Electricity and New Energy

Power Factor Correction

Course Sample

8123642

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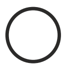
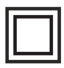
General Safety Symbols and Procedures

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	**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 danger. Consult the relevant user documentation.
	Caution, risk of electric shock.
	Caution, lifting hazard.
	Caution, hot surface.
	Caution, risk of fire.

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.
∿	Alternating current.

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

Preface

Electrical energy is part of our life since more than a century and the number of applications using electric power keeps increasing.

This phenomenon is illustrated by the steady growth in electric power demand observed worldwide. In reaction to this phenomenon, the production of electrical energy using renewable natural resources (e.g., wind, sunlight, rain, tides, geothermal heat, etc.) has gained much importance in recent years since it helps to meet the increasing demand for electric power and is an effective means of reducing greenhouse gas (GHG) emissions.

To help answer the increasing needs for training in the wide field of electrical energy, Festo Didactic developed a series of modular courses. These courses are shown below as a flow chart, with each box in the flow chart representing a course.

Teaching includes a series of courses providing in-depth coverage of basic topics related to the field of electrical energy such as dc power circuits, ac power circuits, and power transformers.

Other courses also provide in-depth coverage of solar power and wind power. Finally, two courses deal with photovoltaic systems and wind power systems, with focus on practical aspects related to these systems.

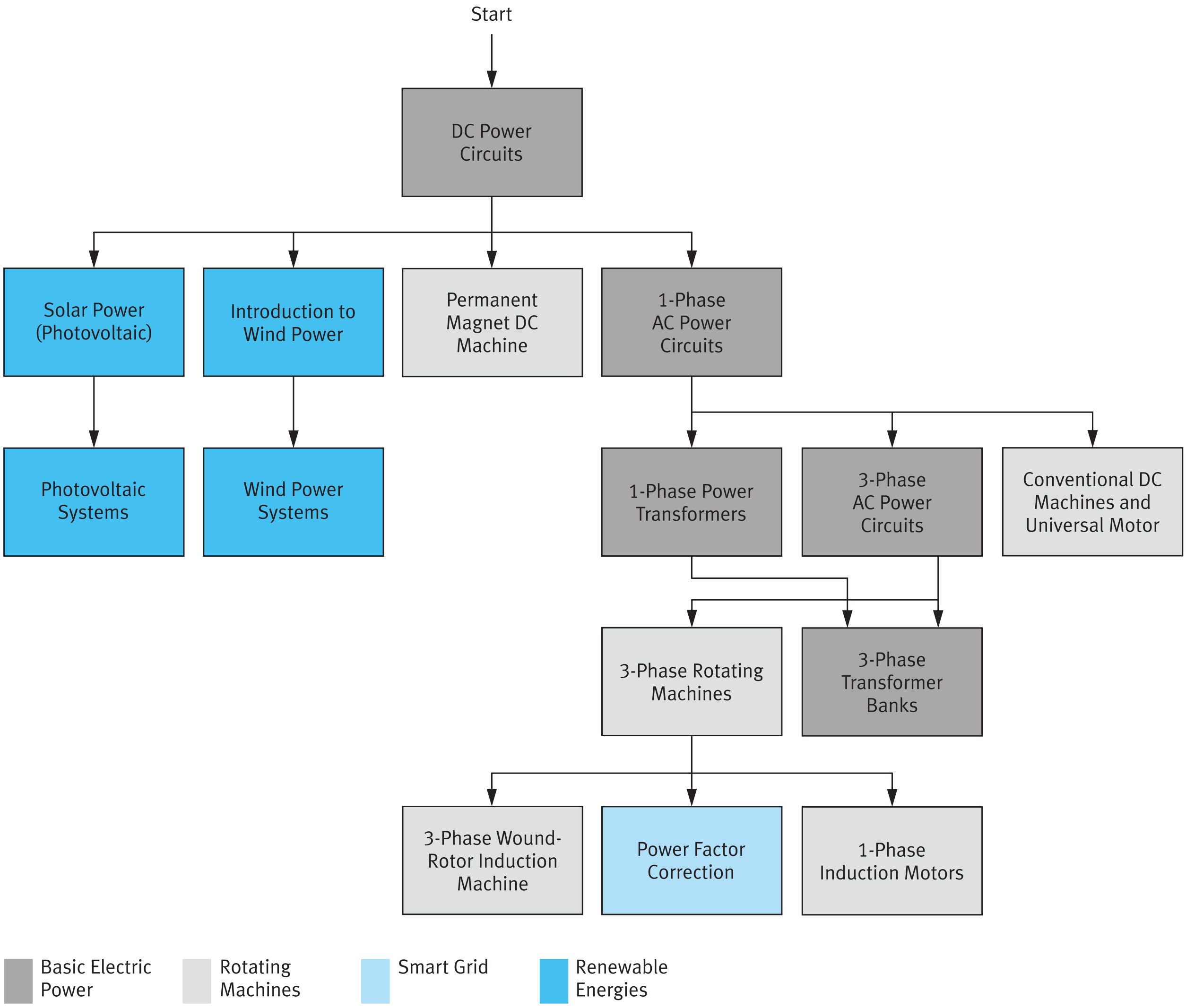


Figure 1: Festo Didactic courses in electrical energy.

Tips, feedback, and suggestions

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

Please send these to:

services.didactic@festo.com

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).

To the Instructor

You will find in this instructor version of the course all the elements included in the student version 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 the instructor 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 the next. For this reason, the results and answers given in this course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and to make observations and measurements similar to those given as answers.

Equipment installation

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

Equipment installation and use

In order for students to be able to safely perform the hands-on exercises in this course, the equipment must have been properly installed, i.e., according to the instructions given in the accompanying Safety Instructions and Commissioning manual. Also, the students must familiarize themselves with the safety directives provided in the Safety Instructions and Commissioning manual and observe these directives when using the equipment.

Sample

Extracted from

Instructor Guide

Three-Phase Transformer Configurations

124 min.

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 (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 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.

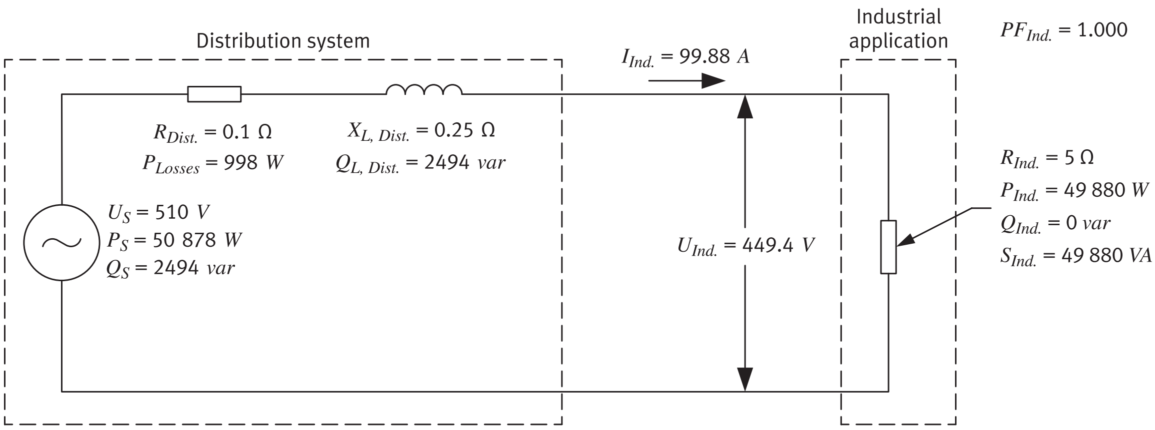


Figure 4: Distribution system supplying active power to an industrial application with a power factor of 1 (one phase shown).

