Electricity and New Energy

Power Factor Correction

Courseware Sample

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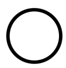
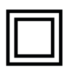
Safety and Common Symbols

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
≂	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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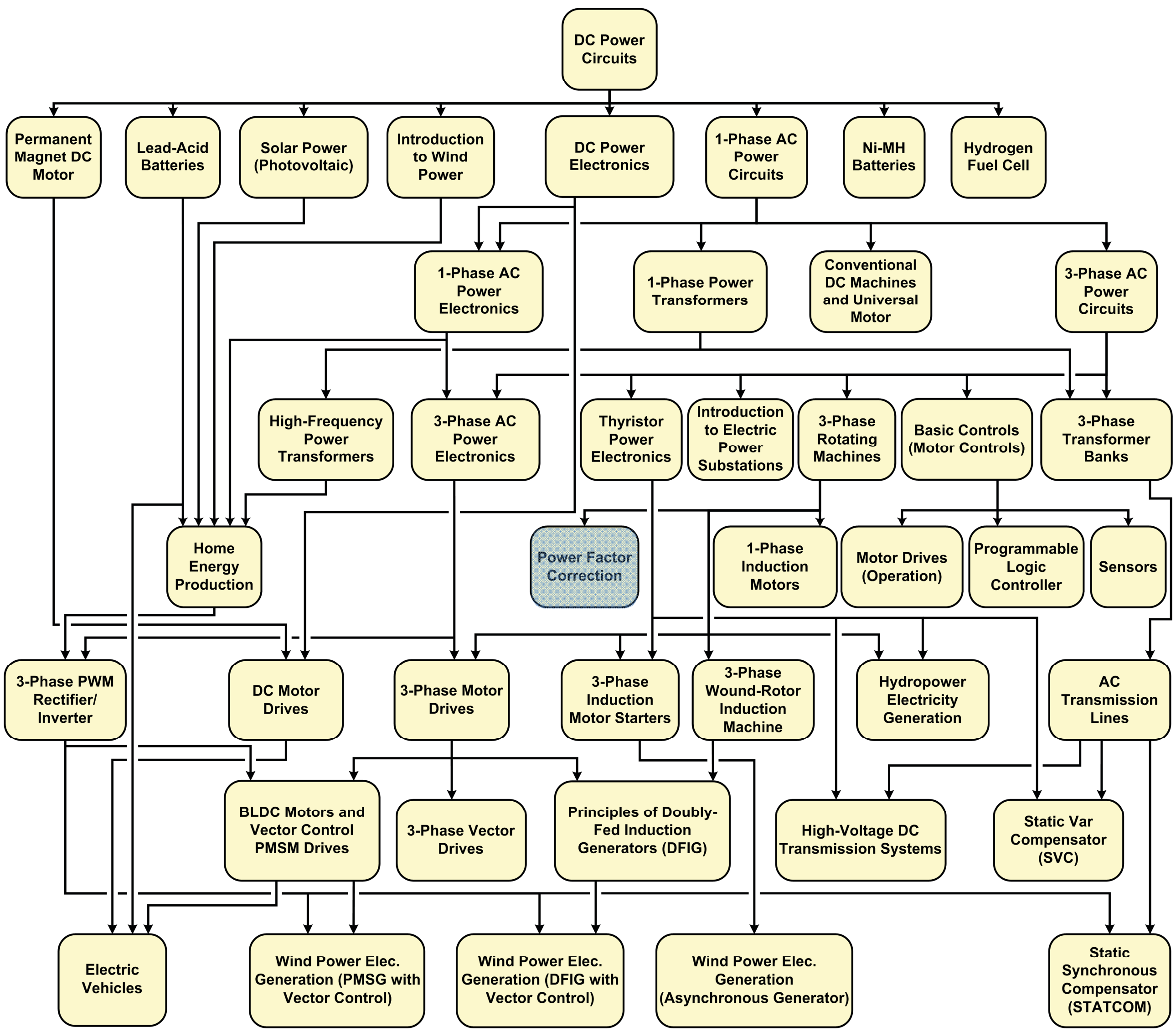
Preface

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

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 manual is then verified by performing various circuit measurements and observations.

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.

About This Manual

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, 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.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

Power Factor Correction

EXERCISE OBJECTIVE

When you have completed this exercise, you will know how to correct the power factor of an industrial application whose reactive power demand is either fixed or variable. You will be introduced to the two main types of power factor correction: plant-wide and distributed. You will be familiar with the power factor correction of three-phase circuits.

DISCUSSION OUTLINE

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
  Plant-wide power factor correction. Distributed power factor correction. Power factor correction comparison: plant-wide versus distributed.
- Power factor correction in three-phase circuits

DISCUSSION

Correcting the power factor of an industrial application

As mentioned in the Introduction to this manual, 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 below:

- The intensity of the current flowing in the distribution lines supplying electric power to the industrial application increases.

- The amount of copper losses (RI^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.

To illustrate these effects, consider the circuit in Figure 2 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.

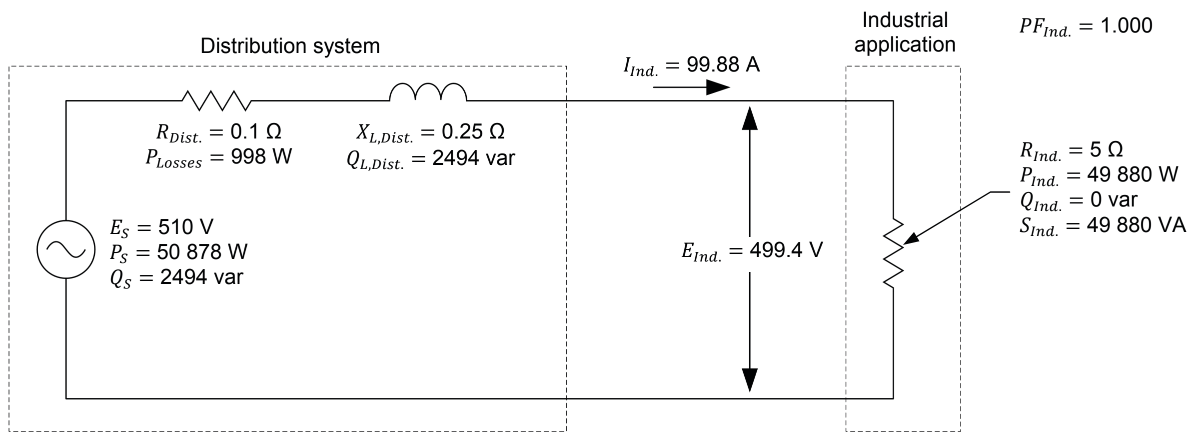


Figure 2. Distribution system supplying active power to an industrial application with a power factor of 1 (one phase shown).

