, distributed power factor correction dispenses with the need for a power factor correction controller, as the capacitors are switched in or out at the same time as the load to which they are connected. Another advantage of distributed power factor correction is that it compensates the reactive power demand directly at each load, thus reducing the intensity of the current flowing through the lines and equipment (e.g., power transformers, contactors, protective devices) in the industrial application that convey power to the loads. This, in turn, allows either reduction of the size and rating of the power lines and equipment in the industrial application or reduction of the heat that they produce due to power losses (RI^2 losses). When the load is located relatively far away from the main power bus of the industrial application, the reduction of the power losses in the internal power lines of the application can represent significant power savings.

The advantages of each type of power factor correction over the other are summarized in Table 1.

Table 1: Advantages of plant-wide power factor correction and distributed power-factor correction in comparison to each other.

Plant-wide power factor correction	Distributed power factor correction
Usually cheaper due to the lower number of capacitors required to achieve a similar level of power factor correction	No need for a power factor correction controller, as the capacitors are switched in or out at the same time as the load to which they are connected
Ensures that the power factor of the whole industrial application is corrected	Reduction of the size and rating of the lines and equipment in the industrial application that supply power to the loads or reduction of the heat produced due to power losses (RI^2 losses) in these lines and equipment

Power factor correction in three-phase circuits

To ease understanding of the principles of power factor correction, all circuit diagrams you have studied so far in this course are single-phase circuits. In industrial applications, however, power factor correction is usually implemented in three-phase circuits. This is because most industrial applications contain resistive and inductive loads that operate with three-phase power.

The principles behind power factor correction in three-phase circuits are identical to those behind power factor correction in single-phase circuits. The only difference is that any capacitor used for power factor correction in one phase must be replicated in the other two phases to ensure equal (i.e., balanced) power factor correction in all three phases. This is illustrated in this figure. In this example, the bank of switched-capacitors used to implement power factor correction consists of two groups of three capacitors connected in delta. Each group of capacitors can be connected in parallel with the three-phase load through a three-phase switch (S_1 and S_2 in this figure).

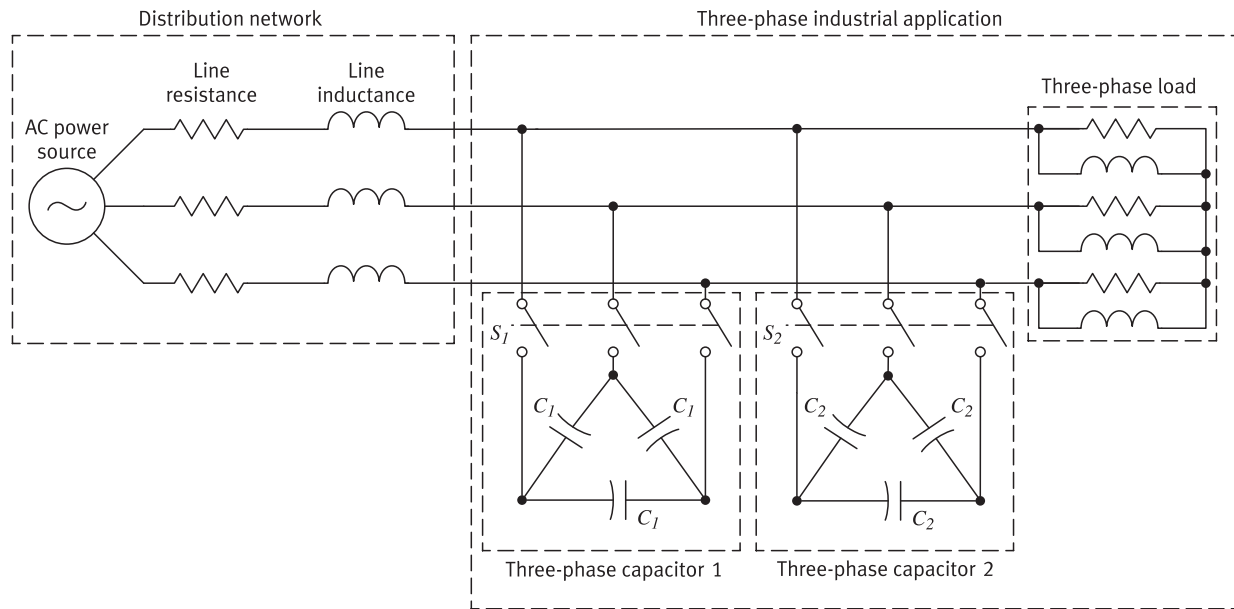


Figure 13: Power factor correction in a three-phase industrial application using a three-phase switched-capacitor bank.

As this figure shows, each group of three capacitors in the switched-capacitor bank is connected in a delta configuration. This is because using capacitors connected in delta configuration for power factor correction presents advantages over capacitors connected in wye (star) configuration. The first advantage of using delta-connected capacitors instead of wye-connected capacitors is that the power factor correction is less unbalanced when one of the capacitors in a group fails and becomes open. Consequently, this limits the amount of voltage imbalance resulting from unbalanced power factor correction caused by a failure of one of the capacitors in a group. Another advantage of the delta configuration over the wye configuration is that it prevents third-harmonic currents from flowing through the capacitors. Third-harmonic currents are undesirable since they can cause problems in the power system.





Figure 14: Example of a power factor correction unit used for plant-wide power factor correction. Notice the bank of capacitors located at the bottom of the unit.

Procedure outline

The Procedure is divided into the following sections:

- Setup and connections
- Industrial application containing a purely resistive load
- Industrial application containing resistive and inductive loads
- Plant-wide power factor correction
- Distributed power factor correction applied to a three-phase industrial application

	 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 section, you will set up the equipment required to study power factor correction of an industrial application containing resistive and inductive loads.

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

Install the required 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, 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, then connect its Power Input to an ac power outlet.

Connect the Power Input of the Data Acquisition and Control Interface to a 24 V ac power supply. 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, then set the Operating Mode switch to Dynamometer. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

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

In the LVDAC-EMS Start-Up window, make sure the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure the Computer-Based Instrumentation function is available for the Data Acquisition and Control Interface. 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. Connect the equipment as shown in Figure 15. Use a single phase of the Power Supply to implement the ac power source. Use one resistor bank in the Resistive Load to implement each of the two load resistors ($R_{\text{Ind.1}}$ and $R_{\text{Ind.3}}$) in the circuit, and use one inductor bank in the Inductive Load to implement each of the two load inductors $X_{\text{L,ind.2}}$ and $X_{\text{L,ind.3}}$. In the circuit of Figure 15, the ac power source represents one phase of the distribution system of the electricity provider. Load 1, Load 2, and Load 3 represent the different resistive and inductive loads in an industrial application that are connected to this phase of the distribution system. Load 1 is a fixed resistive load that represents purely

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resistive devices in the application, such as the heating and lighting systems. Load 2 represents loads in the industrial application that draw reactive power for the most part (e.g., power transformers that are very lightly loaded). Load 3 represents loads in the application that draw both active power and reactive power, such as induction motors.