As Figure 4 shows, the intensity of the current $I_{\text{Ind.}}$ flowing in the distribution lines supplying power to the industrial application is equal to 99.88 A, the amount of active power $P_{\text{Ind.}}$ 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 $U_{\text{Ind.}}$ at the main power bus of the industrial application is slightly lower than the distribution system source voltage U_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).

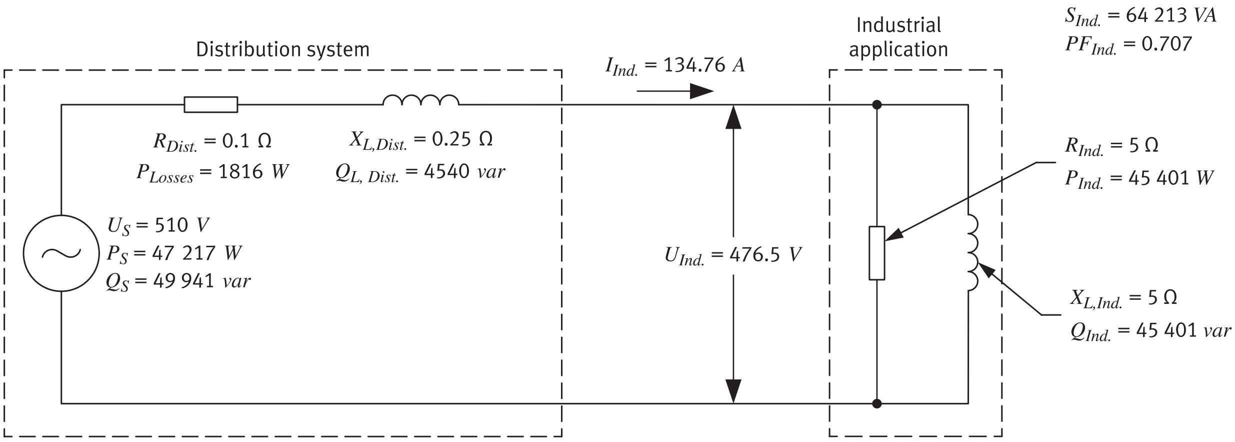


Figure 5: Distribution system supplying active power and reactive power to an industrial application with a power factor of 0.707 (one phase shown).

As Figure 5 shows, the reactive power $Q_{\text{Ind.}}$ (45 401 var) which the industrial application draws from the distribution system causes the apparent power $S_{\text{Ind.}}$ supplied to the application to increase significantly (from 49 880 VA to 64 213 VA). This, in turn, makes the intensity of the current $I_{\text{Ind.}}$ 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 $I_{\text{Ind.}}$ 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 $I_{\text{Ind.}}$ also causes the voltage $U_{\text{Ind.}}$ 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 $P_{\text{Ind.}}$ 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 $PF_{\text{Ind.}}$ 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.

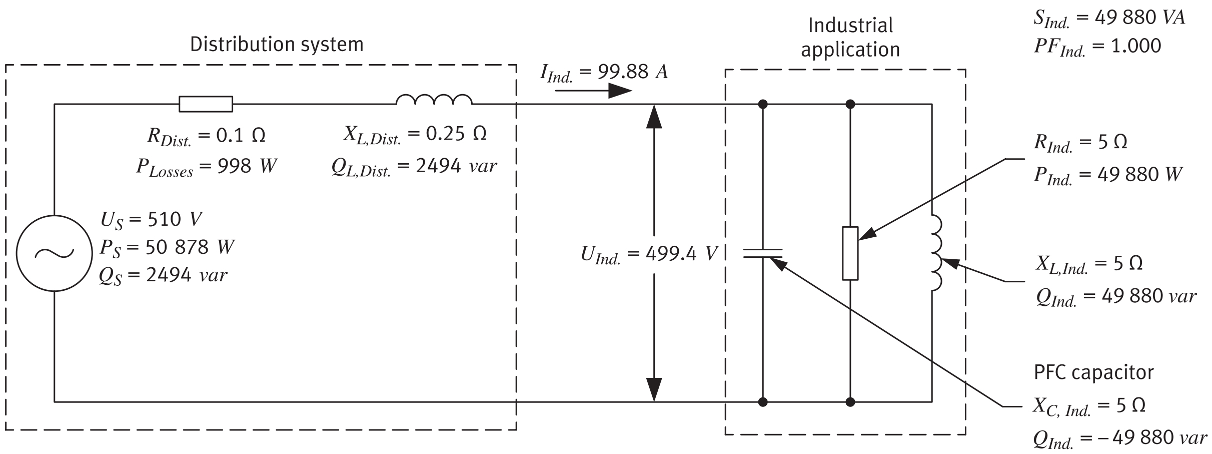


Figure 6: Distribution system supplying active power to an industrial application whose power factor of 0.707 is corrected to 1.000 using a capacitor connected in parallel at the main power bus of the application (one phase shown).

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.

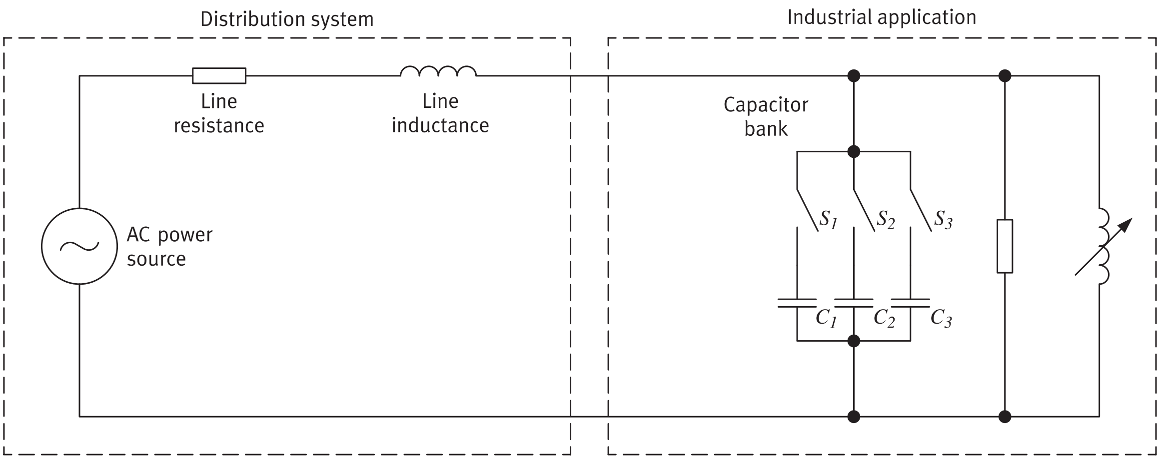


Figure 7: A bank of switched capacitors of different capacitance values allows the power factor of an industrial application to be corrected even when the inductive reactance of the load varies (single-phase diagram shown).

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}.