As Figure 2 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 3 representing the same distribution system as in Figure 2, 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).

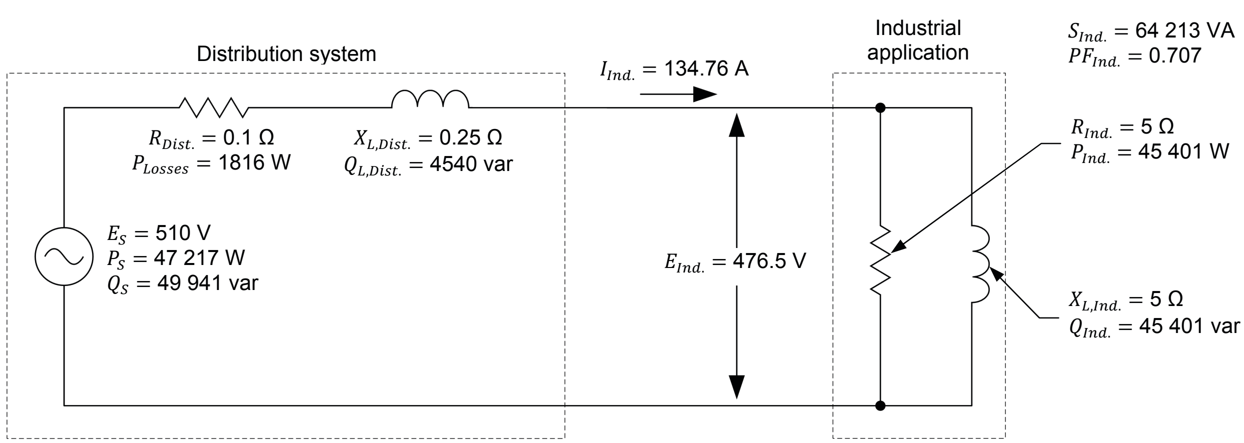


Figure 3. Distribution system supplying active power and reactive power to an industrial application with a power factor of 0.707 (one phase shown).

As Figure 3 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 illustrated in Figure 4.

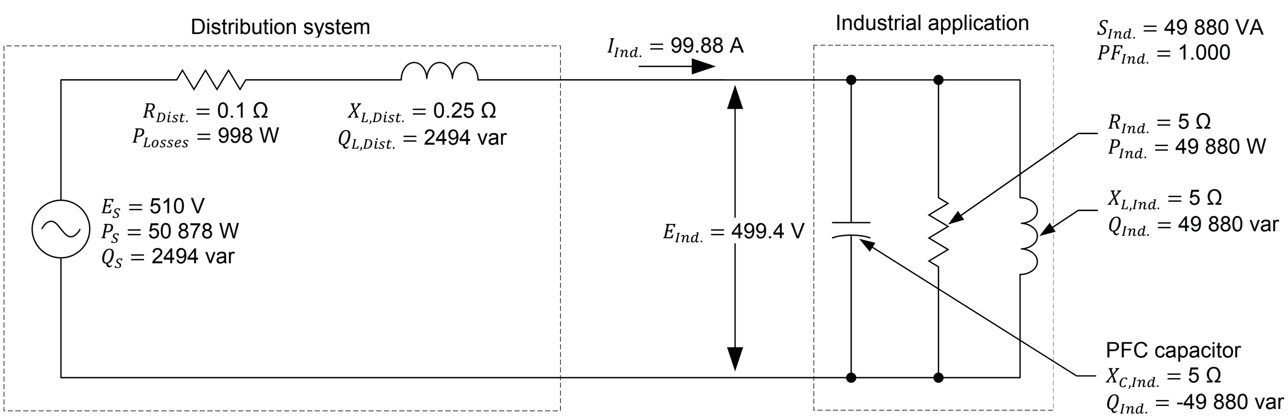


Figure 4. Distribution system supplying active power to an industrial application whose power factor of 0.707 is corrected to 1.000 using a capacitor connected in parallel at the main power bus of the application (one phase shown).

Figure 4 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 2. Similarly, the values of all other parameters of the industrial application in the circuit of Figure 4 are equal to those calculated in the circuit of Figure 2. This means that an industrial application containing both resistive and inductive loads whose power factor is corrected to 1.000 operates exactly as an ideal industrial application that only contains purely resistive loads.

Using banks of switched capacitors for variable power factor correction

Figure 4 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 5.