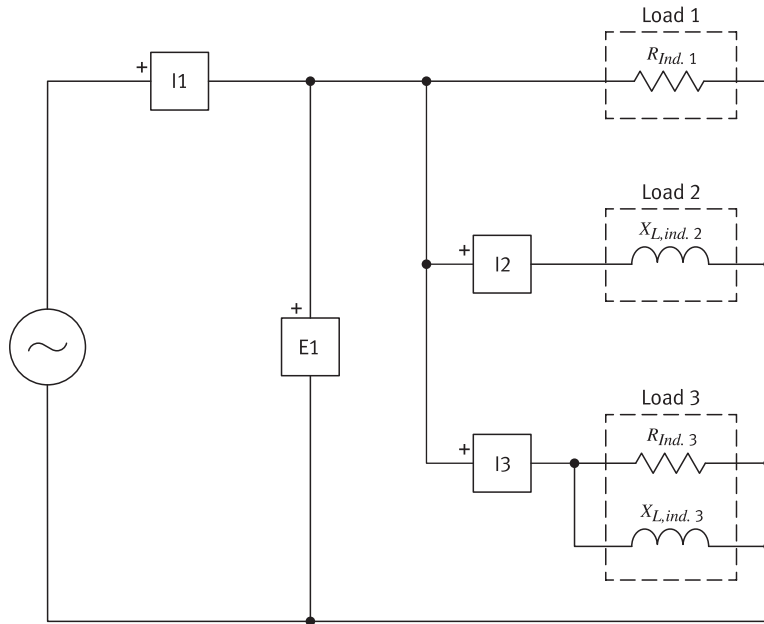


Figure 15: AC power source supplying power to an industrial application containing resistive and inductive loads.

Table 2: Resistance and reactance values to be used for Loads 1, 2, and 3 of the industrial application.

Local ac power network		Resistance values of the different loads (Ω)		Reactance values of the different loads (Ω)	
Voltage (V)	Frequency (Hz)	$R_{Ind.1}$	$R_{Ind.3}$	$X_{L,ind.2}$	$X_{L,ind.3}$
120	60	171	∞	∞	∞
220	50	629	∞	∞	∞
220	60	629	∞	∞	∞
240	50	686	∞	∞	∞

7. Make the necessary switch settings on the Resistive Load and on the Inductive Load so that load resistances $R_{Ind.1}$ and $R_{Ind.3}$, as well as load reactances $X_{L,ind.2}$ and $X_{L,ind.3}$ of the industrial application, are equal to the values indicated in the table of Figure 15. As you can see, all resistance and reactance

values of Load 2 and Load 3 are set to infinite. In practice, this means that these loads are switched off, leaving only Load 1 in circuit.



The values of resistance, inductive reactance, and capacitive reactance used in the circuits of this course depend on the local ac power network voltage and frequency. Whenever necessary, a table below the circuit diagram indicates the value of each component for ac power network voltages of 120 V, 220 V, and 240 V, and for ac power network frequencies of 50 Hz and 60 Hz. Make sure to use the component values corresponding to the local ac power network voltage and frequency.



Appendix B lists the switch settings required on the Resistive Load, the Inductive Load, and the Capacitive Load to obtain various resistance (or reactance) values.

8. In LVDAC-EMS, open the Metering window. Make the required settings to measure the rms value (ac) of the industrial application voltage $E_{\text{Ind.}}$ (input E1) and current $I_{\text{Ind.}}$ (input I1). Set three meters to measure the active power $P_{\text{Ind.}}$ supplied to the industrial application, the reactive power $Q_{\text{Ind.}}$ which the industrial application exchanges with the distribution system (i.e., the ac power source), and the apparent power $S_{\text{Ind.}}$ delivered to the industrial application. In all three cases, use metering function PQS1 (E1, I1). Finally, set a meter to measure the power factor $PF_{\text{Ind.}}$ of the industrial application [metering function PF (E1, I1)].

Industrial application containing a purely resistive load

In this section, you will turn the ac power source on and measure the different parameters of the industrial application. You will then analyze the measured values and determine if power factor correction is necessary for an industrial application containing a purely resistive load.

9. On the Power Supply, turn the three-phase ac power source on.
10. In the Metering window, measure the values of the industrial application voltage $E_{\text{Ind.}}$, current $I_{\text{Ind.}}$, apparent power $S_{\text{Ind.}}$, active power $P_{\text{Ind.}}$, reactive power $Q_{\text{Ind.}}$, and power factor $PF_{\text{Ind.}}$. Record the values below.

Voltage $E_{\text{Ind.}} = \text{_____ V}$

Current $I_{\text{Ind.}} = \text{_____ A}$

Active power $P_{\text{Ind.}} = \text{_____ W}$

Reactive power $Q_{\text{Ind.}} = \text{_____ var}$

Apparent power $S_{\text{Ind.}} = \text{_____ VA}$

Power factor $PF_{\text{Ind.}} = \text{_____}$

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11. From the values recorded in the previous step, is it necessary to correct the power factor of an industrial application containing only a purely resistive load? Explain briefly.

Industrial application containing resistive and inductive loads

In this section, you will switch in Load 2 of the industrial application and measure the different parameters of the application. You will then analyze the measured values and determine if power factor correction is necessary for an industrial application containing resistive and inductive loads.

12. Make the necessary switch settings on the Inductive Load so that reactance $X_{L,ind.2}$ is equal to the value indicated in Table 3. These switch settings put Load 2 of the industrial application in circuit. Do not modify the other switch settings on the Resistive Load and Inductive Load.

Table 3: Resistance and reactance values to be used for Loads 1, 2, and 3 of the industrial application.

Local ac power network		Load 1	Load 2	Load 3	
Voltage (V)	Frequency (Hz)	$R_{Ind.1}$ (Ω)	$X_{L,ind.2}$ (Ω)	$R_{Ind.3}$ (Ω)	$X_{L,ind.3}$ (Ω)
120	60	171	171	∞	∞
220	50	629	629	∞	∞
220	60	629	629	∞	∞
240	50	686	686	∞	∞

13. In the Metering window, measure the values of the industrial application voltage $E_{Ind.}$, current $I_{Ind.}$, apparent power $S_{Ind.}$, active power $P_{Ind.}$, reactive power $Q_{Ind.}$, and power factor $PF_{Ind.}$. Record the values below.