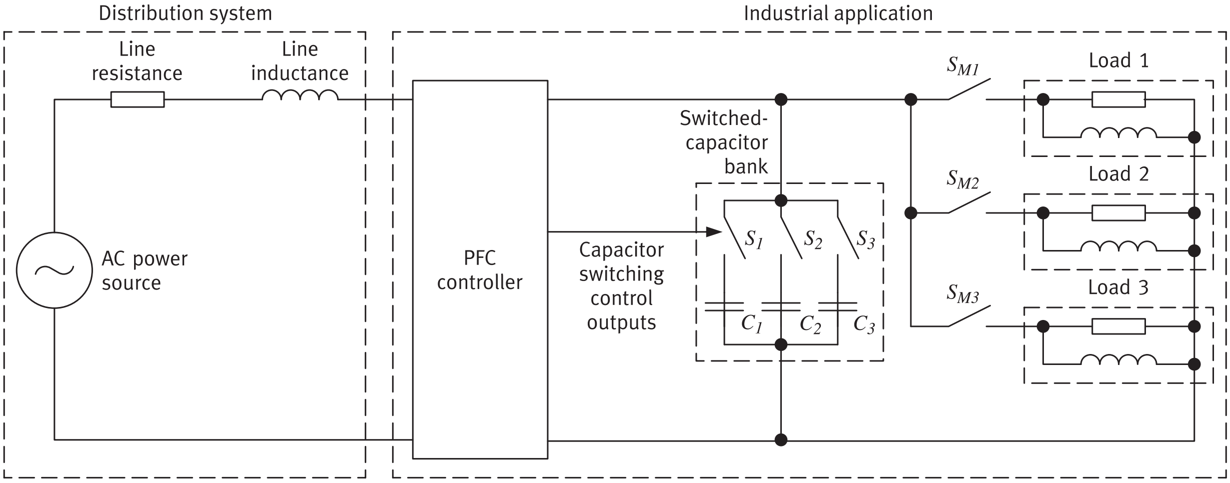


Figure 9: In plant-wide power factor correction, the switched-capacitor bank is connected in parallel to the main power bus of the industrial application (single-phase diagram shown).

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.

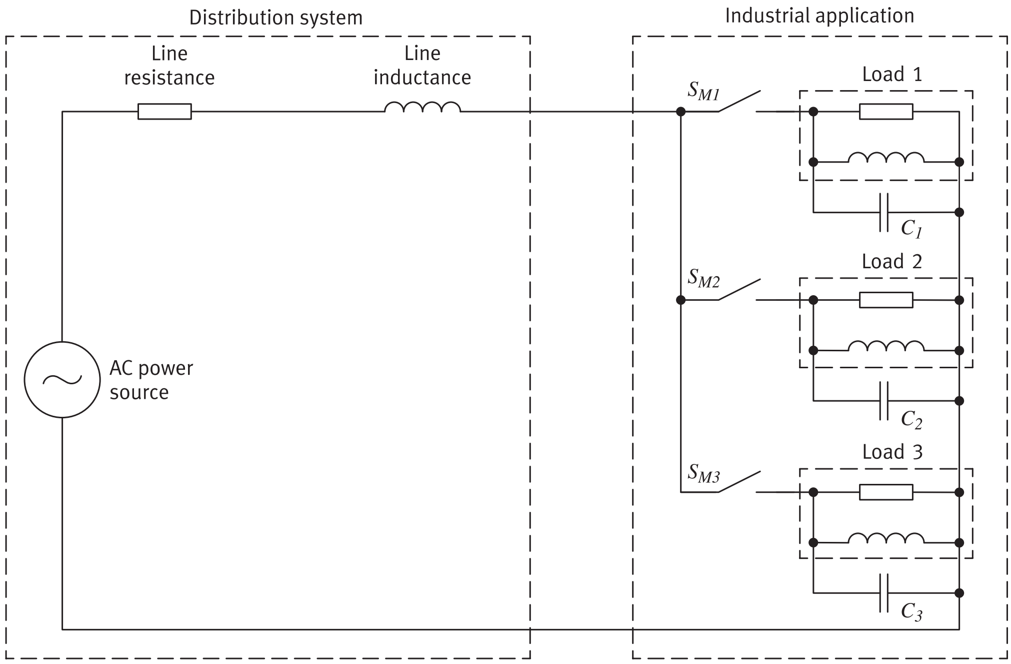


Figure 10: In distributed power factor correction, a capacitor is connected in parallel with each significant resistive-inductive load in the industrial application (single-phase diagram shown).

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 in-creases but the inductive reactance varies very little.

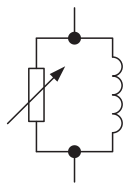


Figure 11: Equivalent electrical representation of an induction motor.

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

Plant-wide power factor correction	Distributed power factor correction
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).

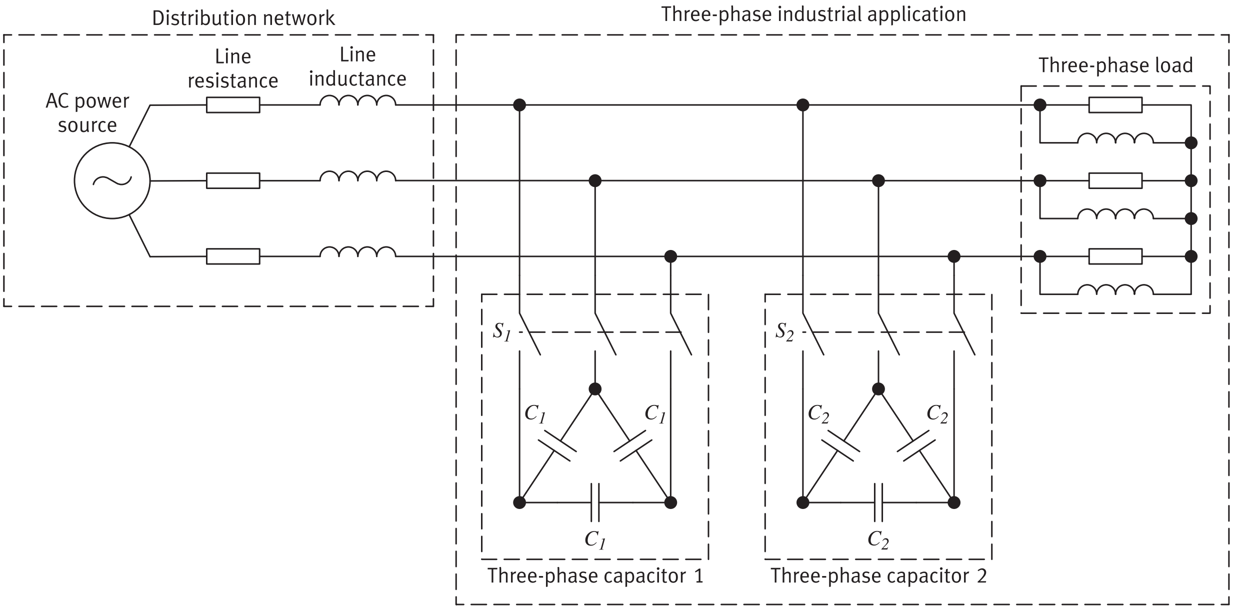


Figure 13: Power factor correction in a three-phase industrial application using a three-phase switched-capacitor bank.

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.

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

To ensure optimal accuracy of torque measurements performed with the equipment, make sure that the code (usually a single letter) on the identification (ID) label affixed to the 4 Quadrant Dynamometer Motor is the same as the code on the motor identification (Motor ID) label affixed to the 4 Quadrant Power Supply and Dynamometer Controller.

2. Install the 4 Quadrant Dynamometer Motor and the Squirrel Cage Induction Machine on the work surface so that they face each other, with the 4 Quadrant Dynamometer Motor to the left and the Squirrel Cage Induction Machine to the right.

   Install the remaining of the equipment in the workstation.