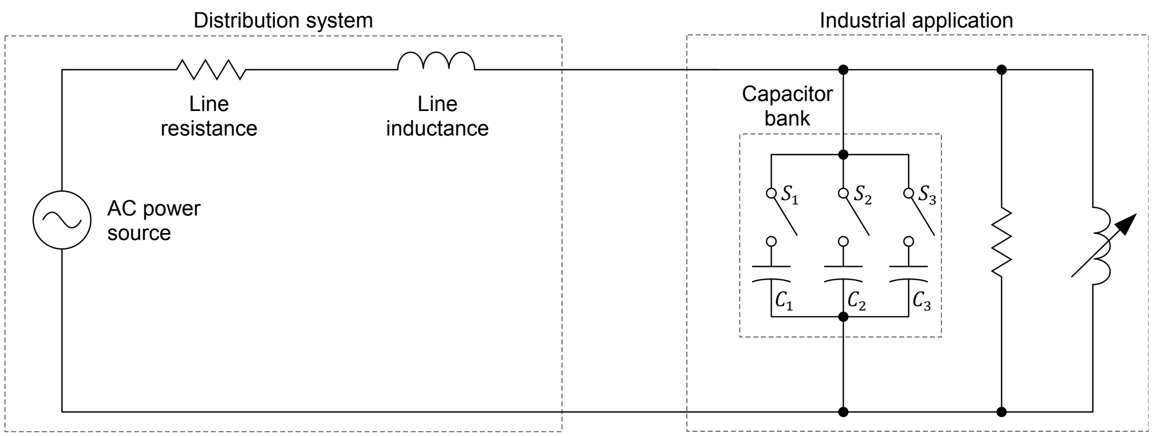


Figure 5. A bank of switched capacitors of different capacitance values allows the power factor of an industrial application to be corrected even when the inductive reactance of the load varies (single-phase diagram shown).

Depending on the current reactive power demand of the industrial application, capacitors are switched in or out in order 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 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 6. 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 7. In the industrial application in Figure 7, 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}.

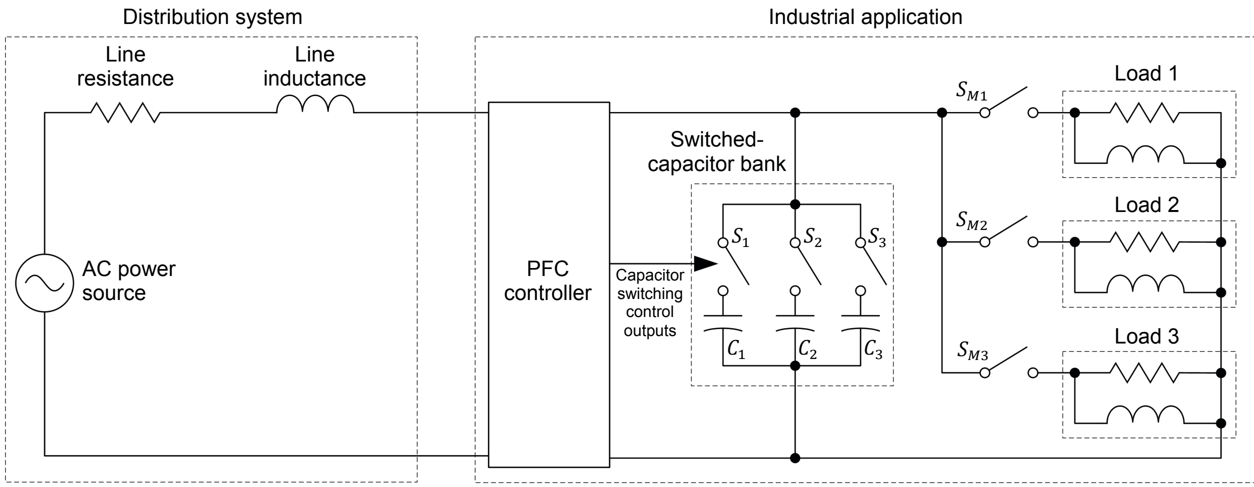


Figure 7. In plant-wide power factor correction, the switched-capacitor bank is connected in parallel to the main power bus of the industrial application (single-phase diagram shown).

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 8. Typically, a single fixed capacitor is used to supply reactive power to each load requiring power factor correction.

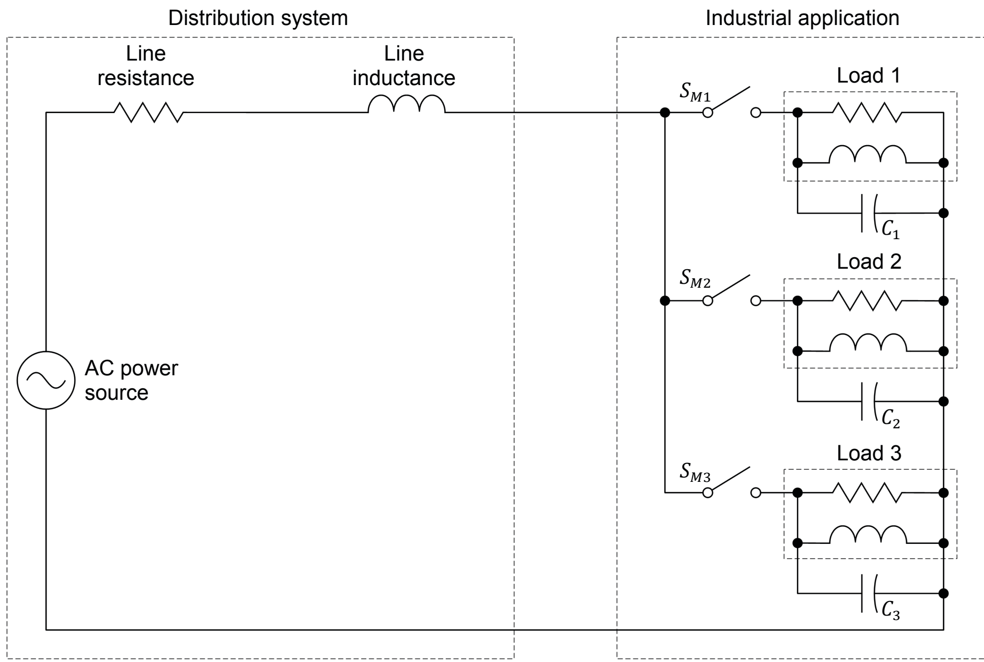


Figure 8. In distributed power factor correction, a capacitor is connected in parallel with each significant resistive-inductive load in the industrial application (single-phase diagram shown).

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 (see sidebar for additional information).

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.

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.

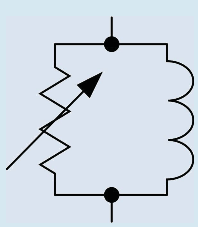


Figure 9. Equivalent electrical representation of an induction motor.