Voltage $E_{Ind.} = \text{_____ V}$

Current $I_{Ind.} = \text{_____ A}$

Active power $P_{Ind.} = \text{_____ W}$

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Reactive power $Q_{\text{Ind.}} = \text{_____ var}$

Apparent power $S_{\text{Ind.}} = \text{_____ VA}$

Power factor $PF_{\text{Ind.}} = \text{_____}$

14. Compare the values of the industrial application parameters measured in the previous step (resistive-inductive load) to those measured in Step 10 (purely resistive load). What happens when the inductive load is added to the purely resistive load?

15. Is the power factor $PF_{\text{Ind.}}$ of the industrial application recorded in the previous step acceptable? Briefly explain why in relation with the electricity bill of the industrial application.

16. Considering the parameters of the industrial application measured in Step 10 and Step 13, what would happen when the inductive load is switched in if a resistor and an inductor representing the impedance of the distribution system were connected in series with the ac power source? Explain briefly.

17. On the Power Supply, turn the three-phase ac power source off.
18. On the 3AC 400V/DC 230V Power Supply, turn the three-phase ac power source off by setting circuit breaker/switch -F1 to the O (off) position.

Plant-wide power factor correction

In this section, you will connect a capacitor in parallel with the loads of the industrial application to implement plant-wide power factor correction. You will turn the ac power source on and adjust the reactance of the capacitor so that the power factor of the industrial application is as close as possible to unity. You will measure the different parameters of the industrial application. You will then analyze the results by comparing the parameters measured when the power factor of the application is compensated to those measured when the power factor of the application is not compensated (recorded in the previous section).

19. Modify the equipment connections to obtain the circuit shown in Figure 16. Note that, in the circuit, a capacitor is added and connected in parallel with the loads of the industrial application. Connect the three capacitor banks of the Capacitive Load in parallel to implement this capacitor. Also, an additional current input is connected in series with the capacitor to allow measurement of the amount of reactive power it supplies. All other circuit connections remain the same.

As you can see from the equipment setup, the power factor of the industrial application is corrected using plant-wide power factor correction (i.e., a single switched-capacitor bank is used to correct the power factor of the whole industrial application).

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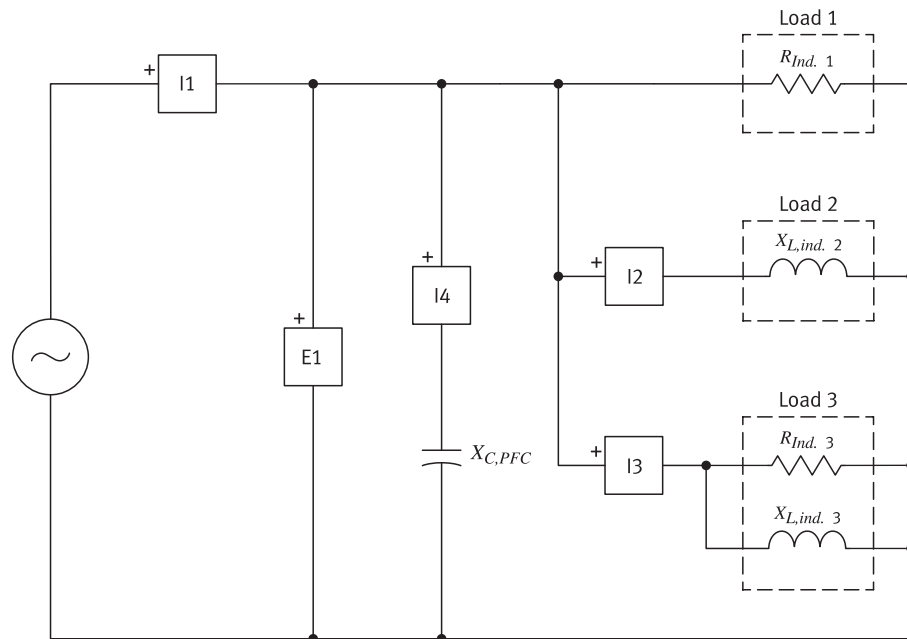


Figure 16: AC power source supplying power to an industrial application containing resistive and inductive loads with power factor correction.

Table 4: Resistance and reactance values to be used for Loads 1, 2, and 3 of the industrial application.

Local ac power network		Resistance values of the different loads (Ω)		Reactance values of the different loads (Ω)		Reactance of the PFC capacitor (Ω)
Voltage (V)	Frequency (Hz)	$R_{ind. 1}$	$R_{ind. 3}$	$X_{L, ind. 2}$	$X_{L, ind. 3}$	$X_{C, PFC}$
120	60	171	∞	171	∞	∞
220	50	629	∞	629	∞	∞
220	60	629	∞	629	∞	∞
240	50	686	∞	686	∞	∞

20. On the Capacitive Load, make the necessary switch settings so that the reactance $X_{C,PFC}$ of the power factor correction capacitor is infinite (no power factor correction), as indicated in the table of Figure 16this figure.
21. In the Metering window, make the required settings in order to measure the amount of reactive power $Q_{Load 2}$ exchanged by Load 2 [metering function PQS (E1, I2)], the amount of reactive power $Q_{Load 3}$ exchanged by Load 3 [metering function PQS (E1, I3)], and the amount of reactive power $Q_{C, PFC}$

exchanged by the power factor correction capacitor [metering function PQS (E1, I4)].

22. On the Power Supply, turn the three-phase ac power source on.
23. On the Capacitive Load, make the necessary switch settings so that the power factor $PF_{\text{Ind.}}$ of the industrial application indicated in the Metering window is as close as possible to unity.

Record below the reactance $X_{C, \text{PFC}}$ of the capacitor used to correct the power factor of the industrial application when Loads 1 and 2 are switched in.

Reactance $X_{C, \text{PFC}} = \text{_____} \Omega$

Compare the reactance $X_{C, \text{PFC}}$ of the power factor capacitor just recorded to the reactance $X_{L, \text{ind.} 2}$ of Load 2. Are both values equal, as expected in theory?

Yes No

24. In the Metering window, measure the values of the industrial application voltage $E_{\text{Ind.}}$, current $I_{\text{Ind.}}$, apparent power $S_{\text{Ind.}}$, active power $P_{\text{Ind.}}$, reactive power $Q_{\text{Ind.}}$, and power factor $PF_{\text{Ind.}}$. Record the values below.

