Electric Power Technology

Automatic Power-Factor Correction Systems

Course Sample

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Course Preliminaries

General safety symbols and procedures

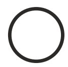
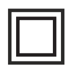
The following table lists the safety and common symbols that may be used in this document and on the equipment. Before performing procedures with the equipment, you should read all sections regarding safety in the User Guide accompanying the equipment.

If applicable, following subsections give general procedures related to the tasks you may be asked to perform in this document. 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.
NOTICE	**NOTICE** 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.

Symbol	Description
	Caution, hot surface.
	Caution, risk of fire.
	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.

Symbol	Description
	Consult the relevant user documentation.
	Radio Equipment Directive (RED) geographical restrictions – consult the relevant user documentation.
	Direct current.
	Alternating current.
	Both direct and alternating current.
	Three-phase alternating current.
	Earth (ground) terminal.
	Protective conductor terminal.
	Frame or chassis terminal.
	Equipotentiality.

Symbol	Description
	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

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions.

The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand.

Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

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

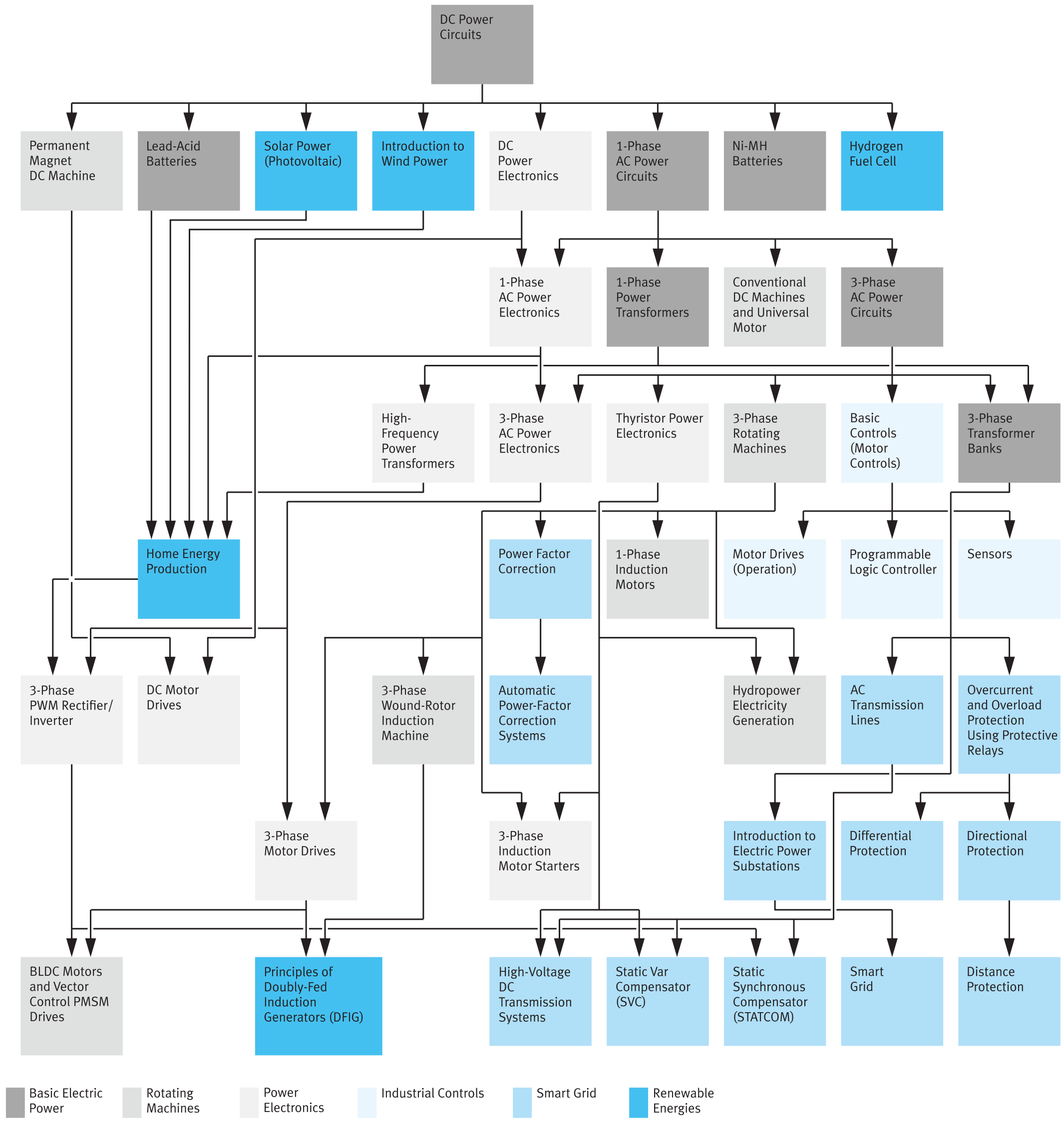


Figure 1: The Electric Power Technology Training Program.

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics.

The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as:

- Home energy production from renewable resources (wind and sunlight)
- Large-scale electricity production from hydropower
- Large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies)

- Smart grid technologies (SVC, STATCOM, HVDC transmission, etc.)
- Storage of electrical energy in batteries
- Drive systems for small electric vehicles and cars

About this course

Industrial applications often include large electric loads (e.g., high-power electric motors) that require a substantial amount of reactive power to operate. In general, this lowers the power factor at the electric power entrance of these applications significantly. This situation is undesirable because most electricity providers add extra charges to the electricity bills of customers whose power factor at the power entrance is below a certain limit. In fact, to comply with the limit imposed by the electricity provider, some means of correcting the power factor at the electric power entrance is required in most industrial applications.

This course covers the various aspects related to the use of an automatic power factor correction (APFC) system to correct the power factor at the power entrance of an application. The first part of the course begins by describing what an APFC system is and explaining how it operates. This part of the course also introduces the power factor (PF) controller, which is an electronic device programmed to control the operation of an APFC system, as well as the various configuration parameters commonly available in most PF controllers. The first part of the course concludes by showing the student how to commission an APFC system, i.e. how to install, connect, configure, and test an APFC system to ensure that it operates correctly.

The second part of the course begins by discussing the large current transient that occurs whenever a capacitor bank is switched on and the resulting stress on the equipment. It continues by describing and explaining the various means that are used in APFC systems to limit the magnitude of the current transient that occurs whenever a capacitor bank is switched on.

The third part of the course begins by introducing the various options available in the PF controller of most APFC systems to control the way the various capacitor banks in the system are switched on and off to correct the power factor. Then, it shows how to set these options properly to optimize the operation of the APFC system and maximize its operating life cycle.

This description is only a brief summary of the topics covered in the course. In fact, the course also covers several other interesting topics related to APFC systems, such as the impact that the electricity billing practice has on the arrangement of an APFC system, how to determine the size of the APFC system required for a specific application, how to determine the value of the targeted power factor required for a specific application, how to determine the resolution of the power factor correction achieved by an APFC system, the relationship between APFC systems and the problems caused by harmonic distortion in the electric power system, and more.