Figure 10. 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 due to the fact that 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 manual 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 Figure 11. 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 Figure 11).

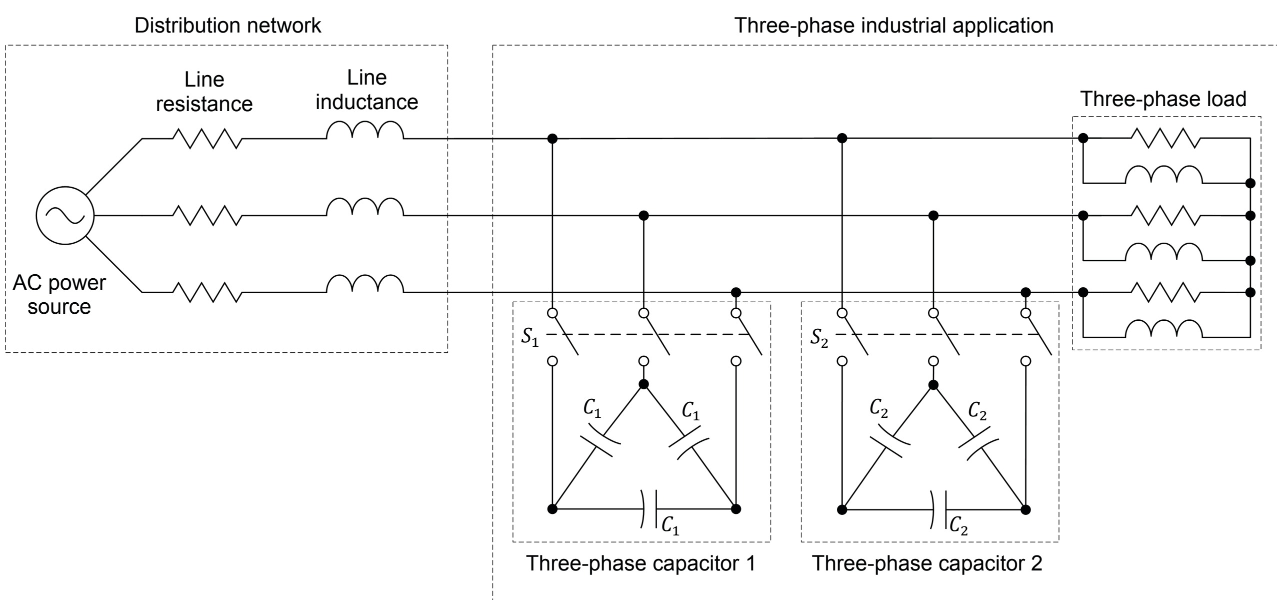


Figure 11. Power factor correction in a three-phase industrial application using a three-phase switched-capacitor bank.

As Figure 11 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 helps reduce the amount of **harmonics** in the power lines feeding the industrial application, thereby making the application friendlier to the power distribution system.

Figure 12. Example of a power factor correction unit used for plant-wide power factor correction. Notice the six capacitors (two per phase) 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

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

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.

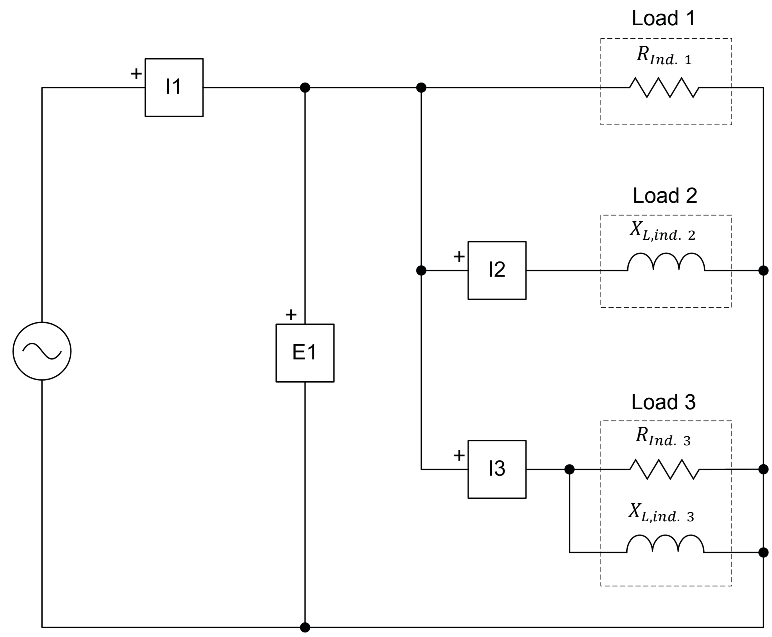
   Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

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 13. 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 ($R_{Ind.\ 1}$ and $R_{Ind.\ 3}$) in the circuit, and use one inductor bank in the Inductive Load to implement each of the two load inductors ($X_{L,ind.\ 2}$ and $X_{L,ind.\ 3}$). In the circuit of Figure 13, 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 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.



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	∞	∞	∞
240	50	686	∞	∞	∞
220	60	629	∞	∞	∞

Figure 13. AC power source supplying power to an industrial application containing resistive and inductive loads.

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 13. 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 manual 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 C lists the switch settings required on the Resistive Load, the Inductive Load, and the Capacitive Load in order to obtain various resistance (or reactance) values.

8. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms value (ac) of the industrial application voltage $E_{Ind.}$ (input *E1*) and current $I_{Ind.}$ (input *I1*). 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 (E1, I1)*. Finally, set a meter to measure the power factor $PF_{Ind.}$ 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 $E_{Ind.}$, 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 $E_{Ind.}$ = _______ V

Current $I_{Ind.}$ = _______ A

Active power $P_{Ind.}$ = _______ W

Reactive power $Q_{Ind.}$ = _______ var

Apparent power $S_{Ind.}$ = _______ VA

Power factor $PF_{Ind.}$ = _______

Voltage $E_{Ind.}$ = 121 V

Current $I_{Ind.}$ = 0.71 A

Active power $P_{Ind.}$ = 86.0 W

Reactive power $Q_{Ind.}$ = 0.02 var

Apparent power $S_{Ind.}$ = 86.0 VA

Power factor $PF_{Ind.}$ = 1.00

11. From the values you 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.

No, it is not necessary to correct the power factor of an industrial application containing only a purely resistive load. This is because the industrial application does not exchange any reactive power with the distribution system (i.e., the ac power source). Therefore, its power factor is always unity, thus rendering power factor correction unnecessary.