Voltage $E_{\text{Ind.}} = \text{_____} \text{ V}$

Current $I_{\text{Ind.}} = \text{_____} \text{ A}$

Active power $P_{\text{Ind.}} = \text{_____} \text{ W}$

Reactive power $Q_{\text{Ind.}} = \text{_____} \text{ var}$

Apparent power $S_{\text{Ind.}} = \text{_____} \text{ VA}$

Power factor $PF_{\text{Ind.}} = \text{_____}$

25. Compare the parameters of the industrial application measured in the previous step to those measured in Step 13 to answer the following three questions about the effects that connecting a capacitor in parallel with the main power bus of the application has on power factor correction.

What happens to the amount of reactive power $Q_{\text{Ind.}}$ which the industrial application exchanges with the distribution system and to the amount of apparent power $S_{\text{Ind.}}$ delivered to the industrial application? Explain briefly.

26. What happens to the intensity of the current $I_{\text{Ind.}}$ which the industrial application draws from the distribution system? Explain briefly.

27. What happens to the power factor $PF_{\text{Ind.}}$ of the industrial application? Explain briefly.

28. From the observations you have made so far, explain the effect that bringing the power factor $PF_{\text{Ind.}}$ of the industrial application back to unity has on electricity consumption (i.e., on the electricity bill) of the application.

29. In the Metering window, measure the amount of reactive power $Q_{\text{Load 2}}$ exchanged by Load 2, as well as the amount of reactive power $Q_{\text{C, PFC}}$ exchanged by the power factor correction capacitor. Record the values below.

Reactive power $Q_{\text{Load 2}} = \text{_____ var}$

Reactive power $Q_{\text{C, PFC}} = \text{_____ var}$

What can you conclude from the reactive power values just recorded, considering the amount of reactive power $Q_{\text{Ind.}}$ of the industrial application recorded in Step 24?

30. Make the necessary switch settings on the Resistive Load and Inductive Load so that resistance $R_{\text{Ind. 3}}$ and reactance $X_{L, \text{ind. 3}}$ are equal to the values indicated in the following table. These switch settings put Load 3 of the industrial application in circuit. Do not modify the other switch settings on the Resistive Load and Inductive Load.

Table 5: Resistance and reactance values to be used for Loads 1, 2, and 3 of the industrial application.

Local ac power network		Resistance values of the different loads (Ω)		Reactance values of the different loads (Ω)	
Voltage (V)	Frequency (Hz)	$R_{\text{Ind. 1}}$	$R_{\text{Ind. 3}}$	$X_{L, \text{ind. 2}}$	$X_{L, \text{ind. 3}}$
120	60	171	240	171	171
220	50	629	880	629	629
220	60	629	880	629	629
240	50	686	960	686	686

31. In the Metering window, measure the values of the industrial application voltage $E_{\text{Ind.}}$, current $I_{\text{Ind.}}$, apparent power $S_{\text{Ind.}}$, active power $P_{\text{Ind.}}$, reactive power $Q_{\text{Ind.}}$, and power factor $PF_{\text{Ind.}}$. Record the values below.

Voltage $E_{\text{Ind.}} = \text{_____ V}$

Current $I_{\text{Ind.}} = \text{_____ A}$

Active power $P_{\text{Ind.}} = \text{_____ W}$

Reactive power $Q_{\text{Ind.}} = \text{_____ var}$

Apparent power $S_{\text{Ind.}} = \text{_____ VA}$

Power factor $PF_{\text{Ind.}} = \text{_____}$

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32. Considering the parameters of the industrial application measured in the previous step, is it acceptable to use a fixed capacitor to correct the power factor of an industrial application whose reactive power demand varies significantly (such as when a load is switched in or switched out)? Explain briefly.

33. On the Capacitive Load, make the necessary switch settings so that the power factor $PF_{Ind.}$ of the industrial application indicated in the Metering window is as close as possible to unity.

Record the reactance $X_{C, PFC}$ of the capacitor used to correct the power factor of the industrial application when Loads 1, 2, and 3 are switched in.

Reactance $X_{C, PFC} = \text{_____} \Omega$

Compare the reactance $X_{C, PFC} =$ of the power factor capacitor just recorded to the combined reactance of Load 2 and Load 3. Are both values equal, as expected in theory?

Yes No

34. In the Metering window, measure the values of the industrial application voltage $E_{Ind.}$, current $I_{Ind.}$, apparent power $S_{Ind.}$, active power $P_{Ind.}$, reactive power $Q_{Ind.}$, and power factor $PF_{Ind.}$. Record the values below.

Voltage $E_{Ind.} = \text{_____} V$

Current $I_{Ind.} = \text{_____} A$

Active power $P_{Ind.} = \text{_____} W$

Reactive power $Q_{Ind.} = \text{_____} var$

Apparent power $S_{Ind.} = \text{_____} VA$

Power factor $PF_{Ind.} = \text{_____}$

35. In the Metering window, measure the amount of reactive power $Q_{Load 2}$ exchanged by Load 2, as well as the amount of reactive power $Q_{Load 3}$ exchanged by Load 3. Calculate the total amount of reactive power $Q_{Load, total}$ exchanged by

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the loads. Finally, measure the amount of reactive power $Q_{C, PFC}$ exchanged by the power factor correction capacitor. Record all values below.

Reactive power $Q_{Load 2} = \text{_____ var}$

Reactive power $Q_{Load 3} = \text{_____ var}$

Reactive power $Q_{Load, total} = \text{_____ var}$

Reactive power $Q_{C, PFC} = \text{_____ var}$

36. Is the amount of reactive power $Q_{C, PFC}$ exchanged by the power factor correction capacitor virtually equal to the total amount of reactive power $Q_{Load, total}$, indicating that the capacitor supplies the reactive power required by the loads?

Yes No

37. Do the results obtained and the observations made in this part of the exercise confirm that a switched-capacitor bank and a controller for switching the capacitors in and out can be used to correct the power factor of an industrial application with a variable reactive power demand?

Yes No

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

Distributed power factor correction applied to a three-phase industrial application

In this section, you will setup a circuit consisting of a three-phase ac power source supplying power to a three-phase resistive load and an induction motor coupled to a constant-torque brake. You will connect a three-phase capacitor in parallel with the induction motor to implement distributed power factor correction. You will vary the mechanical load applied to the motor and observe the effect on the distributed power factor correction.

39. Connect the equipment as shown in Figure 17. Use the Power Supply to implement the ac power source. Use the Resistive Load to implement the three-phase resistor and the Capacitive Load to implement the three-phase capacitor. The three-phase resistor represents purely resistive loads in the application, such as the heating and lighting systems, while the three-phase capacitor is used for distributed power factor correction (i.e., to correct the power factor of the three-phase induction motor in the industrial application).