3. Make the connections required to earth the equipment properly.

If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

⚠ WARNING

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

4. Mechanically couple the Squirrel Cage Induction Machine to the 4 Quadrant Dynamometer Motor using the direct coupling, then install the protective guard.

If necessary, check with the instructor to ensure that the machines, the direct coupling, and the protective guard are properly installed.

5. Connect the connection cable of the 4 Quadrant Dynamometer Motor to the corresponding connector on the 4 Quadrant Power Supply and Dynamometer Controller.

6. On the 3AC 400V/DC 230V Power Supply, make sure that circuit breakers/switches -F1 and -F2 are set to the O (off) position, then connect the module to a three-phase ac power outlet that is properly protected.

   Make sure that the main power switch on the 4 Quadrant Power Supply and Dynamometer Controller is set to the O (off) position, then connect its Power Input to an ac power outlet that is properly protected.

   Make sure that the main power switch on the AC 24V Power Supply is set to the O (off) position, then connect its Power Input to an ac power outlet that is properly protected.

If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

7. Connect the Power Input of the Data Acquisition and Control Interface to the Power Output of the AC 24V Power Supply.

   Connect the Auxiliary Power Input of the Squirrel Cage Induction Machine to the Power Output of the AC 24V Power Supply.

8. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.

9. Observe the phase sequence LED indicator on the front panel of the 3AC 400V/DC 230V Power Supply. If this LED is lit in blue, the phase sequence at terminals L1, L2, and L3 of the 3AC 400V/DC 230V Power Supply is correct. Go to the next step of the procedure. Otherwise, (phase sequence LED indicator is lit in red), continue the present step.

   The phase sequence LED indicator is lit in red. This indicates that the phase sequence at terminals L1, L2, and L3 of the 3AC 400V/DC 230V Power Supply is reversed. To correct the situation, make sure that electric power is turned off, then interchange the connection of the leads at terminals L1 and L2 of the 3AC 400V/DC 230V Power Supply.

   Turn electric power on again. The phase sequence LED indicator on the 3AC 400V/DC 230V Power Supply should light up in blue, thereby indicating that the phase sequence is correct.

10. Turn the AC 24V Power Supply on.

11. Turn the 4 Quadrant Power Supply and Dynamometer Controller on, then set the Operating Mode switch to Dynamometer. This setting allows the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor to operate as a prime mover, a brake, or both, depending on the selected function.

12. 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 4 Quadrant Power Supply and Dynamometer Controller to a USB port of the host computer.

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

    In LVDAC-EMS, make sure that the Data Acquisition and Control Interface and the 4 Quadrant Power Supply and Dynamometer Controller are detected. Make sure that the Computer-Based Instrumentation (one phase) function for the Data Acquisition and Control Interface is available. Also make sure that the Standard Functions (computer-based control) for the 4 Quadrant Power Supply and Dynamometer Controller are available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network.

14. Connect the equipment as shown in Figure 15.

    - Use a single phase of the 3AC 400V/DC 230V 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 resistive devices in the application, such as 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.

Appendix C shows in more detail the equipment and the connections that are required for several of the circuit diagram symbols used in this course.

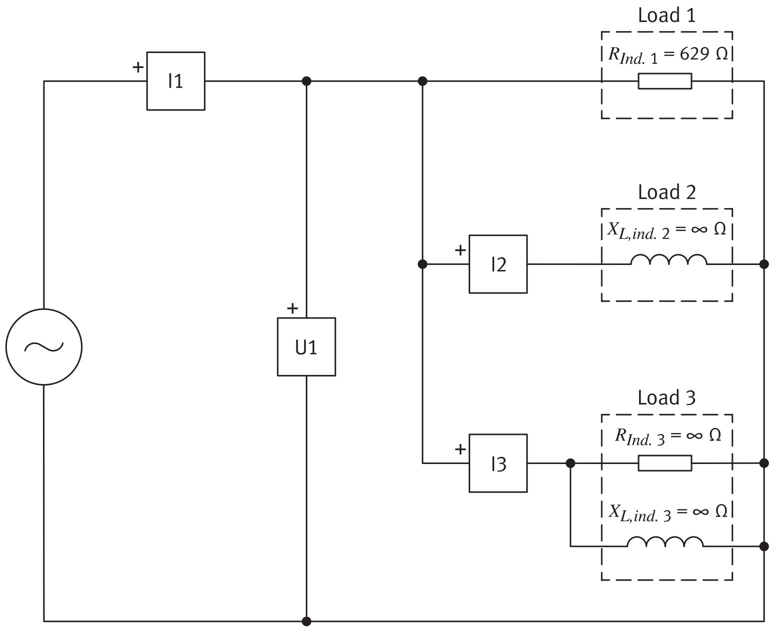


Figure 15: AC power source supplying power to an industrial application containing resistive and inductive loads.

15. Make the necessary switch settings on the Resistive Load and on the Inductive Load so that load resistances $R_{\text{Ind. 1}}$ and $R_{\text{Ind. 3}}$, as well as load reactances $X_{\text{L, ind. 2}}$ and $X_{\text{L, ind. 3}}$ of the industrial application, are equal to the values indicated in Figure 15. Since the resistance and reactance values of Load 2 and Load 3 are set to infinite, these loads are switched off, thereby leaving only Load 1 in circuit.

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.

16. In LVDAC-EMS, set meters to measure the following parameters:

- the rms (ac) values of the industrial application voltage $U_{\text{Ind.}}$ and current $I_{\text{Ind.}}$ (inputs U1 and I1, respectively).
- the active power $P_{\text{Ind.}}$ supplied to the industrial application (inputs U1 and I1).
- the reactive power $Q_{\text{Ind.}}$ which the industrial application exchanges with the distribution system, i.e., the ac power source (inputs U1 and I1).

- the apparent power $S_{\text{Ind.}}$ delivered to the industrial application (inputs U1 and I1).
- the power factor $PF_{\text{Ind.}}$ of the industrial application (inputs U1 and 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.

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

18. In LVDAC-EMS, read the values of the industrial application voltage $U_{\text{Ind.}}$, current $I_{\text{Ind.}}$, apparent power $S_{\text{Ind.}}$, active power $P_{\text{Ind.}}$, reactive power $Q_{\text{Ind.}}$, and power factor $PF_{\text{Ind.}}$ indicated by the meters. Record the values below.

    Voltage $U_{\text{Ind.}} =$ ________ V

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

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

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

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

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

    Voltage $U_{\text{Ind.}} =$ 230 V ± 10%

    Current $I_{\text{Ind.}} =$ 0.37 A ± 10%

    Active power $P_{\text{Ind.}} =$ 84.8 W ± 10%

    Reactive power $Q_{\text{Ind.}} =$ [-1.0 var,1.0 var]

    Apparent power $S_{\text{Ind.}} =$ 84.8 VA ± 10%

    Power factor $PF_{\text{Ind.}} =$ 1.00 ± 10%

19. 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.

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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, so that power factor correction is 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.

20. Make the necessary switch settings on the Inductive Load so that reactance $X_{\mathrm{L,\,ind.\,2}}$ of the industrial application is equal to 629 Ω. This puts Load 2 of the industrial application in circuit. Do not modify the other switch settings on the Resistive Load and Inductive Load.

21. In LVDAC-EMS, read the values of the industrial application voltage $U_{\mathrm{Ind.}}$, current $I_{\mathrm{Ind.}}$, apparent power $S_{\mathrm{Ind.}}$, active power $P_{\mathrm{Ind.}}$, reactive power $Q_{\mathrm{Ind.}}$, and power factor $PF_{\mathrm{Ind.}}$. Record the values below.