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 2. 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 2. 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)	$R_{Ind.\ 1}$	$X_{L,ind.\ 2}$	$R_{Ind.\ 3}$	$X_{L,ind.\ 3}$
120	60	171	171	∞	∞
220	50	629	629	∞	∞
240	50	686	686	∞	∞
220	60	629	629	∞	∞

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 $E_{Ind.}$ = _______ V

Current $I_{Ind.}$ = _______ A

Active power $P_{Ind.}$ = _______ W

Reactive power $Q_{Ind.}$ = _______ var

Apparent power $S_{Ind.}$ = _______ VA

Power factor $PF_{Ind.}$ = _______

Voltage $E_{Ind.}$ = 121 V

Current $I_{Ind.}$ = 1.05 A

Active power $P_{Ind.}$ = 95.3 W

Reactive power $Q_{Ind.}$ = 84.1 var

Apparent power $S_{Ind.}$ = 127 VA

Power factor $PF_{Ind.}$ = 0.75

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

Reactive power $Q_{Ind.}$ is drawn from the distribution system in addition to the active power $P_{Ind.}$ drawn by the purely resistive load. This makes the apparent power $S_{Ind.}$ delivered to the industrial application increase significantly, thereby causing the power factor $PF_{Ind.}$ of the industrial application to decrease significantly. This also causes the current $I_{Ind.}$ which the industrial application draws from the distribution system to increase significantly.

The amount of active power $P_{Ind.}$ drawn by the industrial application increases slightly when the inductive load is added because it is not purely inductive.

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

No, the power factor $PF_{Ind.}$ of the industrial application is not acceptable. This is due to the fact that most electricity providers charge extra costs to industrial customers with a low power factor. Electricity providers consider a power factor of 0.75 to be low, and thus, extra charges would appear on the electricity bill of the industrial application.

16. Considering the parameters of the industrial application that you measured in steps 10 and 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.

If a resistor and an inductor representing the impedance of the distribution system were connected in series with the ac power source, the increase of current $I_{Ind.}$ that occurs when the inductive load is switched in would cause the power losses in the distribution system (i.e., the active power dissipated in the resistor representing the resistance of the distribution system) to increase significantly. Furthermore, the increase of current $I_{Ind.}$ would also cause a significant increase of the voltage drop across the distribution system (i.e., the voltage drop across the resistor and inductor representing the impedance of the distribution system), thereby making the voltage $E_{Ind.}$ at the industrial application decrease slightly. This, in turn, would cause the active power $P_{Ind.}$ supplied to the industrial application to decrease.

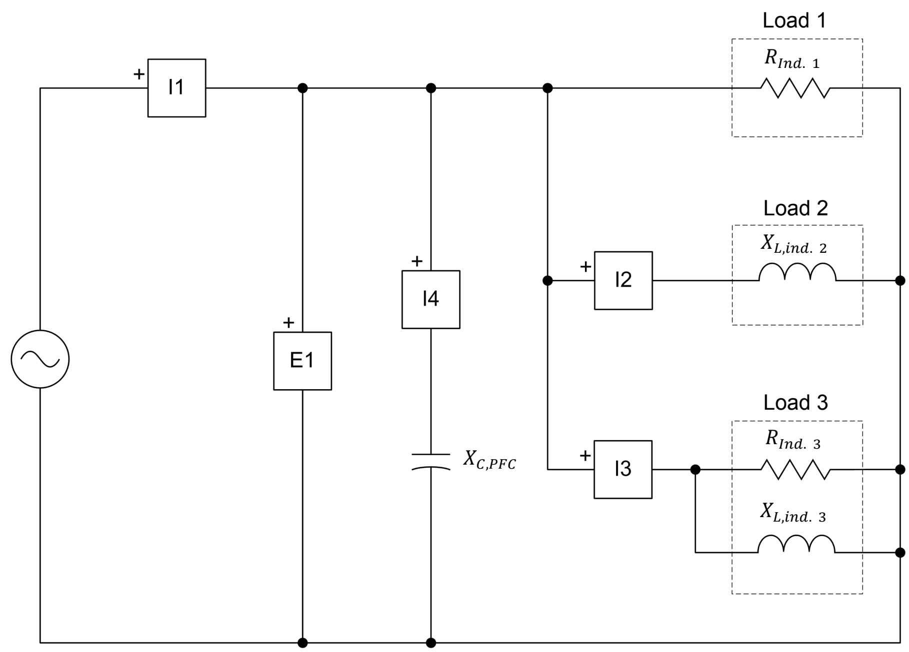
17. On the Power Supply, turn the three-phase ac power source off.

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).

18. Modify the equipment connections to obtain the circuit shown in Figure 14. 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 in order 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).



Local ac power network		Resistance of the different loads (Ω)		Reactance 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	∞	∞
240	50	686	∞	686	∞	∞
220	60	629	∞	629	∞	∞

Figure 14. AC power source supplying power to an industrial application containing resistive and inductive loads with power factor correction.

19. 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 14.

20. 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)*].

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

22. 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 you used to correct the power factor of the industrial application when Loads 1 and 2 are switched in.