Figure 2: Industrial applications often include large electric loads that require a substantial amount of reactive power to operate, thereby resulting in a low power factor. To comply with the power factor limit imposed by the electricity provider, some means of correcting the power factor (e.g., an APFC system) at the electric power entrance is required in most industrial applications.

Prerequisites

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
- Power Factor Correction

System of units

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

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.

Sample

Extracted from

Workbook - instructor

Commissioning an APFC System

199 min.

Discussion outline

Learning outcomes

After completing this section, you will be able to:

- Enumerate and describe the main steps to be performed to commission an APFC system.
- Connect the current and voltage inputs of the PF controller in an APFC system.
- Describe the configuration parameters in the PF controller that define the fundamental characteristics of an APFC system.
- Explain why the power factor correction achieved by an APFC system has a finite resolution.
- Determine the value of the targeted power factor required for a specific application.
- Commission an APFC system and confirm that it operates correctly.
- Use the automatic initialization function of a PF controller to facilitate the commissioning of an APFC system.

The discussion of this exercise covers the following points:

- Commissioning an APFC system
- Connection of the current and voltage measurement inputs of the PF controller in an APFC system
- Configuration parameters of the PF controller
- Configuration parameters defining the fundamental characteristics of an APFC system
- Setting the configuration parameters in the PF controller of an APFC system
- Completing the commissioning of an APFC system
- Resolution of the power factor correction achieved by an APFC system

- Determining the targeted power factor value required for a specific application
- The Festo Power Factor Controller module

Commissioning an APFC system

Commissioning an APFC system is basically a three-step process. These steps are described below.

1. Install the APFC system and connect it to the electric power system according to the instructions of the manufacturer.
2. Configure the APFC system to meet the requirements of the specific application in which it is used. This is achieved by setting various configuration parameters in the PF controller of the APFC system.
3. Start automatic correction of the power factor by the APFC system, and confirm that the system operates correctly (i.e., it properly corrects the power factor at the power entrance of the application).

These three steps, which should be performed in the order above, are described and explained in the next sections of this course.

Connection of the current and voltage measurement inputs of the PF controller in an APFC system

The PF controller in most APFC systems measures one line current and either one line-to-neutral (LN) voltage or one line-to-line (LL) voltage to determine the three-phase power values and power factor at the power entrance of the application. Consequently, it is assumed that the load in the application is balanced. The following figure shows the corresponding two types of connection possible for measuring the current and voltage at the power entrance of the application. These two types of connection are commonly identified as 3Ph-1LN1 when one line-to-neutral (LN) voltage is measured and 3Ph-1LL1 when one line-to-line (LL) voltage is measured. In these identifiers, the first 1 indicates the number of voltages measured and the second 1 indicates the number of currents measured.

Certain PF controllers measure the three line currents and either the three line-to-neutral (LN) voltages or the three line-to-line (LL) voltages to determine the three-phase power values and power factor at the power entrance of the application. Consequently, the power values and the power factor can be determined accurately even if the load is unbalanced. These other two types of connection are commonly identified as 3Ph-3LN3 when line-to-neutral (LN) voltages are measured and 3Ph-3LL3 when line-to-line (LL) voltages are measured.

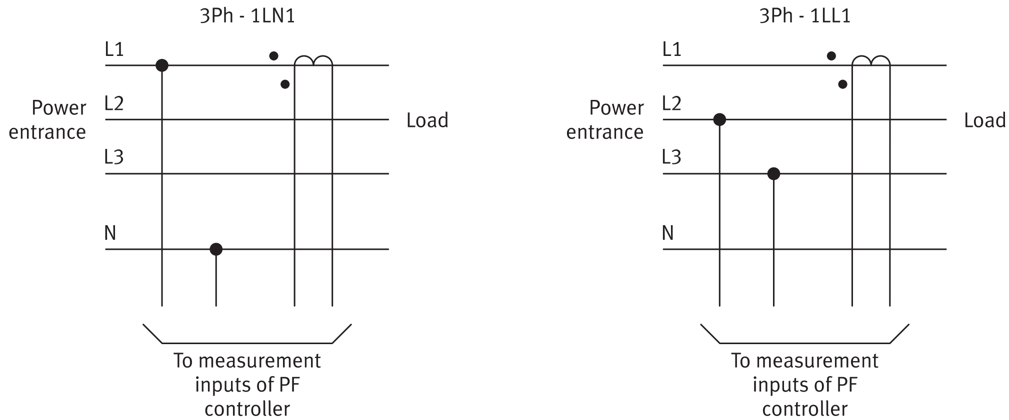


Figure 16: Types of connection 3Ph-1LN1 and 3Ph-1LL1 are commonly used in APFC systems to measure the current and voltage at the power entrance of the application.

Proper connection of the current and voltage measurement inputs of a PF controller

To calculate power values, the PF controller assumes that a specific line current (e.g., line current I_1) and a specific voltage (e.g., line-to-neutral voltage E_{1-N}) are measured. The current and voltage measurement inputs of the PF controller must be connected in accordance to ensure proper calculation of the active power, reactive power, apparent power, and power factor at the power entrance of the application. The following figure shows the proper connection of the current and voltage measurement inputs of a PF controller in which calculation of the power values and the power factor assumes that line current I_1 and line-to-neutral voltage E_{1-N} are measured.

In general, the calculation of the power values and the power factor in PF controllers assumes that one line current and the corresponding line-to-neutral voltage (i.e., I_1 and E_{1-N}, I_2 and E_{2-N}, or I_3 and E_{3-N}) are measured.

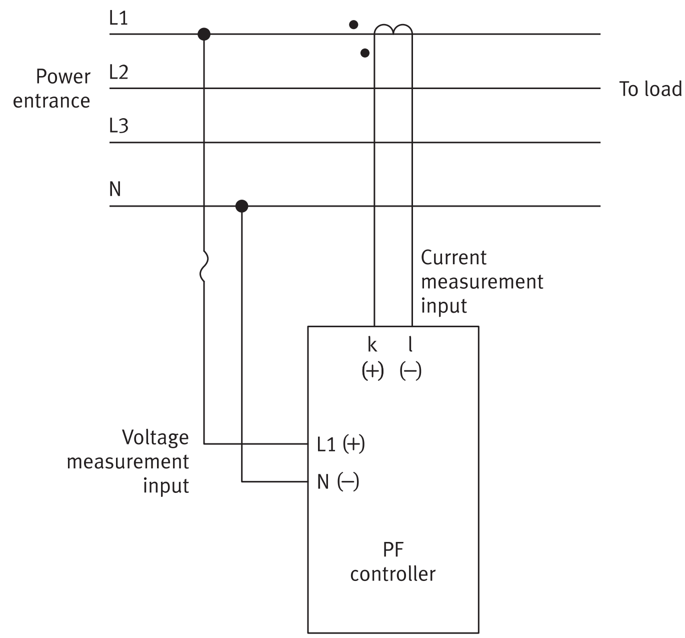


Figure 17: Proper connection of the current and voltage measurement inputs of a PF controller in which calculation of the power values and the power factor assumes that line current I_1 and line-to-neutral voltage E_{1-N} are measured.