    Voltage $U_{\mathrm{Ind.}} =$ ________ V

    Current $I_{\mathrm{Ind.}} =$ ________ A

    Active power $P_{\mathrm{Ind.}} =$ ________ W

    Reactive power $Q_{\mathrm{Ind.}} =$ ________ var

    Apparent power $S_{\mathrm{Ind.}} =$ ________ VA

    Power factor $PF_{\mathrm{Ind.}} =$ ________

Voltage $U_{\text{Ind.}}$ = 230 V ± 10%

Current $I_{\text{Ind.}}$ = 0.55 A ± 10%

Active power $P_{\text{Ind.}}$ = 92.6 W ± 10%

Reactive power $Q_{\text{Ind.}}$ = 86.5 var ± 10%

Apparent power $S_{\text{Ind.}}$ = 126.7 VA ± 10%

Power factor $PF_{\text{Ind.}}$ = 0.73 ± 10%

22. Compare the values of the industrial application parameters measured in the previous step (resistive-inductive load) to those measured in Step 18 (purely resistive load). What happens when the inductive load is added to the purely resistive load?

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

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

23. 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.

No, the power factor $PF_{\text{Ind.}}$ of the industrial application is not acceptable. This is because most electricity providers charge extra costs to industrial customers with a low power factor. Electricity providers consider a power factor of 0.73 to be low, and thus, extra charges would appear on the electricity bill of the industrial application.

24. Considering the parameters of the industrial application measured in Step 18 and Step 21, 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 $I_{\text{Ind.}}$ 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 $I_{\text{Ind.}}$ 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 $U_{\text{Ind.}}$ at the industrial application decrease slightly. This, in turn, would cause the active power $P_{\text{Ind.}}$ supplied to the industrial application to decrease.

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

26. 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).

27. 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).

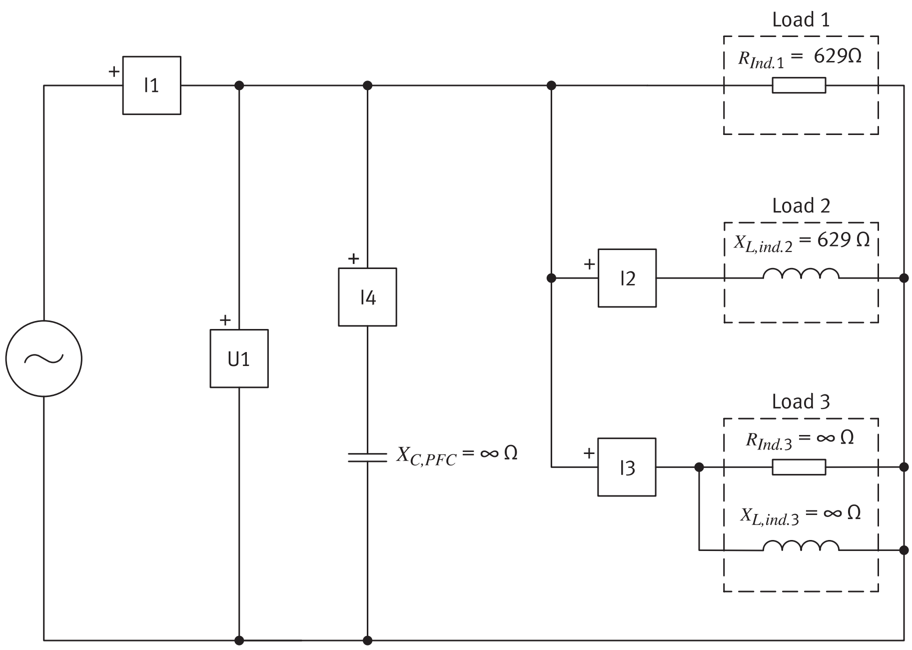

Figure 16: AC power source supplying power to an industrial application containing resistive and inductive loads with power factor correction.

28. On the Capacitive Load, make the necessary switch settings so that the reactance $X_{\mathrm{C,\,PFC}}$ of the power factor correction capacitor is infinite (no power factor correction), as indicated in .

29. In LVDAC-EMS, set meters to measure the following additional parameters:

- the reactive power $Q_{\mathrm{Load}\,2}$ at Load 2 (inputs U1 and I2).
- the reactive power $Q_{\mathrm{Load}\,3}$ at Load 3 (inputs U1 and I3).
- the reactive power $Q_{\mathrm{C,\,PFC}}$ at the power factor correction capacitor (inputs U1 and I4).

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

31. On the Capacitive Load, make the necessary switch settings so that the power factor $PF_{\mathrm{Ind.}}$ of the industrial application indicated in LVDAC-EMS is as close as possible to unity.

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

Reactance $X_{\mathrm{C,\,PFC}} =$ ________ Ω

Reactance $X_{\mathrm{C,\,PFC}} = 629\ \Omega$

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

☐ Yes ☐ No

Yes

32. In LVDAC-EMS, read the values of the industrial application voltage $U_{\mathrm{Ind.}}$, current $I_{\mathrm{Ind.}}$, apparent power $S_{\mathrm{Ind.}}$, active power $P_{\mathrm{Ind.}}$, reactive power $Q_{\mathrm{Ind.}}$, and power factor $PF_{\mathrm{Ind.}}$. Record the values below.

Voltage $U_{\mathrm{Ind.}} =$ ________ V

Current $I_{\mathrm{Ind.}} =$ ________ A

Active power $P_{\mathrm{Ind.}} =$ ________ W

Reactive power $Q_{\mathrm{Ind.}} =$ ________ var

Apparent power $S_{\mathrm{Ind.}} =$ ________ VA

Power factor $PF_{\mathrm{Ind.}} =$ ________

Voltage $U_{\text{Ind.}} = 230$ V ± 10%

Current $I_{\text{Ind.}} = 0.41$ A ± 10%

Active power $P_{\text{Ind.}} = 92.9$ W ± 10%

Reactive power $Q_{\text{Ind.}} = [-5 \text{ var}, 5 \text{ var}]$

Apparent power $S_{\text{Ind.}} = 93.5$ VA ± 10%

Power factor $PF_{\text{Ind.}} = 0.99$ ± 10%

33. Compare the parameters of the industrial application measured in the previous step to those measured in Step 21 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.

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The amount of reactive power $Q_{\text{Ind.}}$ which the industrial application exchanges with the distribution system decreases from 86.5 var to about 0 var. This causes the apparent power $S_{\text{Ind.}}$ delivered to the industrial application to decrease substantially (from 126.7 VA to 93.5 VA). This is because the reactive power absorbed by the industrial application is now supplied by the power factor correction capacitor.

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

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The intensity of the current $I_{\text{Ind.}}$ which the industrial application draws from the distribution system decreases significantly (from 0.55 A to 0.41 A). This is because 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.

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

The power factor $PF_{\text{Ind.}}$ of the industrial application increases significantly (from 0.73 to virtually unity). This is because the distribution system no longer has to exchange reactive power with the industrial application (i.e., the reactive power $Q_{\text{Ind.}}$ is virtually 0 var).

36. 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.

Bringing the power factor $PF_{\text{Ind.}}$ of the industrial application back to unity results in a lower electricity bill. This is because 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., that it corresponds only to the amount of active power consumed by the application).

37. In LVDAC-EMS, read the values of the reactive power $Q_{\text{Load 2}}$ at Load 2 and reactive power $Q_{\text{C, PFC}}$ at the power factor correction capacitor. Record the values below.