Reactance $X_{C,PFC}$ = _______ Ω

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

❑ Yes ❑ No

Reactance $X_{C,PFC}$ = 171 Ω

Yes

23. 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 $E_{Ind.}$ = _______ V

Current $I_{Ind.}$ = _______ A

Active power $P_{Ind.}$ = _______ W

Reactive power $Q_{Ind.}$ = _______ var

Apparent power $S_{Ind.}$ = _______ VA

Power factor $PF_{Ind.}$ = _______

Voltage $E_{Ind.}$ = 122 V

Current $I_{Ind.}$ = 0.80 A

Active power $P_{Ind.}$ = 96.8 W

Reactive power $Q_{Ind.}$ = -2.65 var

Apparent power $S_{Ind.}$ = 97.5 VA

Power factor $PF_{Ind.}$ = 0.99

24. Compare the parameters of the industrial application you 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 to the main power bus of the application has on power factor correction.

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

The amount of reactive power $Q_{Ind.}$ which the industrial application exchanges with the distribution system decreases from 84.1 var to about 0 var. This causes the apparent power $S_{Ind.}$ delivered to the industrial application to decrease substantially (from 127 VA to 97.5 VA). This is because the reactive power absorbed by the industrial application is now supplied by the power factor correction capacitor.

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

The intensity of the current $I_{Ind.}$ which the industrial application draws from the distribution system decreases significantly (from 1.05 A to 0.80 A). This is due to the fact that the distribution system no longer supplies reactive power to the industrial application, thereby reducing the intensity of the current flowing in the lines supplying power to the industrial application.

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

The power factor $PF_{Ind.}$ of the industrial application increases significantly (from 0.75 to virtually unity). This is due to the fact that the distribution system no longer has to exchange reactive power with the industrial application (i.e., the reactive power $Q_{Ind.}$ is virtually 0 var).

25. What is the effect of the observations you just made on the electricity bill of the industrial application? Explain briefly.

The return of the power factor $PF_{Ind.}$ of the industrial application to unity results in a lower electricity bill. This is due to the fact that most electricity providers charge extra costs to industrial customers operating with a low power factor. Therefore, maintaining the power factor at unity eliminates any additional charges related to operation at a low power factor and ensures that the electricity bill of the industrial application is as low as possible (i.e., corresponds only to the amount of active power consumed by the application).

26. 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 $Q_{C,PFC}$ exchanged by the power factor correction capacitor. Record the values below.

Reactive power $Q_{Load\ 2}$ = _______ var

Reactive power $Q_{C,PFC}$ = _______ var

Reactive power $Q_{Load\ 2}$ = 85.1 var

Reactive power $Q_{C,PFC}$ = -88.1 var

What can you conclude from the reactive power values you just recorded, considering the amount of reactive power $Q_{Ind.}$ of the industrial application you recorded in step 23?

The reactive power values recorded above indicate that the reactive power absorbed by Load 2 is supplied by the power factor correction capacitor. This is confirmed by the amount of reactive power $Q_{Ind.}$ of the industrial application which is virtually equal to 0 var. This indicates that the reactive power required by Load 2 is supplied internally by the industrial application.

27. Make the necessary switch settings on the Resistive Load and Inductive Load so that resistance $R_{Ind.\ 3}$ and reactance $X_{L,ind.\ 3}$ are equal to the values indicated in Table 3. 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 3. Resistance and reactance values to be used for Loads 1, 2 and 3 of the industrial application.

Local ac power network		Resistance of the different loads (Ω)		Reactance 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	240	171	171
220	50	629	880	629	629
240	50	686	960	686	686
220	60	629	880	629	629

28. 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 $E_{Ind.}$ = _______ V

Current $I_{Ind.}$ = _______ A

Active power $P_{Ind.}$ = _______ W

Reactive power $Q_{Ind.}$ = _______ var

Apparent power $S_{Ind.}$ = _______ VA

Power factor $PF_{Ind.}$ = _______

Voltage $E_{Ind.}$ = 119 V

Current $I_{Ind.}$ = 1.52 A

Active power $P_{Ind.}$ = 162 W

Reactive power $Q_{Ind.}$ = 80.8 var

Apparent power $S_{Ind.}$ = 182 VA

Power factor $PF_{Ind.}$ = 0.89

29. Considering the parameters of the industrial application you 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 for example)? Explain briefly.

No, it is not acceptable to use a fixed capacitor to correct the power factor of an industrial application whose reactive power demand varies significantly. This is because, when the reactive power demand of the application varies, the capacitor is no longer adequately sized to supply the exact amount of reactive power required to correct the power factor of the application. This is confirmed by the fact that the power factor $PF_{Ind.}$ of the industrial application decreases from virtually unity to 0.89 when Load 3 is switched in, which would result in a higher electricity bill for the application.

30. 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 you used to correct the power factor of the industrial application when Loads 1, 2, and 3 are switched in.

Reactance $X_{C,PFC}$ = _______ Ω

Reactance $X_{C,PFC}$ = 86 Ω

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

❑ Yes ❑ No

Yes

31. 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 $E_{Ind.}$ = _______ V

Current $I_{Ind.}$ = _______ A

Active power $P_{Ind.}$ = _______ W

Reactive power $Q_{Ind.}$ = _______ var

Apparent power $S_{Ind.}$ = _______ VA

Power factor $PF_{Ind.}$ = _______

Voltage $E_{Ind.}$ = 120 V

Current $I_{Ind.}$ = 1.38 A

Active power $P_{Ind.}$ = 164 W

Reactive power $Q_{Ind.}$ = -4.13 var

Apparent power $S_{Ind.}$ = 165 VA

Power factor $PF_{Ind.}$ = 0.99

32. 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 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 $Q_{Load\ 2}$ = _______ var