Incorrect connection of the current and voltage measurement inputs of a PF controller

Incorrect connection of the current and voltage measurement inputs of the PF controller is a common cause of malfunction in a newly installed APFC system. This is because the incorrect connection of the current and voltage measurement inputs of the PF controller introduces a phase shift between the measured voltage and current. This phase shift, which is not as expected by the PF controller, is undesirable because it leads to inaccurate values of the active power, reactive power, apparent power, and power factor measured at the power entrance of the application. Fortunately, most PF controllers can compensate for any phase shift introduced by the incorrect connection of the current and voltage measurement inputs. To do so, the PF controller applies a corrective phase shift to either the measured voltage or the measured current that compensates for the phase shift between the measured voltage and current introduced by the incorrect connection of the current and voltage measurement inputs. In general, todays PF controllers have an automatic initialization function (sometimes referred to as the automatic commissioning function) that can determine and set the phase shift value required to compensate for the phase shift introduced by the incorrect connection of the current and voltage measurement inputs.

The user can also determine the phase shift between the measured voltage and current that is introduced by the incorrect connection of the current and voltage measurement inputs, and then, manually enters in the PF controller the phase shift value required for the compensation.

For instance, consider an APFC system in which the PF controller assumes that line current I_1 and line-to-neutral voltage E_{1-N} are measured to determine the power values and power factor at the power entrance of the application. In this case, the PF controller assumes that the measured voltage and current are in phase when the power factor is equal to 1.0. The following procedure can be used to determine the phase shift between the measured voltage and current that is introduced by the connection of the current and voltage measurement inputs.

- Consult the wiring diagram of the APFC system to know how the current and voltage measurements inputs are actually connected. Then, use this information to determine the line current and the voltage that the PF controller measures.
- Draw a phasor diagram that represents the current and voltage that the PF controller measures, assuming a unity power factor.
- Use the phasor diagram that you drew to determine the phase shift between the measured voltage and current (more specifically, the phase advance of the measured voltage over the measured current).

If the PF controller actually measures line current I_1 and line-to-line voltage E_{3-2} instead of measuring line current I1 and line-to-neutral voltage E_{1-N}, the phase shift between the measured voltage and current determined using the above procedure is 90°, as is shown in the following figure. This phase shift value should be entered in the PF controller to compensate for the phase shift introduced by the incorrect connection of the current and voltage measurement inputs.

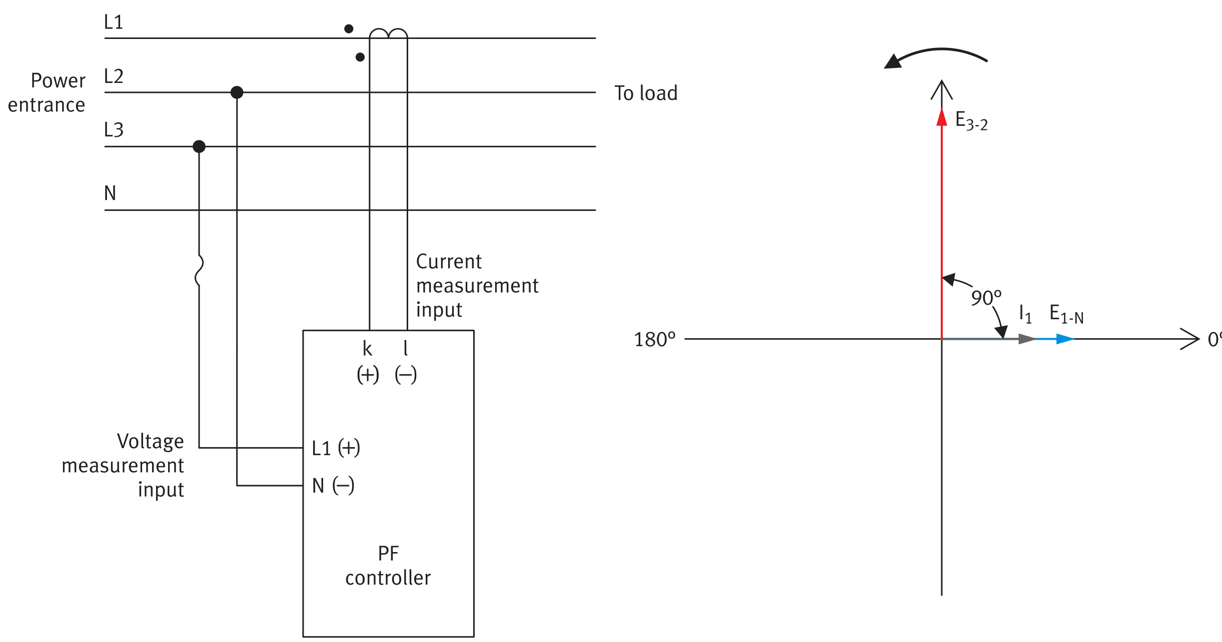


Figure 18: Determining the phase shift between the measured voltage and current that is introduced by the incorrect connection of the current and voltage measurement inputs of the PF controller.

Connection of the measurement inputs of the Festo Power Factor Controller module

The PF controller in the Festo Power Factor Controller module assumes that line current I_1 and line-to-neutral voltage E_{1-N} are measured for the purpose of calculating the power values and the power factor at the power entrance of the application. Consequently, the phase shift between the measured voltage and current is 0° (at unity power factor) when the current and voltage measurement inputs of the PF controller are actually connected to measure line current I_1 and line-to-neutral voltage E_{1-N}, as is shown in the first row of the following table. The table also shows all possible values of phase shift between the measured voltage and current that can be introduced by the way the voltage and current measurement inputs of the PF controller are actually connected (more specifically, the values shown are the phase advance of the measured voltage with respect to the measured current). Note that all phase shift values are for a unity power factor.

Many ways of connecting the voltage and current measurement inputs of the PF controller other than these shown in the following table are possible. However, no matter how the voltage and current measurement inputs of the PF controller are connected, the resulting phase shift can only have one of the values listed in the table.

Table 3: Values of the phase shift between the measured voltage and current (at unity power factor) introduced by the way the voltage and current measurement inputs of the PF controller in the Festo Power Factor Controller module are connected.