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

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

Reactive power $Q_{\text{Load 2}} =$ 86.8 var ± 10%

Reactive power $Q_{\text{C, PFC}} =$ -85.1 var ± 10%

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 32?

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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 $Q_{\text{Ind.}}$ 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.

38. Make the necessary switch settings on the Resistive Load and Inductive Load so that resistance $R_{\text{Ind. 3}}$ and reactance $X_{\text{L, ind. 3}}$ are equal to 880 Ω and 629 Ω, respectively. 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.

39. In LVDAC EMS, read the values of the industrial application voltage $U_{\text{Ind.}}$, 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 $U_{\text{Ind.}} =$ ________ V

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

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

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

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

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

Voltage $U_{\text{Ind.}} =$ 230 V ± 10%

Current $I_{\text{Ind.}} =$ 0.80 A ± 10%

Active power $P_{\text{Ind.}} =$ 160 W ± 10%

Reactive power $Q_{\text{Ind.}} =$ 87.0 var ± 10%

Apparent power $S_{\text{Ind.}} =$ 183 VA ± 10%

Power factor $PF_{\text{Ind.}} =$ 0.88 ± 10%

40. 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.

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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 $PF_{\text{Ind.}} =$ of the industrial application decreases from virtually unity to 0.88 when Load 3 is switched in, which would result in a higher electricity bill for the application.

41. On the Capacitive Load, make the necessary switch settings so that the power factor $PF_{\text{Ind.}} =$ of the industrial application indicated in LVDAC-EMS is as close as possible to unity.

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

Reactance $X_{\text{C, PFC}} =$ ________ Ω

Reactance $X_{\text{C, PFC}} =$ 314 Ω

Compare the reactance $X_{\text{C, PFC}} =$ 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

Yes

42. In LVDAC EMS, read the values of the industrial application voltage $U_{\text{Ind.}}$, 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 $U_{\text{Ind.}} =$ ________ V

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

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

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

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

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

Voltage $U_{\text{Ind.}} =$ 230 V ± 10%

Current $I_{\text{Ind.}} =$ 0.71 A ± 10%

Active power $P_{\text{Ind.}} =$ 161 W ± 10%

Reactive power $Q_{\text{Ind.}} =$ 2.02 var ± 10%

Apparent power $S_{\text{Ind.}} =$ 163 VA ± 10%

Power factor $PF_{\text{Ind.}} =$ 0.99 ± 10%

43. In LVDAC-EMS, read the values of the reactive power $Q_{\text{Load 2}}$ at Load 2 and reactive power $Q_{\text{Load 3}}$ at Load 3. Record the values below.

Calculate the total amount of reactive power $Q_{\text{Load, total}}$ at the loads. Record your result below.

Finally, read the value of the reactive power $Q_{\text{C, PFC}}$ at the power factor correction capacitor in LVDAC-EMS. Record the value below.

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

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

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

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

Reactive power $Q_{\text{Load 2}} =$ 86.6 var ± 10%

Reactive power $Q_{\text{Load 3}} =$ 85.9 var ± 10%

Reactive power $Q_{\text{Load, total}} =$ 173 var ± 10%

Reactive power $Q_{\text{C, PFC}} =$ -170 var ± 10%

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

☐ Yes ☐ No

Yes

45. 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

Yes

46. 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.

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

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

47. Connect the equipment as shown in Figure 17.

- In this circuit, the three-phase ac power source is implemented using the 3AC 400V/DC 230V Power Supply.
- The squirrel-cage induction motor is implemented using the Squirrel-Cage Induction Machine.
- The brake is implemented using the 4 Quadrant Dynamometer Motor.
- The three-phase resistor is implemented using the Resistive Load.
- The three-phase capacitor is implemented using the Capacitive Load.

The three-phase resistor represents purely resistive loads in the application, such as 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 squirrel-cage induction motor in the industrial application).

Appendix C shows in more detail the equipment and the connections that are required for several of the circuit diagram symbols used in this course.

In the rest of this exercise, the Squirrel-Cage Induction Machine is referred to as the squirrel-cage induction motor, or induction motor, since it operates as a motor.

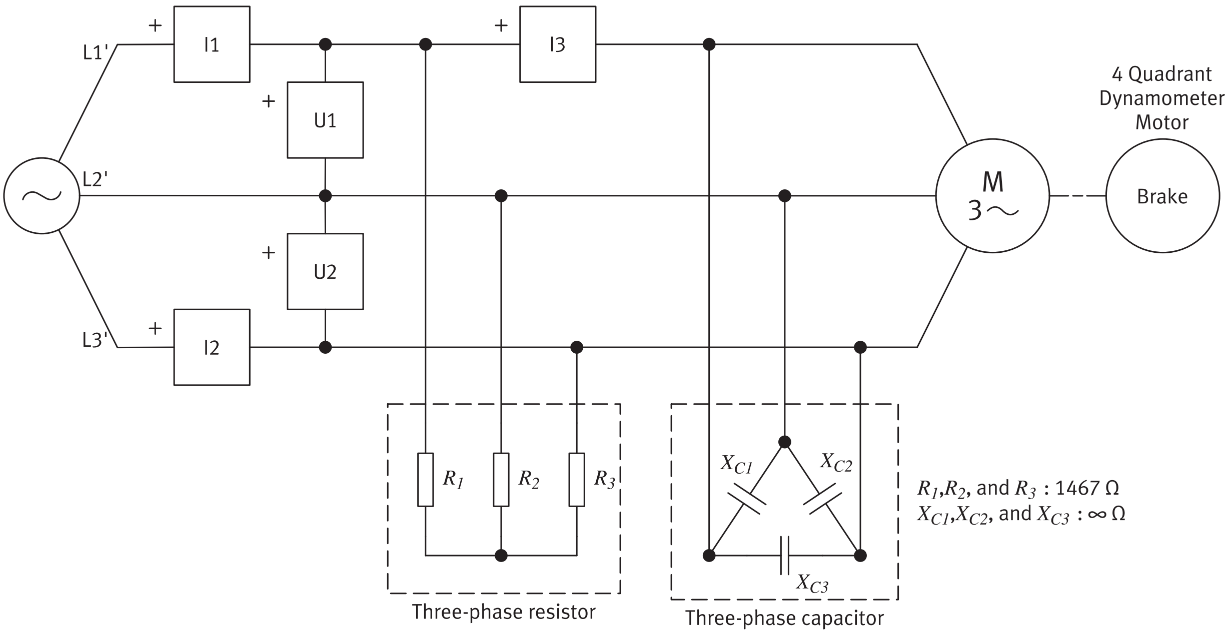

Figure 17: Three-phase ac power source supplying power to a resistive load and a squirrel-cage induction motor.

48. 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 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).

49. In LVDAC-EMS, set meters to measure the following parameters:

    - the rms (ac) values of the industrial application line voltage $U_{\text{Ind.}}$ and current $I_{\text{Ind.}}$ (inputs U1 and I1, respectively).
    - the rms (ac) value of the induction motor current $I_{\text{Mot.}}$ (input I3).
    - the active power $P_{\text{Ind.}}$ supplied to the industrial application (two-wattmeter method).
    - the reactive power $Q_{\text{Ind.}}$ which the industrial application exchanges with the distribution system, i.e., the three-phase ac power source (two-wattmeter method).
    - the apparent power $S_{\text{Ind.}}$ delivered to the industrial application (two-wattmeter method).
    - the power factor $PF_{\text{Ind.}}$ of the industrial application (two-wattmeter method).