Reactive power $Q_{Load\ 3}$ = _______ var

Reactive power $Q_{Load,total}$ = _______ var

Reactive power $Q_{C,PFC}$ = _______ var

Reactive power $Q_{Load\ 2}$ = 82.8 var

Reactive power $Q_{Load\ 3}$ = 82.7 var

Reactive power $Q_{Load,total}$ = 166 var

Reactive power $Q_{C,PFC}$ = -170 var

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

Yes

33. Do the results you obtained and the observations you 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

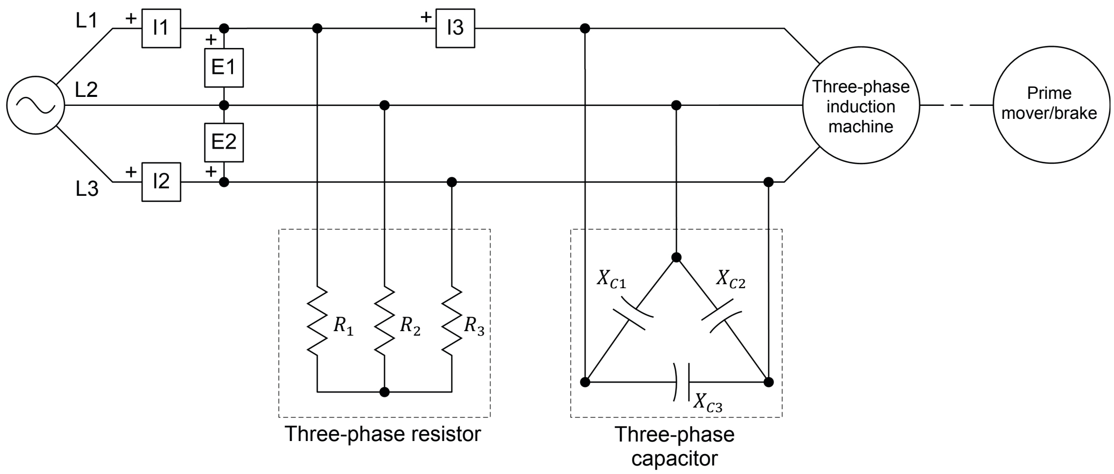
Yes

34. 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.

35. Connect the equipment as shown in Figure 15. 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).



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

Figure 15. Three-phase ac power source supplying power to an induction motor.

36. 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 15.

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

37. In the Metering window, make the required settings in order 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 (EI1, EI2)*].

38. 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*.

39. 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*.

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

Set the Data Table to record the voltage $E_{Ind.}$, current $I_{Ind.}$, active power $P_{Ind.}$, reactive power $Q_{Ind.}$, apparent power $S_{Ind.}$, and power factor $PF_{Ind.}$ of the industrial application, as well as the induction motor current $I_{Mot.}$ (indicated in the Metering window). Also set the Data Table to record the induction motor torque $T_{Mot.}$ 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.

41. 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.

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The results are presented in the following table.

Measured industrial application and induction motor parameters when the power factor of the application is not corrected.

Industrial application parameters						Induction motor parameters		
Voltage $E_{Ind.}$ (V)	Current $I_{Ind.}$ (A)	Active power $P_{Ind.}$ (W)	Reactive power $Q_{Ind.}$ (var)	Apparent power $S_{Ind.}$ (VA)	Power factor $PF_{Ind.}$	Torque $T_{Mot.}$ (N·m [lbf·in])	Current $I_{Mot.}$ (A)	Mechanical power P_M (W)
208	0.93	213	270	344	0.620	0.00 (0.00)	0.72	0.16
208	0.96	232	268	355	0.655	0.10 (0.89)	0.73	18.7
208	1.00	253	267	368	0.687	0.20 (1.77)	0.75	37.3
208	1.04	273	267	382	0.715	0.30 (2.66)	0.77	55.4
208	1.10	294	268	398	0.740	0.40 (3.54)	0.80	75.2
208	1.14	315	268	413	0.761	0.50 (4.43)	0.83	92.6
208	1.19	336	269	431	0.781	0.60 (5.31)	0.87	111
208	1.24	358	270	449	0.799	0.70 (6.20)	0.90	128
208	1.30	381	271	468	0.815	0.80 (7.08)	0.94	146
208	1.36	404	273	487	0.829	0.90 (7.97)	0.99	163
208	1.41	427	275	507	0.841	1.00 (8.85)	1.03	180
208	1.47	450	277	528	0.851	1.10 (9.74)	1.08	196
208	1.54	475	281	552	0.861	1.20 (10.6)	1.14	211

42. Observe the data you just recorded in the Data Table. Describe what happens to the amount of reactive power absorbed by the three-phase induction motor (it corresponds to the industrial application reactive power $Q_{Ind.}$) as the mechanical load varies.

The amount of reactive power absorbed by the induction motor varies very little 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 three-phase induction motor)? Explain briefly.

Yes, it would be possible to correct the power factor of the industrial application using distributed power factor correction. This is because the reactive power demand of the three-phase induction motor varies very little no matter the mechanical load applied to the motor. Therefore, a properly-sized fixed capacitor could be used to supply the amount of reactive power required by the induction motor.

43. In the Data Table window, save the recorded data, then clear the Data Table without modifying the record settings.

44. 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 $PF_{Ind.}$ 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 you used to correct the power factor of the three-phase induction motor.

Reactances X_{C1}, X_{C2}, and X_{C3} = _______ Ω

Reactances X_{C1}, X_{C2}, and X_{C3} = 600 Ω

45. Using the measured voltage $E_{Ind.}$, 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_{PFC} = _______ var

Three-phase capacitor reactive power Q_{PFC} = 216 var

Is the calculated value relatively close (within 75 var) to the amount of reactive power which the three-phase induction motor absorbs (see data recorded in step 41)?

❑ Yes ❑ No

Yes

46. In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.00 N·m (0.00 lbf·in).

47. In the Data Table window, click the Record Data button to record the parameters.

48. 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.

The results are presented in the following table.

Measured industrial application and induction motor parameters when the power factor of the application is corrected.