Measured current	Measured voltage	Phase shift (phase advance of E vs I)
I_1	E_{1-N}	0°
I_1	E_{1-2}	30°
I_1 (reversed phase)	E_{2-N}	60°
I_1	E_{3-2}	90°
I_1	E_{3-N}	120°
I_1	E_{3-1}	150°
I_1 (reversed phase)	E_{1-N}	180°

Measured current	Measured voltage	Phase shift (phase advance of E vs I)
I_1 (reversed phase)	E_{1-2}	210°
I_1	E_{2-N}	240°
I_1	E_{2-3}	270°
I_1 (reversed phase)	E_{3-N}	300°
I_1 (reversed phase)	E_{3-1}	330°

Configuration parameters of the PF controller

An APFC system can be configured to meet the requirements of the specific application in which it is used. This is achieved by setting various configuration parameters in the PF controller of the APFC system. The following table lists the configuration parameters that most PF controllers include. Notice that the configuration parameters are separated in four different groups. The first two groups (named "General" and "Capacitor banks") contain the configuration parameters defining the fundamental characteristics of the APFC system. The last two groups (named "Capacitor bank switching control" and "Capacitor bank switching control delays") contain the configuration parameters related to the switching control of the capacitor banks.

All the configuration parameters in the table can be set manually by the user to meet the requirements of the specific application in which the APFC system is used. As mentioned before, todays PF controllers generally have an automatic initialization function (sometimes referred to as the automatic commissioning function) that can set the key configuration parameters, i.e., the parameters that are critical for correct operation of the APFC system, in your place. The key configuration parameters that the automatic initialization function can generally set are identified by an asterisk in the table.

The configuration parameters defining the fundamental characteristics of the APFC system as well as the operation of the automatic initialization function in PF controllers are discussed in the next sections of this course. On the other hand, the parameters related to the switching control of the capacitor banks are discussed later in the course.

Table 4: Configuration parameters available in most PF controllers.

Parameter group	Parameter name
General	• Targeted power factor ($\cos\phi_{\text{Targeted}}$) • *Phase shift • Current transformer ratio • *Measured voltage • Voltage transformer ratio (when required)
Capacitor banks	• *Number of capacitor banks • *Reactive-power step size (Q_{Step}) • *Bank sequence • Output/bank status
Capacitor bank switching control	• Switching control mode • Maximum one-step power switching • Integration time • Bank switching trigger point
Capacitor bank switching control delays	• Switch-on delay • Switch-off delay • Discharge time

Configuration parameters defining the fundamental characteristics of an APFC system

Introduction

This section presents the configuration parameters defining the fundamental characteristics of an APFC system, i.e., the parameters in the "General" and "Capacitor banks" groups in Table 4. All these parameters should normally be configured at commissioning to ensure that the APFC system operates correctly and meets the requirements of the application in which it is used.

The asterisks in the table identify the key configuration parameters of an APFC system that can generally be set by the automatic initialization function in most PF controllers.

Targeted power factor (cos $\varphi_{\text{Targeted}}$)

This configuration parameter sets the value at which the PF controller try to maintain the power factor by switching capacitor banks on and off in the APFC system. It also specifies the nature (inductive or capacitive) of the targeted power factor. The "Targeted power factor" parameter (also commonly referred to as the "$\cos \phi_{\text{Targeted}}$" parameter) can generally be set to values between 0.1 and 1, inductive or capacitive.

Phase shift

This configuration parameter sets the phase shift value that the PF controller applies to either the measured voltage or the measured current to take into account the way its current and voltage measurement inputs are actually connected in the APFC system. Refer to the documentation of the PF controller to know the exact phase shift values required for various ways of connecting the current and voltage measurement inputs of the unit.

PF controllers with an automatic initialization function can determine the phase shift value required to compensate for the way the current and voltage measurement inputs are actually connected and set the "Phase shift" parameter to the value required.

Current transformer ratio

This configuration parameter corresponds to the ratio of the current transformer used to measure the line current at the power entrance of the application in which the APFC system is installed. On some PF controllers, the current transformer ratio is programmed by entering in the unit the nominal values of the primary current and secondary current of the transformer (e.g., 250 A and 5 A). On some other PF controllers, the current transformer ratio (e.g., 50 for a 250 A:5 A current transformer) is entered directly in the unit.

Measured voltage

This configuration parameter corresponds to the value of the voltage at the voltage measurement input of the PF controller. For instance, when the PF controller is connected for direct measurement of the line-to-neutral voltage at the power entrance of the application in which the APFC system is installed, the "Measured voltage" parameter should be set to the value of the line-to-neutral voltage of the electric power system (e.g., 120 V). Similarly, when the PF controller is connected for direct measurement of the line-to-line voltage at the power entrance of the application, the "Measured voltage" parameter should be set to the value of the line-to-line voltage of the electric power system (e.g., 208 V). On the other hand, when the PF controller is connected to measure voltage at the power entrance of the application via a voltage transformer, the "Measured voltage" parameter should be set to the value of voltage expected at the secondary of the voltage transformer (in general, this corresponds to the nominal value of the secondary voltage of the transformer).

PF controllers with an automatic initialization function can set the "Measured voltage" parameter to the value of voltage that is detected at the voltage measurement input of the unit.

Voltage transformer ratio

This configuration parameter corresponds to the ratio of the voltage transformer (if any) used to measure voltage at the power entrance of the application in which the APFC system is installed. On some PF controllers, the voltage transformer ratio is programmed by entering the nominal values of the primary voltage and secondary voltage of the transformer (e.g., 4.8 kV and 120 V) in the unit. On some other PF controllers, the voltage transformer ratio (e.g., 40 for a 4.8 kV:120 V voltage transformer) is entered directly in the unit. Finally, note that the "Voltage transformer ratio" parameter should be ignored or left to the default value (i.e., 1.00) when no voltage transformer is used to measure voltage at the power entrance of the application.

Number of capacitor banks

This configuration parameter corresponds to the number of capacitor banks in the APFC system, i.e., the number of capacitor banks that are connected to the control outputs of the PF controller.

PF controllers with an automatic initialization function can detect the number of capacitor banks that are connected to their control outputs and set the "Number of capacitor banks" parameter accordingly.

Reactive-power step size (Q_{Step})

This configuration parameter corresponds to the size of the smallest change in reactive power that the APFC system can perform to correct the power factor. The smallest change in reactive power corresponds to the nominal power rating of the smallest capacitor bank in the APFC system. For instance, in an APFC system containing two 10 kvar capacitor banks and four 20 kvar capacitor banks, the "Reactive-power step size" parameter (also commonly referred to as the "Q_{Step}" parameter) should be set to 10 kvar.

PF controllers with an automatic initialization function can measure the smallest change in reactive power that the APFC system is able to perform and set the "Reactive-power step size" parameter accordingly.

Bank sequence

This configuration parameter corresponds to the relative power ratings (relative sizes) of the capacitor banks available in the APFC system. More specifically, this parameter corresponds to the power ratings of these banks with respect to each other, the power rating of the smallest capacitor bank in the APFC system being attributed a value of 1. To ensure that the APFC system operates properly, the "Bank sequence" parameter must be set to match the actual sequence of the capacitor banks in the system. For instance, when the APFC system contains two 50 kvar capacitor banks and four 100 kvar capacitor banks, the "Bank sequence" parameter should be set to 1, 1, 2, 2, 2, 2. The two 1s and the four 2s in the "Bank sequence" parameter correspond to the relative sizes of the two 50 kvar capacitor banks and the four 100 kvar capacitor banks, respectively.