50. In LVDAC-EMS, do the settings required so that the 4 Quadrant Power Supply and Dynamometer Controller and the 4 Quadrant Dynamometer Motor operate as a brake. Then, set the brake as follows:

    - Braking torque control: (manual) knob

- Braking torque: 0.00 N·m
- Pulley ratio: 1:1 (direct coupling)

The braking torque setting above determines the magnitude of the braking torque that the 4 Quadrant Dynamometer Motor applies to the machine to which it is coupled (machine under test), i.e., the squirrel-cage induction motor.

In LVDAC-EMS, enable continuous refresh of the speed, torque, power, and energy meters of the brake. These meters indicate the values of the speed, torque, power, and energy at the shaft of the machine under test, i.e., at the the squirrel-cage induction motor.

Do not start the brake for now.

51. On the 3AC 400V/DC 230V Power Supply, turn the three-phase ac power source on by setting circuit breaker/switch -F1 to the I (on) position. Observe that the Squirrel-Cage Induction Machine starts rotating. Also, observe that electric power is supplied to the three-phase resistive load as indicated by the meters in LVDAC-EMS.

    In LVDAC-EMS, start the brake. Observe that the meters of the brake indicate the rotation speed of the squirrel-cage induction motor, as well as the torque and mechanical power produced by the motor.

52. In LVDAC-EMS, access the data table.

    Set the data table to record the parameters of the industrial application and squirrel-cage induction motor listed below.

    - Line voltage $U_{\mathrm{Ind.}}$
    - Line current $I_{\mathrm{Ind.}}$
    - Active power $P_{\mathrm{Ind.}}$
    - Reactive power $Q_{\mathrm{Ind.}}$
    - Apparent power $S_{\mathrm{Ind.}}$
    - Power factor $PF_{\mathrm{Ind.}}$
    - Induction motor current $I_{\mathrm{Mot.}}$
    - Induction motor torque $T_{\mathrm{Mot.}}$
    - Induction motor mechanical power $P_{\mathrm{Mot.}}$

53. In LVDAC-EMS, make the braking torque vary from 0 to 1.4 N·m in steps of 0.1 N·m. For each braking torque value, wait for the induction motor speed to stabilize, then record in the data table of LVDAC-EMS the parameters of the industrial application and induction motor.

Typical results are presented in this 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 $U_{Ind.}$ (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)
400	0.34	170	166	237	0.715	0.16	0.26	24.6
400	0.34	169	167	237	0.713	0.16	0.26	24.6
400	0.35	176	168	242	0.723	0.20	0.27	31.0
400	0.37	192	168	255	0.752	0.30	0.28	46.0
400	0.40	209	171	269	0.775	0.40	0.29	60.7
400	0.42	227	174	285	0.794	0.50	0.31	75.4
400	0.44	246	177	303	0.811	0.60	0.33	90.2
400	0.47	263	180	318	0.825	0.70	0.35	104
400	0.49	280	183	335	0.838	0.80	0.37	118
400	0.52	298	185	351	0.849	0.90	0.39	132
400	0.54	318	190	370	0.859	1.00	0.42	145
400	0.57	336	194	388	0.866	1.10	0.44	158
400	0.60	355	198	407	0.874	1.20	0.47	171
400	0.63	376	203	427	0.880	1.30	0.49	183
400	0.66	396	208	447	0.885	1.40	0.52	195

54. Observe the data recorded in the data table of LVDAC-EMS. 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.

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The amount of reactive power absorbed by the induction motor varies 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 induction motor)? Explain briefly.

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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 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.

55. In LVDAC-EMS, save the recorded data. Then, clear the data recorded in the data table.

56. On the Capacitive Load, make the necessary switch settings to correct the power factor of the induction motor. In other words, make the necessary switch settings so that the power factor $PF_{\text{Ind.}}$ of the industrial application indicated in LVDAC-EMS 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} $=$ ________ Ω

Reactances X_{C1}, X_{C2}, and X_{C3} $=$ 2200 Ω

57. Using the measured voltages $U_{\text{Ind.}}$, 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 $Q_{\text{PFC}} =$ ________ var

Three-phase capacitor reactive power $Q_{\text{PFC}} =$ 216 var ± 10%

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 53)?

☐ Yes ☐ No

No

58. In LVDAC-EMS, set the braking torque to 0.00 N·m.

59. Record in the data table of LVDAC-EMS the parameters of the industrial application and induction motor.

60. In LVDAC-EMS, make the braking torque vary from 0 to 1.4 N·m in steps of 0.1 N·m. For each braking torque value, wait for the induction motor speed to stabilize, then record in the data table of LVDAC-EMS the parameters of the industrial application and the induction motor.

Typical results are presented in this table.

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

Industrial application parameters						Induction motor parameters		
Voltage $U_{Ind.}$ (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)
400	0.25	168	-55.3	177	0.950	0.16	0.12	24.6
400	0.25	168	-55.8	177	0.949	0.16	0.12	24.6
400	0.27	176	-54.6	184	0.955	0.20	0.13	31.0
400	0.28	191	-52.8	198	0.964	0.30	0.14	45.8
400	0.31	209	-50.1	214	0.972	0.40	0.16	60.8
400	0.33	226	-47.7	231	0.978	0.50	0.18	75.4
400	0.36	243	-45.1	248	0.983	0.60	0.20	90.0
400	0.38	261	-42.5	265	0.987	0.70	0.23	104
400	0.41	279	-38.7	282	0.991	0.80	0.25	118
400	0.43	297	-35.0	300	0.993	0.90	0.28	131
400	0.46	316	-31.6	317	0.995	1.00	0.30	145
400	0.49	335	-27.3	336	0.997	1.10	0.33	158
400	0.52	355	-22.5	356	0.998	1.20	0.36	171
400	0.54	375	-17.4	375	0.999	1.30	0.39	183
400	0.57	395	-11.9	395	1.00	1.40	0.41	195

61. In LVDAC-EMS, save the data recorded in the data table.

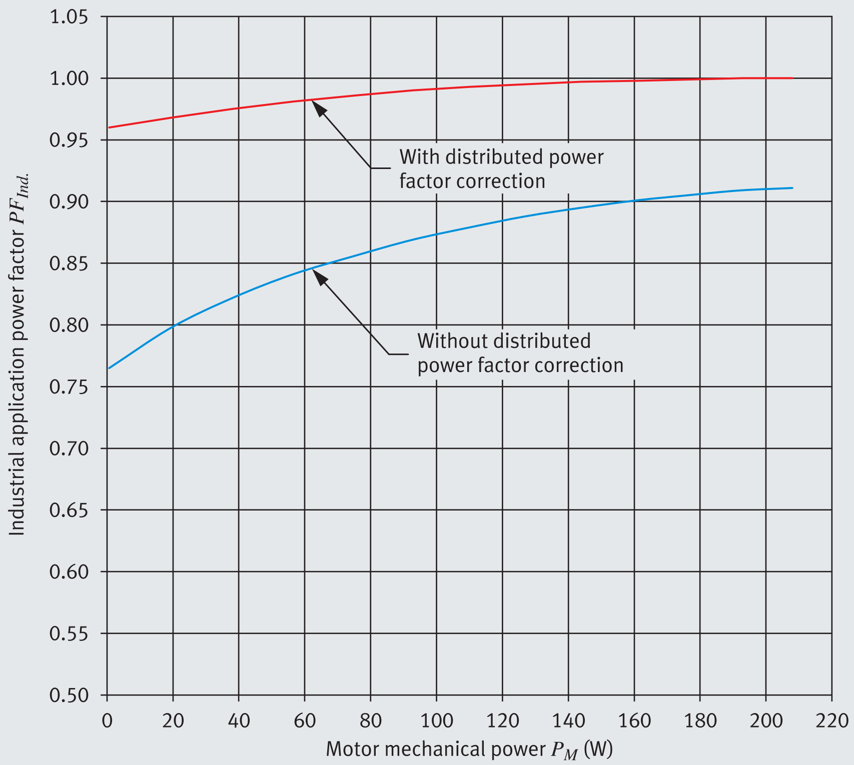
62. In LVDAC-EMS, stop the brake.