Industrial application parameters						Induction motor parameters		
Voltage $E_{Ind.}$ (V)	Current $I_{Ind.}$ (A)	Active power $P_{Ind.}$ (W)	Reactive power $Q_{Ind.}$ (var)	Apparent power $S_{Ind.}$ (VA)	Power factor $PF_{Ind.}$	Torque $T_{Mot.}$ (N·m [lbf·in])	Current $I_{Mot.}$ (A)	Mechanical power P_M (W)
208	0.61	213	50.0	219	0.974	0.00 (0.00)	0.17	0.14
208	0.65	233	47.2	237	0.980	0.10 (0.89)	0.12	18.4
208	0.70	252	46.9	256	0.983	0.20 (1.77)	0.23	37.2
208	0.76	274	47.9	278	0.985	0.30 (2.66)	0.29	55.5
208	0.81	291	48.1	295	0.987	0.41 (3.63)	0.33	76.6
208	0.87	314	48.7	317	0.988	0.50 (4.43)	0.39	92.6
208	0.93	335	49.1	339	0.989	0.60 (5.31)	0.45	110
208	1.00	358	50.3	361	0.990	0.70 (6.20)	0.51	128
208	1.06	378	51.0	382	0.991	0.80 (7.08)	0.58	146
208	1.12	401	53.0	405	0.991	0.90 (7.97)	0.63	163
208	1.19	425	55.6	429	0.992	1.00 (8.85)	0.70	180
208	1.25	447	56.9	451	0.992	1.10 (9.74)	0.76	196
208	1.33	472	60.0	476	0.992	1.21 (10.7)	0.84	213

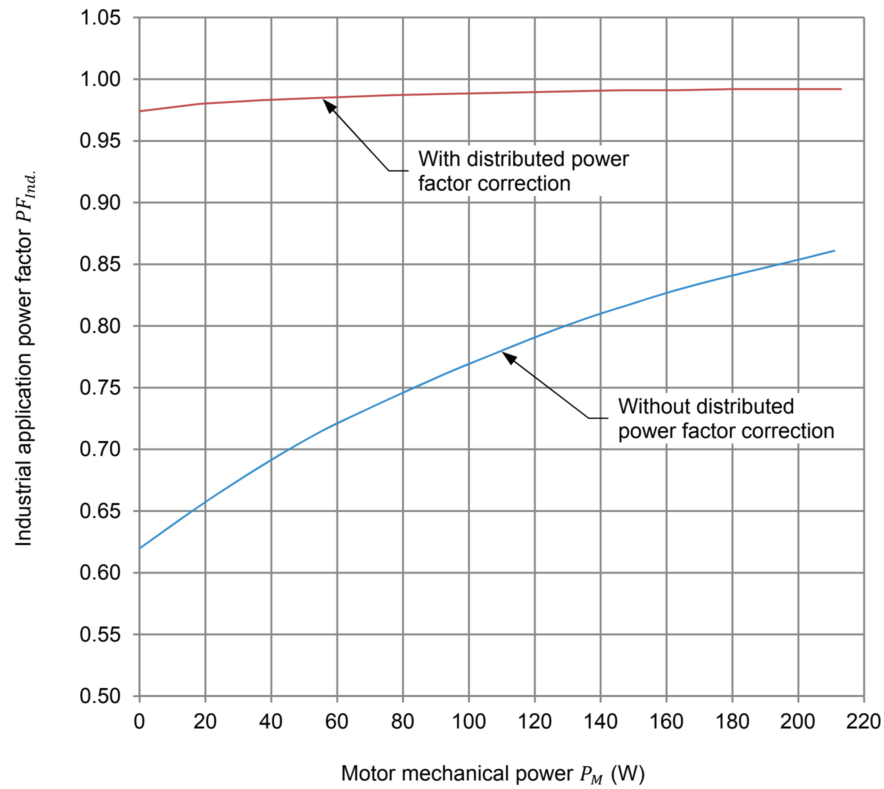
49. In the Data Table window, save the recorded data.

50. 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.

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

The resulting graph is shown below:



Power factor $PF_{Ind.}$ 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 at the motor.

52. Observe the graph you 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 with a virtually fixed reactive power demand (such as the three-phase induction motor) significantly improves the power factor $PF_{Ind.}$ of the industrial application? Explain briefly.

Yes. The graph shows that without distributed power factor correction, the power factor of the industrial application is always significantly lower than unity, although it increases with the mechanical power P_M produced by the induction motor. On the other hand, when using distributed power factor correction, the power factor of the industrial application is maintained virtually at unity at all times.

53. Observe the data you recorded in the Data Table at steps 41 and 48 (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 $I_{Mot.}$ measured without distributed power factor correction to that measured with distributed power factor correction. What can you conclude?

The intensity of the induction motor current $I_{Mot.}$ measured without distributed power factor correction at the motor is always significantly higher than that measured with distributed power factor correction at the motor.

Considering your answer to the above 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 the industrial application that conveys power to the induction motor? Explain briefly.

Using distributed power factor correction allows either reduction of the size and rating of the power lines and equipment in the industrial application that conveys power to the induction motor or reduction of the heat that they produce due to power losses (RI^2 losses).

54. Based on the results you 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

Yes

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

Conclusion

In this exercise, you learned how to correct the power factor of an industrial application whose reactive power demand is either fixed or variable. You were introduced to the two main types of power factor correction: plant-wide and distributed. You became familiar with power factor correction in three-phase circuits.

Review Questions

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

Power factor correction consists of increasing the power factor of a load to as close as possible to unity. This is generally achieved by connecting capacitors to the load in order to supply the exact amount of reactive power that it requires. When properly sized, the capacitors supply all the reactive power that the load requires and thus bring the power factor to unity.

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?

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 are listed below:

- The intensity of the current flowing in the distribution lines supplying electric power to the industrial application increases.
- The amount of copper losses (RI^2 losses) in the distribution lines, as well as in the equipment (transmission lines, transformers, etc.) upstream in the 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.

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

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. Also, plant-wide power factor correction ensures that the power factor of the whole industrial application is corrected, and not just the power factor of each individual load.

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

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. Distributed power factor correction also allows reduction of the size and rating of the lines and equipment in the industrial application that supply power to the load or reduction of the heat that they produce due to power losses (RI^2 losses).

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.

The delta configuration is preferable for a three-phase switched-capacitor bank used to implement power factor correction. This is because delta-connected three-phase capacitors present advantages over wye-connected three-phase capacitors in this situation. Firstly, 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. Secondly, it helps reduce the amount of harmonics in the power lines feeding the industrial application, thereby making the application friendlier to the power distribution system.

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