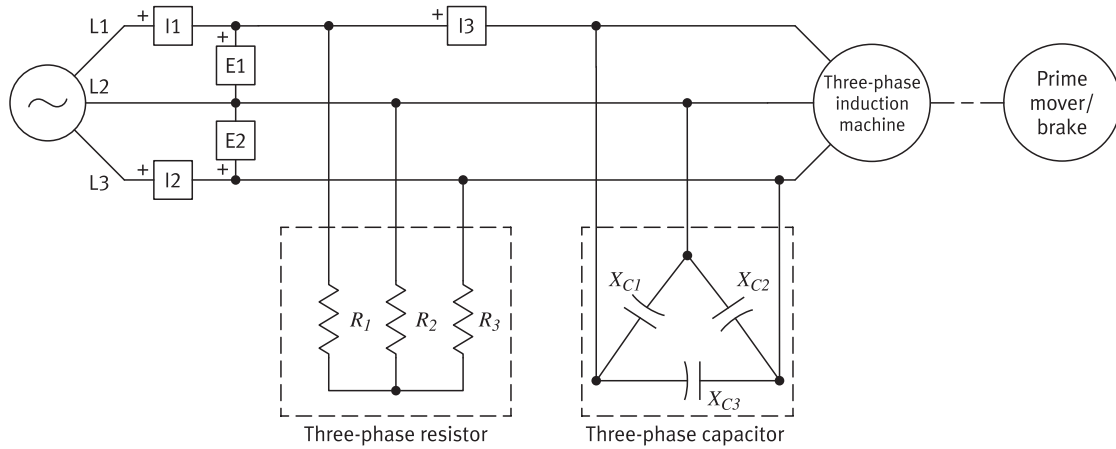


Figure 17: Three-phase ac power source supplying power to an induction motor.

Table 6: Resistance and reactance values to be used in the circuit.

Local ac power network		Resistance of the three-phase resistor	Reactance of the three-phase capacitor
Voltage (V)	Frequency (Hz)	$R_1, R_2, \text{ and } R_3$ (Ω)	$X_{C1}, X_{C2}, \text{ and } X_{C3}$ (Ω)
120	60	240	∞
220	50	880	∞
220	60	880	∞
240	50	960	∞

40. Make the necessary switch settings on the Resistive Load so that the resistance of the three-phase resistor is equal to the value indicated in the table of Figure 17.

Make the necessary switch settings on the Capacitive Load so that the reactance of the three-phase capacitor is infinite (no power factor correction).

41. In the Metering window, make the required settings to measure the rms value (ac) of the industrial application line voltage $E_{Ind.}$ (input E1) and current $I_{Ind.}$ (input I1), as well as the rms value of the induction motor current $I_{Mot.}$ (input I3). Set three meters to measure the active power $P_{Ind.}$ supplied to the industrial application, the reactive power $Q_{Ind.}$ which the industrial application exchanges with the distribution system (i.e., the ac power source), and the apparent power $S_{Ind.}$ delivered to the industrial application. In all three cases, use metering function PQS1 + PQS2. Finally, set a meter to measure the power factor $PF_{Ind.}$ of the industrial application [metering function PF (E1, E2)].

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

- Set the Function parameter to Negative Constant-Torque Prime Mover/ Brake.
- Make sure the Torque Control parameter is set to Knob.
- Set the Torque parameter to 0.00 N·m (0.00 lbf·in).
- Make sure the Pulley Ratio parameter is set to 24:24.
- Set the Thermistor Type parameter to LV Type 2.
- Make sure the Status parameter is set to Stopped.

43. On the Power Supply, turn the three-phase ac power source on to supply power to the three-phase resistive load and the three-phase induction motor.

In the Four-Quadrant Dynamometer/Power Supply window, start the Negative Constant-Torque Prime Mover/Brake.

44. In LVDAC-EMS, open the Data Table window.

Set the Data Table to record the voltage $E_{\text{Ind.}}$, current $I_{\text{Ind.}}$, active power $P_{\text{Ind.}}$, reactive power $Q_{\text{Ind.}}$, apparent power $S_{\text{Ind.}}$, and power factor $PF_{\text{Ind.}}$ of the industrial application, as well as the induction motor current $I_{\text{Mot.}}$ (indicated in the Metering window). Also set the Data Table to record the induction motor torque $T_{\text{Mot.}}$ and the amount of mechanical power P_M produced by the induction motor indicated in the Four-Quadrant Dynamometer/Power Supply window.

Click the Record Data button to record the parameters.

45. In the Four-Quadrant Dynamometer/Power Supply window, vary the Torque parameter from 0.00 N·m (0.00 lbf·in) to -1.20 N·m (-10.6 lbf·in) if the ac power network frequency is 60 Hz, or from 0.00 N·m (0.00 lbf·in) to -1.40 N·m (-12.4 lbf·in) if the ac power network frequency is 50 Hz, in steps of 0.10 N·m (0.89 lbf·in). At each step, wait for the induction motor speed to stabilize, then click the Record Data button in the Data Table to record the parameters.

46. Observe the data recorded in the Data Table. Describe what happens to the amount of reactive power absorbed by the induction motor (which corresponds to the industrial application reactive power $Q_{\text{Ind.}}$) as the mechanical load varies.

Considering your answer to the previous question, would it be possible to correct the power factor of the industrial application using distributed power factor correction (i.e., by connecting a fixed capacitor in parallel with the induction motor)? Explain briefly.

47. In the Data Table window, save the recorded data, then clear the Data Table without modifying the record settings.
48. On the Capacitive Load, make the necessary switch settings to correct the power factor of the three-phase induction motor. In other words, make the necessary switch settings so that the power factor $PF_{\text{Ind.}}$ of the industrial application indicated in the Metering window is as close as possible to unity.

Record the reactance (X_{C1} , X_{C2} , and X_{C3}) of the capacitor used to correct the power factor of the induction motor.

Reactances X_{C1} , X_{C2} , and $X_{C3} = \text{_____ } \Omega$

49. Using the measured voltages $E_{\text{Ind.}}$, calculate the amount of reactive power Q_{PFC} which the three-phase capacitor used for distributed power factor correction supplies.

Three-phase capacitor reactive power $Q_{\text{PFC}} = \text{_____ var}$

Is the calculated value relatively close (within 75 var) to the amount of reactive power which the induction motor absorbs (see data recorded in Step 45)?