63. On the 3AC 400V/DC 230V Power Supply, turn the three-phase ac power source off to stop the squirrel-cage induction motor.

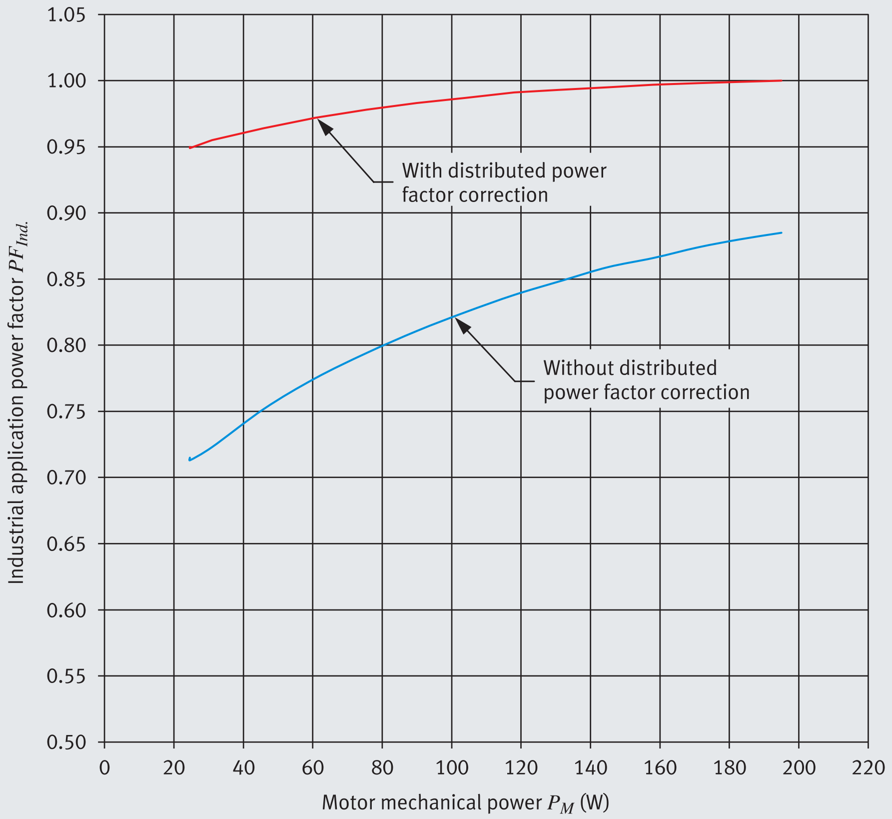
Manipulations

64. 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.

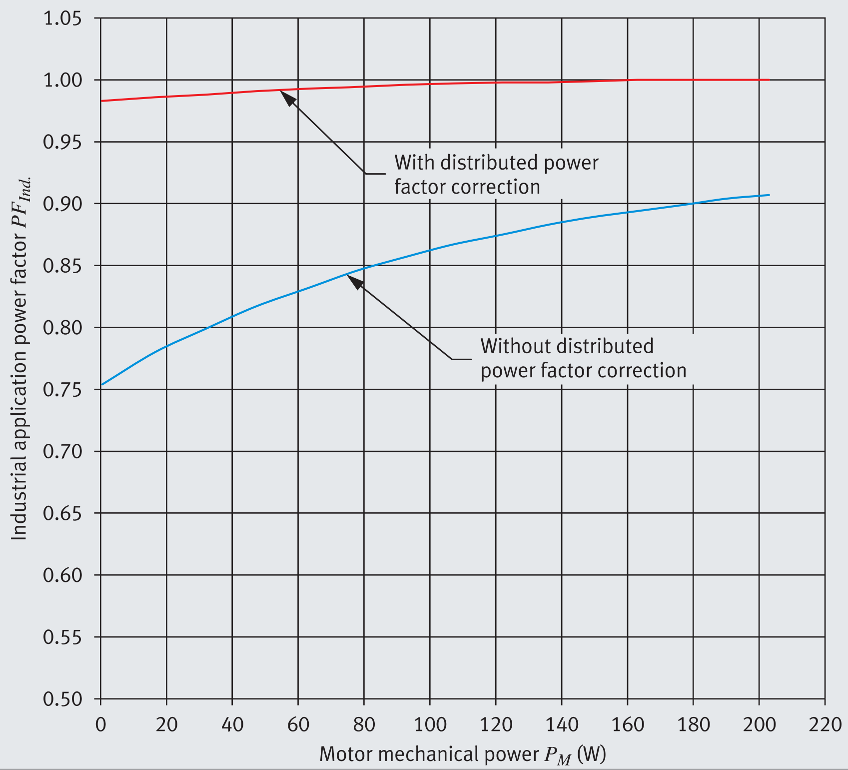
Typical results are shown in this graph.



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 at the motor.



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 at the motor.



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 at the motor.

65. 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.

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.

66. Observe the data recorded in the data table at Step 53 and Step 60 (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?

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

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

68. 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

Yes

69. Close LVDAC-EMS.

Turn the 4 Quadrant Power Supply and Dynamometer Controller off.

Turn the AC 24V Power Supply off.

Turn electric power off at your workstation, if applicable.

Remove all circuit connections, finishing with the equipment earthing connections.

Remove the protective guard. Remove the timing belt that mechanically couples the 4 Quadrant Dynamometer Motor to the Squirrel-Cage Induction Machine.

Return all equipment to its storage location.

Review questions

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

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   Power factor correction consists in increasing the power factor of a load to as close as possible to unity. This is generally achieved by connecting capacitors to the load 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. 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 (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 prevents third-harmonic currents from flowing through the capacitors. Third-harmonic currents are undesirable since they can cause problems in the power system.

Appendix D

Bibliography

Boylestad, Robert L., Introductory Circuit Analysis, 11th Edition, Upper Saddle River, Prentice Hall, 2006, ISBN 978-0131730441.

Dunlop, Jim, Photovoltaic Systems, Homewood, Illinois: American Technical Publishers in partnership with National Joint Apprenticeship and Training Committee for the Electrical Industry, 2007, ISBN 978-0-8269-1287-9.

Jackson, Herbert W, Introduction to Electric Circuits, 8th Edition, Oxford: Oxford University Press, 2008, ISBN 0-19-542310-0.

Linden, David, and Reddy, Thomas B., Handbook of Batteries, 3rd Edition, New York: McGraw-Hill, 2002, ISBN 0-07-135978-8.

Marion, William and WILCOX, Stephen, Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors, Golden, Colorado: National Renewable Energy Laboratory-(NREL), NREL/TP-463-5607, 1994.

Masters, Gilbert M., Renewable and Efficient Electric Power Systems, Hoboken: John Wiley & Sons, 2004, ISBN 0-471-28060-7.

Wildi, Theodore, Electrical Machines, Drives, and Power Systems, 6th Edition, Upper Saddle River, Prentice Hall, 2005, ISBN 978-0131776913.