In most PF controllers, the default value of the "Bank sequence" parameter is 1, 1, 1, 1, 1, 1 (for a PF controller having 6 outputs). PF controllers with an automatic initialization function can measure the reactive power produced by each capacitor bank in the APFC system and set the "Bank sequence" parameter accordingly.

The following table shows examples of capacitor bank sequences that are commonly used in APFC systems. In these examples, the APFC systems contain 12 capacitor banks.

The choice of a capacitor bank sequence for a specific application is largely influenced by several factors such as the billing practice of the local electric power utility, the size (i.e., the installed power) of the application in which the APFC system is used, and the market availability of components (i.e., capacitor banks and capacitor contactors commonly available are preferred).

Table 5: Capacitor bank sequences commonly used in APFC systems.

Sequence number	Sequence (relative sizes of the capacitor banks)
1	1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1
2	1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2
3	1, 2, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3
4	1, 2, 3, 4, 4, 4, 4, 4, 4, 4, 4, 4
5	1, 2, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4
6	1, 2, 3, 6, 6, 6, 6, 6, 6, 6, 6, 6
7	1, 2, 4, 8, 8, 8, 8, 8, 8, 8, 8, 8
8	1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 2
9	1, 1, 1, 1, 1, 6, 6, 6, 6, 6, 6, 6
10	1, 1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2
11	1, 1, 2, 2, 2, 4, 4, 4, 4, 4, 4, 4
12	1, 1, 2, 2, 4, 4, 4, 4, 4, 4, 4, 4

Sequence number	Sequence (relative sizes of the capacitor banks)
13	1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 2, 2
14	1, 1, 2, 3, 3, 3, 3, 3, 3, 3, 3, 3
15	1, 1, 2, 4, 4, 4, 4, 4, 4, 4, 4, 4
16	1, 1, 2, 4, 8, 8, 8, 8, 8, 8, 8, 8
17	1, 2, 2, 3, 3, 3, 3, 3, 3, 3, 3, 3
18	1, 2, 3, 4, 4, 8, 8, 8, 8, 8, 8, 8
19	1, 2, 2, 4, 4, 4, 4, 4, 4, 4, 4, 4
20	1, 2, 2, 2, 4, 4, 4, 4, 4, 4, 4, 4

Output/bank status

This configuration parameter sets the status of each control output of the PF controller, and consequently, the status of the capacitor bank controlled by each output. For each control output, the "Output/bank status" parameter can generally be set to one of the following three options: "fixed off", "fixed on", and "automatic".

Setting the "Output/bank status" parameter of a specific control output of the PF controller to "fixed off" de-energizes this output, and thus, permanently switches off the corresponding capacitor bank (e.g., for the maintenance of a capacitor bank). Inversely, setting the "Output/bank status" parameter of a specific control output of the PF controller to "fixed on" energizes this output, and thus, permanently switches on the corresponding capacitor bank (e.g., to set a fixed amount of reactive power for power factor correction). Finally, setting the "Output/bank status" parameter of a specific control output to "automatic" lets the PF controller energize or de-energize this control output to switch the corresponding capacitor bank on or off as required to correct the power factor.

In many PF controllers, the "Output/bank" status parameter of each control output is set to "automatic" by default.

Setting the configuration parameters in the PF controller of an APFC system

Automatic setting of the key configuration parameters in the PF controller

To facilitate commissioning of an APFC system, most PF controllers have an automatic initialization function (sometimes referred to as the automatic commissioning function) that can set the key configuration parameters, i.e., the parameters that are critical for correct operation of the APFC system, in your place. The automatic initialization function in PF controllers performs a series of tasks to determine the proper values for each of the key configuration parameters, then sets these parameters accordingly. The following table presents the tasks that the automatic initialization function in a PF controller generally performs and the key configuration parameters that are set.

The automatic initialization function leaves all other configuration parameters to the default values established by the manufacturer of the PF controller.

Table 6: Tasks generally performed by the automatic initialization function in a PF controller and key configuration parameters that are set.

Task name	Task description and set configuration parameter
Detection of the measurement input connection	Detects how the current and voltage measurement inputs of the PF controller are connected to the electric power system and sets the "Phase shift" parameter to the value required.
Voltage measurement	Measures the value of the voltage applied to the voltage measurement input of the PF controller and sets the "Measured voltage" parameter accordingly.
Detection of the active control outputs	Detects which control outputs of the PF controller are actually used to switch capacitor banks on and off and sets the "Number of capacitor banks" parameter accordingly.
Measurement of the reactive-power step size	Measures the smallest change in reactive power that the APFC system can perform and sets the "Reactive-power step size" parameter (" Q_{Step} " parameter) accordingly.
Detection of the capacitor bank sequence	Determines the capacitor bank sequence by measuring the reactive power produced by each capacitor bank in the APFC system, and sets the "Bank sequence" parameter accordingly.

To be able to set the key configuration parameters properly, the automatic initialization function requires some basic information about the APFC system in which the PF controller is used. The basic information required is generally the ratio of the current transformer used to measure the line current at the power entrance of the application in which the APFC system is installed or the nominal power rating of the smallest capacitor bank in the APFC system. The automatic initialization function generally asks the user to enter this information immediately after it is started.

Once the automatic initialization is finished, it is highly recommended to check the values of the key configuration parameters in the PF controller (listed in the following table) to make sure that they have been set in accordance with the characteristics of the APFC system. Also, it is a good practice to check that the "Output/bank status" parameter of each of the control outputs of the PF controller that are actually used to switch capacitor banks in the APFC system is set correctly (i.e., set to "automatic"). Finally, the "Targeted power factor" parameter ("$\cos \phi_{\text{Targeted}}$ " parameter) in the PF controller must be set to the value required to ensure that the APFC system maintains the power factor at the value desired for the application in which it is used.

When a voltage transformer is used to measure voltage at the power entrance of the application in which the APFC system is installed, its voltage ratio should be entered in the PF controller after the automatic initialization is finished. Doing so ensures that the PF controller displays the correct values (i.e., correctly scaled values) of the voltage and power measured at the power entrance of the application in which the APFC system is installed.

Table 7: Key configuration parameters in the PF controller to be checked after the automatic initialization is finished.

Key configuration parameters to be checked
Phase shift
Measured voltage
Number of capacitor banks
Reactive power step size (Q_{Step})
Bank sequence

Setting of the parameters related to the bank switching control in the PF controller

As mentioned previously in the course, the automatic initialization function sets the key configuration parameters in the PF controller, i.e., the parameters that are critical for correct operation of the APFC system, and leaves all other configuration parameters (i.e., the configuration parameters related to the capacitor bank switching control for the most part) to the default values established by the manufacturer of the PF controller. The settings of the configuration parameters in the PF controller that are related to the switching control of the capacitor banks must be reviewed and corrected manually as required to ensure that the APFC system meets the requirements of the specific application in which it is used. This step should normally be done just after the setting of the key configuration parameters in the PF controller is finished.