Yes No

50. In the Four-Quadrant Dynamometer/Power Supply window, set the Torque parameter to 0.00 N·m (0.00 lbf·in).
51. In the Data Table window, click the Record Data button to record the parameters.
52. In the Four-Quadrant Dynamometer/Power Supply window, vary the Torque parameter from 0.00 N·m (0.00 lbf·in) to -1.20 N·m (-10.6 lbf·in) if the ac power network frequency is 60 Hz, or from 0.00 N·m (0.00 lbf·in) to -1.40 N·m (-12.4 lbf·in) if the ac power network frequency is 50 Hz, in steps of 0.10 N·m (0.89 lbf·in). At each step, wait for the induction motor speed to stabilize, then click the Record Data button in the Data Table to record the parameters.
53. In the Data Table window, save the recorded data.

54. In the Four-Quadrant Dynamometer/Power Supply window, stop the Negative Constant-Torque Prime Mover/Brake.

On the Power Supply, turn the three-phase ac power source off to stop the three-phase induction motor.

Manipulations

55. Using the data just recorded, plot on a same graph the curves of the power factor $PF_{\text{Ind.}}$ of the industrial application as a function of the mechanical power P_M produced by the induction motor, with and without distributed power factor correction.

56. Observe the graph plotted in the previous step. Does the graph show that using distributed power factor correction to correct the power factor of a resistive-inductive load having a virtually fixed reactive power demand (such as the three-phase induction motor) significantly improves the power factor $PF_{\text{Ind.}}$ of the industrial application? Explain briefly.

57. Observe the data recorded in the Data Table at Step 45 and Step 52 (i.e., the data obtained without and with distributed power factor correction at the induction motor, respectively). Compare the intensity of the induction motor current $I_{\text{Mot.}}$ measured without distributed power factor correction to that measured with distributed power factor correction. What can you conclude?

58. Considering your answer to the previous question, what are the effects of using distributed power factor correction on the lines and equipment (e.g., a power transformer, a contactor, a protective device) in an industrial application that conveys power to an induction motor? Explain briefly.

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59. Based on the results obtained in this part of the exercise, can you conclude that distributed power factor correction can be used to correct the power factor of an industrial application containing resistive-inductive loads with a virtually fixed reactive power demand, such as induction motors?

Yes No

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

Review questions

1. What is power factor correction and how is it generally achieved? Explain briefly.

2. What are the four main detrimental effects which operating an industrial application with a low power factor has on the distribution system of the electricity provider and on the industrial application itself?

3. What are the advantages of plant-wide power factor correction over distributed power factor correction?

4. What are the advantages of distributed power factor correction over plant-wide power factor correction?

5. Which type of configuration (wye or delta) is preferable for a three-phase switched-capacitor bank used to implement power factor correction? Briefly explain why.

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Equipment Utilization Chart

The following equipment is required to perform the exercises in this course.

Equipment		Exercise
Model	Description	1
30004-2	24 V AC Power Supply	1
8331	Capacitive Load	1
8951-L	Connection Leads	1
9063-B ⁽¹⁾	Data Acquisition and Control Interface	1
8221-2 ⁽²⁾	Four-Pole Squirrel Cage Induction Motor	1
8960-C ⁽³⁾	Four-Quadrant Dynamometer/Power Supply	1
8321	Inductive Load	1
8823	Power Supply	1
8311 ⁽⁴⁾	Resistive Load	1
8942	Timing Belt	1
8134 ⁽⁵⁾	Workstation	1
<ol style="list-style-type: none"> 1. Model 9063-B consists of the Data Acquisition and Control Interface, Model 9063, with the Computer-Based Instrumentation function set, Model 9069-1. 2. Model 8221-0 can also be used. 3. Model 8960-C consists of the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, with the Standard Functions (manual control) set, Model 8968-1, and the Standard Functions (computer-based control) set, Model 8968-2. 4. Resistive Load unit with voltage rating corresponding to your local ac power network voltage. Use model variant -00, -01, -02, -05, -06, -07, or -0A. 5. The Mobile Workstation, Model 8110, can also be used. 		

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Impedance Table for the Load Modules

The following table gives impedance values which can be obtained using either the Resistive Load, Model 8311, the Inductive Load, Model 8321, or the Capacitive Load, Model 8331. The following figure shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

Table 7: Impedance table for the load modules.

Impedance (Ω)			Position of the switches								
120 V 60 Hz	220/230 V 50/60 Hz	240 V 50 Hz	1	2	3	4	5	6	7	8	9
1200	4400	4800									
600	2200	2400									
300	1100	1200									
400	1467	1600									
240	880	960									
200	733	800									
171	629	686									
150	550	600									
133	489	533									
120	440	480									
109	400	436									
100	367	400									
92	338	369									
86	314	343									
80	293	320									
75	275	300									

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Impedance (Ω)			Position of the switches								
120 V 60 Hz	220/230 V 50/60 Hz	240 V 50 Hz	1	2	3	4	5	6	7	8	9
71	259	282									
67	244	267									
63	232	253									
60	220	240									
57	210	229									

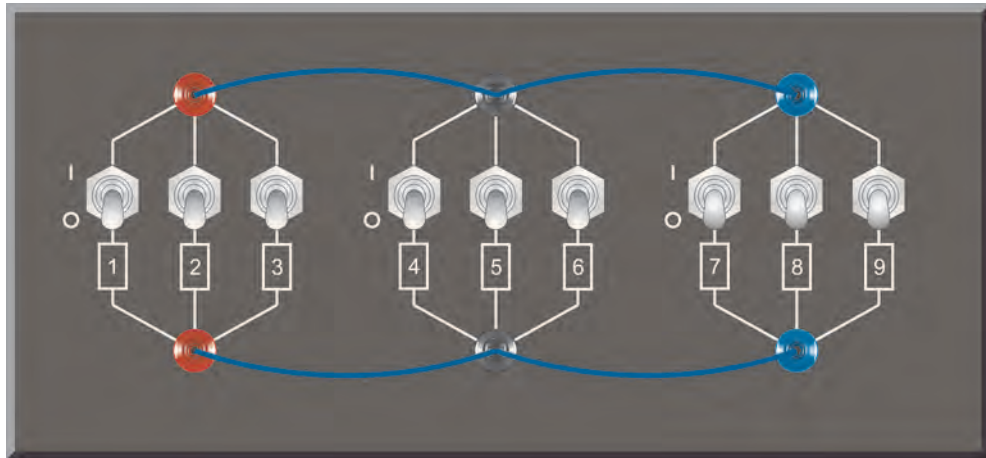


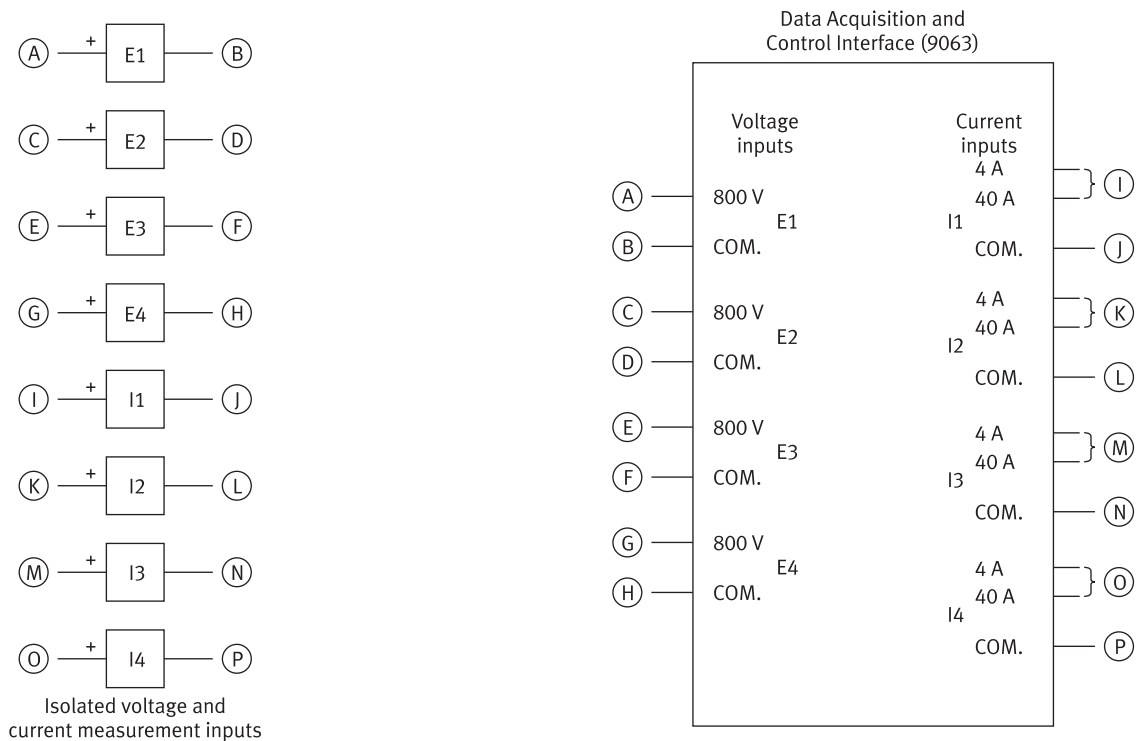
Figure 18: Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

Circuit Diagram Symbols

Symbols and corresponding equipment connections

Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using the equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown in the circuit diagram, and thus, makes it easier to understand the circuit operation.

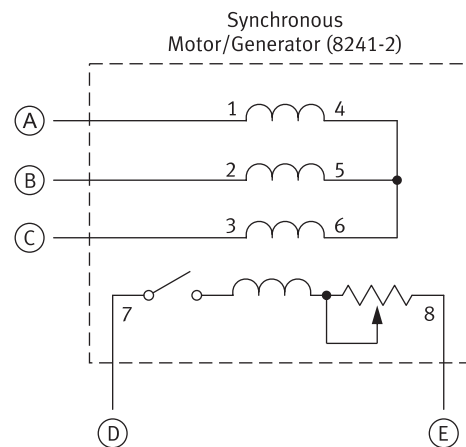
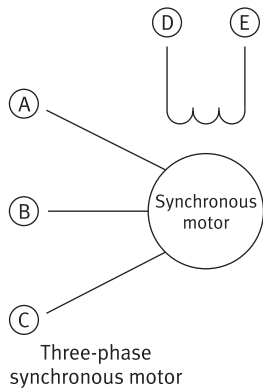
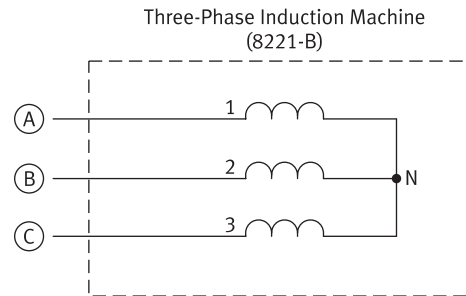
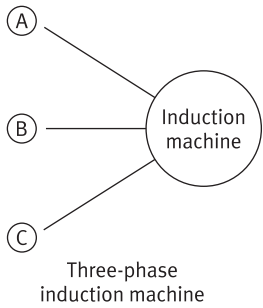
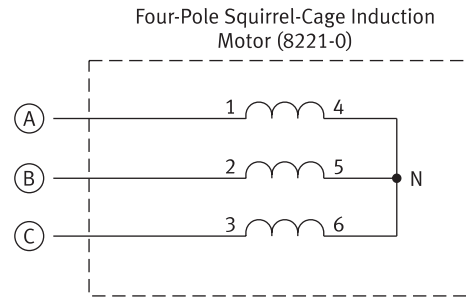
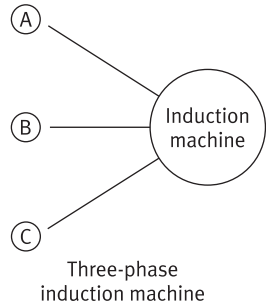
For each symbol other than those of power sources, resistors, inductors, and capacitors, this appendix gives the name of the device which the symbol represents, as well as the equipment and the connections required to properly connect the device to a circuit. Notice that the terminals of each symbol are identified using circled letters. The same circled letters identify the corresponding terminals in the Equipment and Connections diagram. Also notice that the numbers (when present) in the Equipment and Connections diagrams correspond to terminal numbering used on the actual equipment.