Detailed information on how to set the configuration parameters in the PF controller that are related to capacitor bank switching control is provided later in this course.

Completing the commissioning of an APFC system

Confirming correct operation of the APFC system

Once an APFC system is installed and connected to the electric power system, and that the configuration parameters in the PF controller have been set as required by the specific application in which the APFC system is used, confirming correct operation of the APFC system is the final step to complete the commissioning of the system. This is done by performing the following procedure.

1. Start automatic correction of the power factor in the PF controller of the APFC system.

2. Observe the operation of the APFC system to verify that it switches on the capacitor banks required to bring the power factor at the power entrance of the application as close as possible to the targeted value. If this is the case, this confirms correct operation of the APFC system, and the procedure is terminated. Otherwise, go to the next step.

3. Review the values of the configuration parameters in the PF controller and make corrections, when necessary, to ensure that all parameters are set as required by the specific application in which the APFC system is used.

4. Make sure that the APFC system components (PF controller, capacitor contactors, capacitor banks, etc.) are correctly wired. Correct the system wiring if a misconnection is found.

   ⚠ WARNING

   Be extremely careful when performing this step of the procedure because high voltage is present in the system.

5. Repeat the procedure.

Resolution of the power factor correction achieved by an APFC system

Introduction

An APFC system achieves power factor correction by switching capacitor banks on and off as required to maintain the reactive power at the power entrance of an application (Q_{Entrance}) as close as possible to the value that makes the power factor equal to the targeted value. This means that an APFC system achieves discrete (step) correction of the power factor. Consequently, the power factor correction achieved by an APFC system has a finite resolution.

The value of reactive power at the power entrance of the application that makes the power factor equal to the targeted value is referred to as the targeted reactive power (Q_{Targeted}). In most cases, the amount of reactive power provided by the capacitor banks that an APFC system switches on to correct the power factor rarely makes reactive power Q_{Entrance} equal to reactive power Q_{Targeted}. Consequently, the value of the corrected power factor is generally a little under the targeted value or a little above the targeted value.

The value of reactive power Q_{Targeted} depends on the displacement angle (ϕ_{Targeted}) associated with the targeted power factor ($\cos\phi_{\text{Targeted}}$) set in the PF controller as well as on the value of the active power at the power entrance (P_{Entrance}). It can be calculated using the following equation.

$$Q_{\text{Targeted}} = P_{\text{Entrance}} \times \tan\phi_{\text{Targeted}} \tag{1}$$

For instance, when the values of the targeted power factor ($\cos\phi_{\text{Targeted}}$) and active power P_{Entrance} are 1.0 and 100 kW, respectively, the value of displacement angle ϕ_{Targeted} is 0°, and thus, the value of reactive power Q_{Targeted} is 0 kvar as shown by the calculation below.

$$Q_{\text{Targeted}} = 100\,\text{kW} \times \tan 0^{\text{o}} = 0\,\text{kvar}$$

On the other hand, when the values of the targeted power factor ($\cos\phi_{\text{Targeted}}$) and active power P_{Entrance} are 0.9 and 100 kW, respectively, the value of displacement angle ϕ_{Targeted} is 25.84°, and thus, the value of reactive power Q_{Targeted} is 48.43 kvar as shown by the calculation below.

$$Q_{\text{Targeted}} = 100\,\text{kW} \times \tan 25.84^{\text{o}} = 48.43\,\text{kvar}$$

Finally, the values of the "reactive-power step size" ("Q_{Step} ") and "Bank switching trigger point" parameters set in the PF controller determine the maximum amount by which reactive power Q_{Entrance} (once corrected by the APFC system) can deviate from the value of reactive power Q_{Targeted}. In other words, these two parameters determine the resolution of the power factor correction achieved by the APFC system. When the "Bank switching trigger point" parameter is set according to standard practice, reactive power Q_{Entrance} can deviate from the value of reactive power Q_{Targeted} by a maximum amount of ±0.66 Q_{Step}. For instance, when the value of reactive power Q_{Targeted} is 50 kvar and the value of the "reactive-power step size" ("Q_{Step}") parameter set in the PF controller is 15 kvar, the APFC system maintains the reactive power Q_{Entrance} to 50 kvar ±9.9 kvar.

The "Bank switching trigger point" parameter is covered later in this course.

APFC system response when the targeted power factor is 1.00

The following figure shows the response of an APFC system when the value of the targeted power factor ($\cos\phi_{\text{Targeted}}$) is 1.00. To make the value of the power factor equal to 1.00, the reactive power at the power entrance of the application (Q_{Entrance}) must be reduced to zero in this situation. To achieve this goal, the APFC system switches capacitor banks on or off until the reactive power Q_{Entrance} is between -0.66 Q_{Step} and +0.66 Q_{Step}. Consequently, the value of the corrected power factor is less than unity, unless the amount of reactive power provided by the APFC system matches the exact amount of reactive power at the load (which rarely happens). When the amount of reactive power provided by the capacitor banks that are switched on to correct the power factor is less than the reactive power at the load (i.e., when reactive power Q_{Entrance} is between 0 and +0.66 Q_{Step}), the power factor at the power entrance is inductive. Conversely, when the amount of reactive power provided by the capacitor banks that are switched on to correct the power factor exceeds the reactive power at the load (i.e., when reactive power Q_{Entrance} is between 0 and -0.66 Q_{Step}), the power factor at the power entrance is capacitive.

To summarize, the finite resolution (±0.66 Q_{Step}) of the APFC system limits its ability to maintain the value of the power factor at the power entrance to exactly 1.00. However, the larger the value of the active power at the power entrance of the application (P_{Entrance}) with respect to the resolution (±0.66 Q_{Step}) of the APFC system, the closer to the targeted value of 1.00 the APFC system can maintain the value of the power factor at the power entrance.