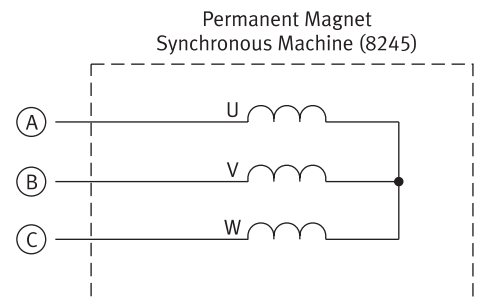
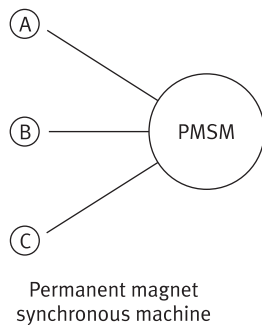
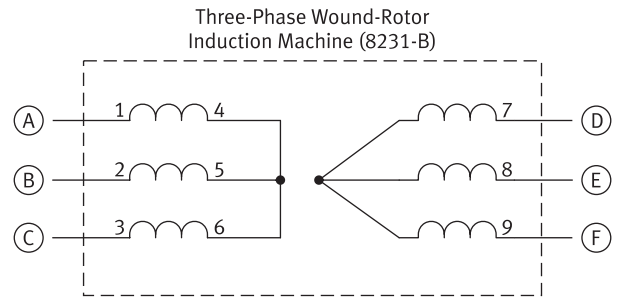
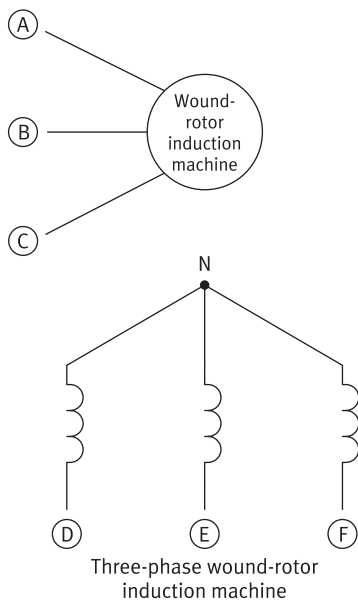
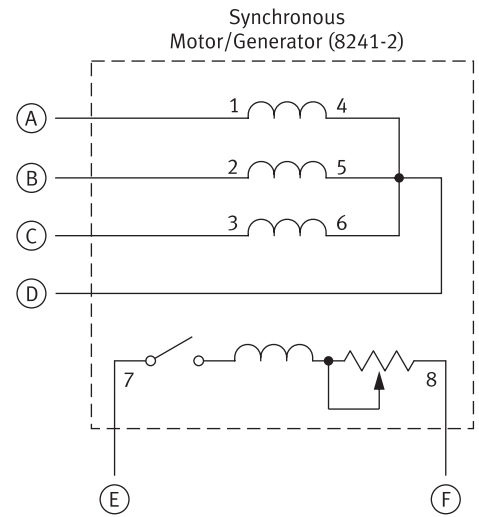
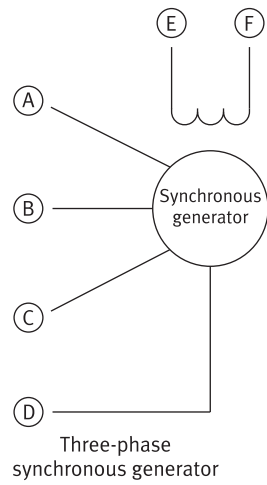


When current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range

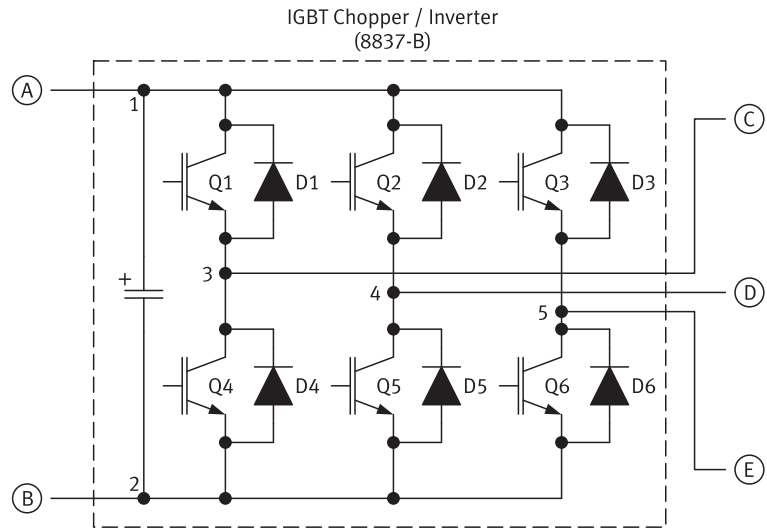
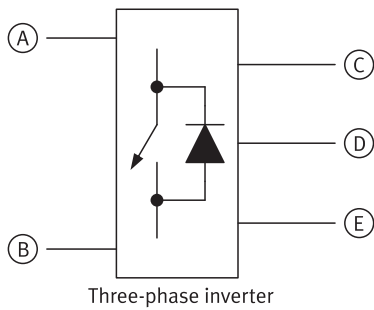
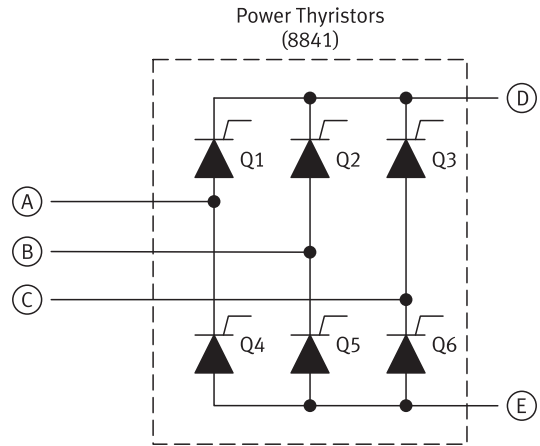
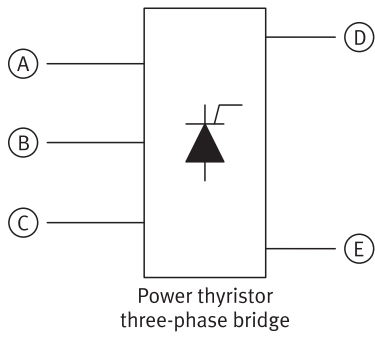
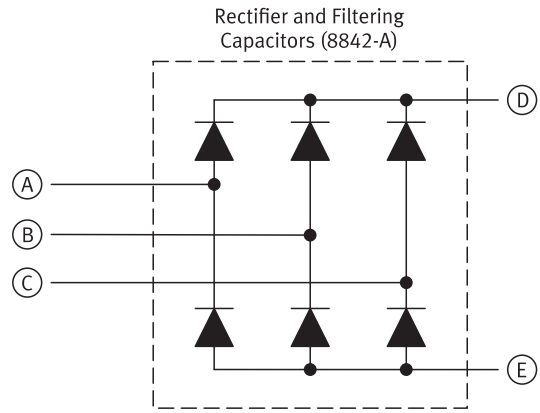
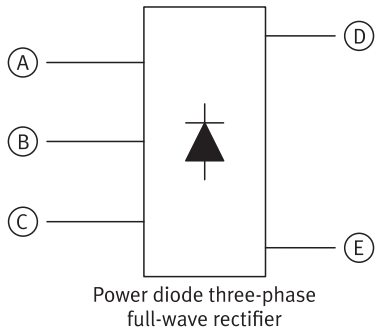
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parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.





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The representation of an electronic power switch used in the three-phase inverter symbol above is neither an IEC symbol nor an ANSI symbol.

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