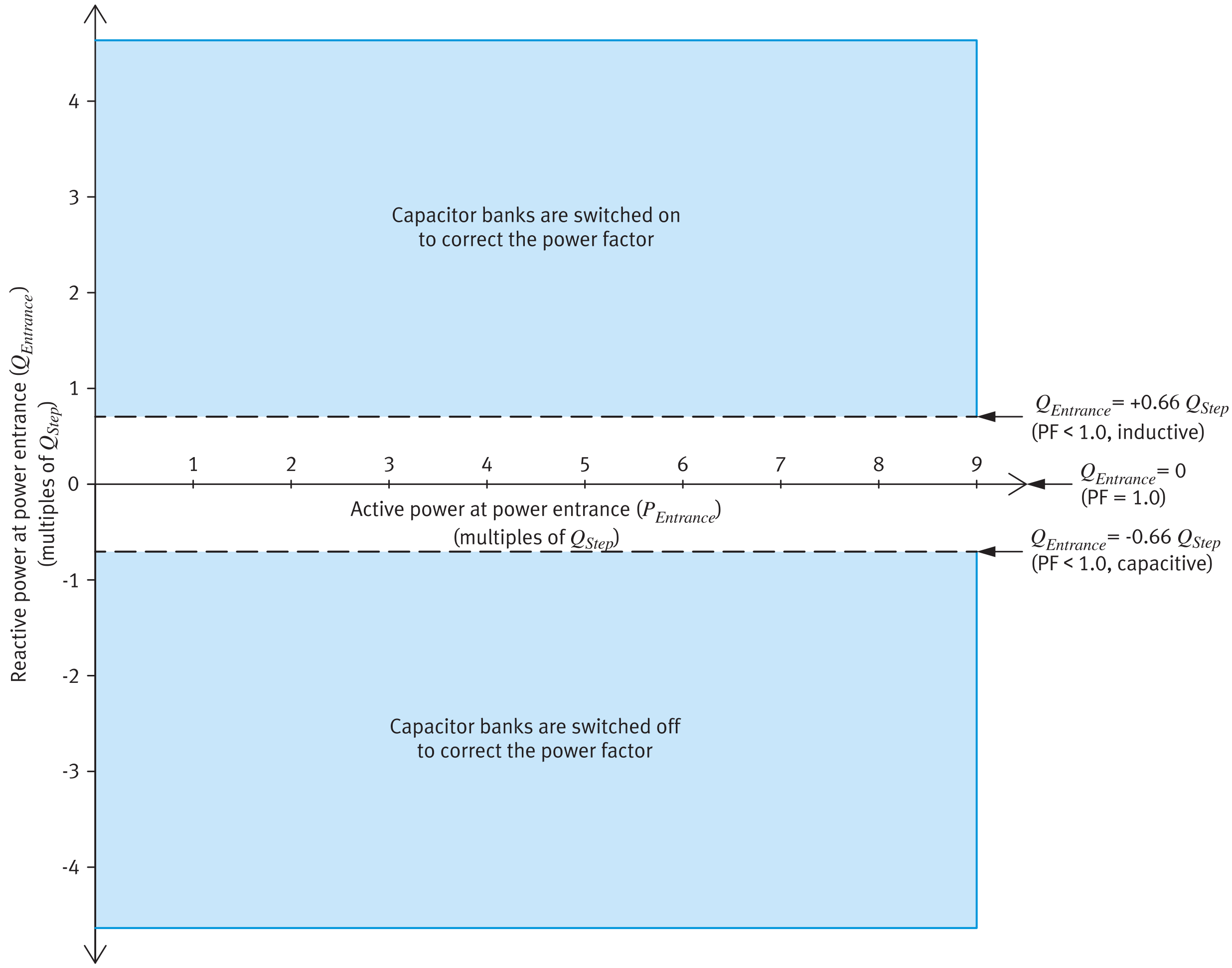


Figure 19: Response of an APFC system when the targeted power factor ($\cos\phi_{\text{Targeted}}$) is 1.00.

APFC system response when the targeted power factor is less than 1.00

The following figure shows the response of an APFC system when the value of the targeted power factor ($\cos\phi_{\text{Targeted}}$) is less than unity (0.90, inductive in this example). To make the value of the power factor equal to 0.90, the reactive power at the power entrance of the application (Q_{Entrance}) must be maintained to the value of reactive power Q_{Targeted}, which in this situation, is equal to 0.484 times the active power at the power entrance of the application (P_{Entrance}). To achieve this goal, the APFC system switches capacitor banks on or off until the reactive power Q_{Entrance} is equal to 0.484 times the active power P_{Entrance} plus or minus 0.66 Q_{Step}. Consequently, the corrected power factor is inductive and its value is below 0.90 or above 0.90, unless the amount of reactive power provided by the APFC system makes reactive power Q_{Entrance} equal to 0.484 times active power P_{Entrance}.

To summarize, the finite resolution (±0.66 Q_{Step}) of the APFC system limits its ability to maintain the value of the power factor at the power entrance to exactly 0.90. However, the larger the value of the active power P_{Entrance} with respect to the resolution (±0.66 Q_{Step}) of the APFC system, the closer to the targeted value of 0.90 the APFC system can maintain the value of the power factor at the power entrance. Also, note that when the value of the active power P_{Entrance} becomes less than about 1.5 times Q_{Step}, the value of the reactive power Q_{Entrance} can be negative. This means that the corrected power factor can be capacitive instead of inductive when the value of active power P_{Entrance} is low.

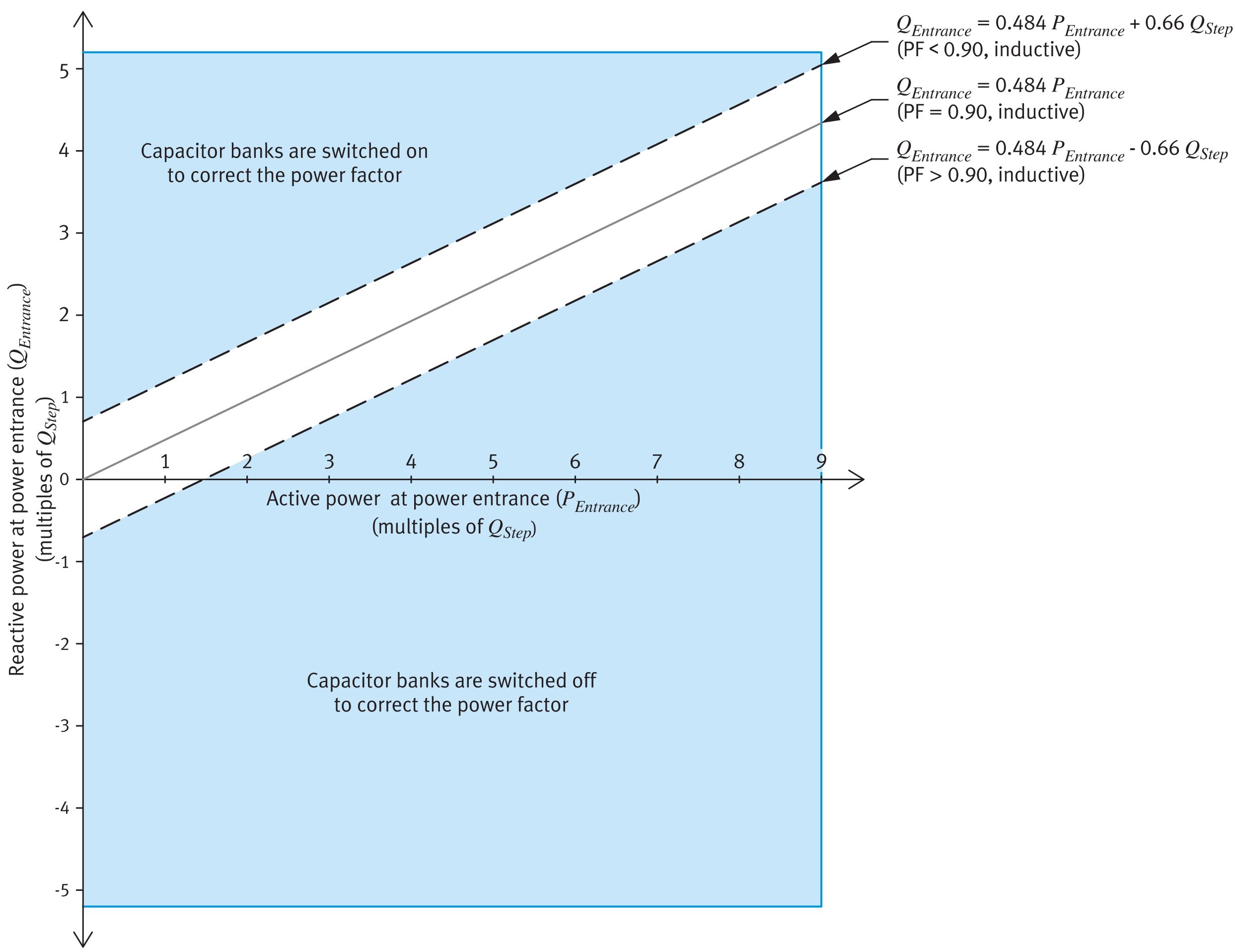


Figure 20: Response of an APFC when the targeted power factor ($\cos\phi_{\text{Targeted}}$) is 0.90, inductive.

Determining the targeted power factor value required for a specific application

Introduction

The power factor of an application after correction by an APFC system may be a little under or a little above the targeted value, as explained previously in this course. However, the long-time average value (e.g., the monthly average value) of the corrected power factor should be very close to the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter set in the PF controller of the APFC system. To avoid any surcharge on the electricity bill due to a low power factor, the above facts must be considered when determining the value at which the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter should be set in the PF controller of the APFC system.

Targeted power factor value versus the billing practice of the electric power utility

When the monthly average value of the power factor is used for billing purpose (e.g., when active power [kW demand] billing with power factor adjustment is used by the local electric power utility), setting the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter in the PF controller of the APFC system 1% or 2% above the power factor limit imposed by the electric power utility is generally sufficient to avoid a surcharge related to a low power factor. For instance, setting the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter in the PF controller to 0.91 or 0.92 when the power factor limit is 0.90 should be sufficient to avoid a surcharge on the electricity bill.

On the other hand, when the kVA demand averaged over a certain period of time (generally 15 minutes) is used for billing purpose (e.g., when apparent power [kVA demand] billing is used by the local electric power utility), the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter in the PF controller of the APFC system should generally be set about 3 to 5% above the power factor limit imposed by the electric power utility to avoid a surcharge related to a low power factor. For instance, setting the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter in the PF controller between 0.98 and 1.00 when the power factor limit is 0.95 should be sufficient to avoid a surcharge on the electricity bill.

To ensure that the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") in the PF controller is set properly, the first electricity bills received after the APFC system is put into service should be examined to see if a surcharge related to a low power factor has been added. If so, the value of the "Targeted power factor" ("$\cos\phi_{\text{Targeted}}$") parameter in the PF controller should be increased gradually (e.g., by steps of 0.01 per billing period) until no surcharge related to a low power factor appears on the subsequent electricity bill.

The Festo Power Factor Controller module

Front panel

The following figure shows the front panel of the Festo Power Factor Controller module.

The module mainly consists of PF controller model BR 7000 manufactured by TDK Electronics. This PF controller determines the three-phase power values and power factor at the power entrance of the application in which the APFC system is used by measuring one voltage (line-to-neutral voltage or line-to-line voltage) and one line current. For this purpose, the unit has a voltage measurement input (terminals labelled L1(L3) and N(L2)) and a current measurement input (terminals labelled k and l). The unit is thus suitable for power factor correction in balanced, three-phase electric power systems.

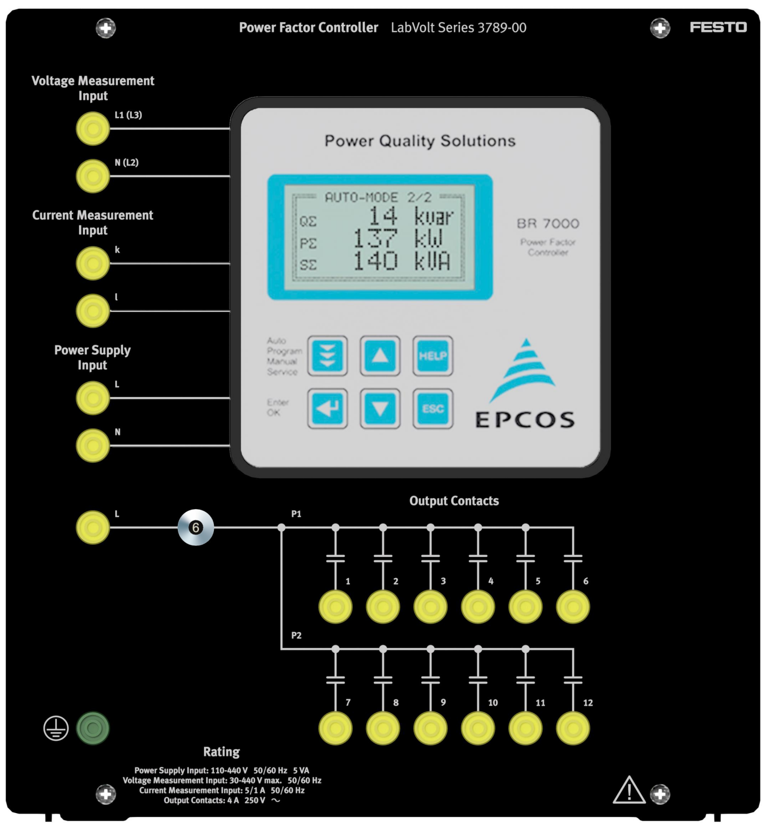


Figure 21: Front panel of the Festo Power Factor Controller module.

The PF controller has 12 control outputs, i.e., it can be used in APFC systems having up to 12 capacitor banks. The control outputs consist of 12 output contacts arranged in two groups (P1 and P2) of 6 contacts. The output contacts in one group are numbered 1 to 6 while the output contacts in the other group are numbered 7 to 12.

A set of buttons located on the front panel of the unit allows the PF controller to be operated and configured. Before going to the laboratory classroom to perform the exercises in this course, it is highly recommended that you read the instruction manual of the PF controller to get familiar with its operation and configuration. You can access the instruction manual of the PF controller using the following link.

Instruction manual of the PF controller.

Names of the configuration parameters

The names of most of the configuration parameters in the Festo Power Factor Controller module differ from the generic names used earlier in the course to introduce the configuration parameters of PF controllers. The following cross-reference table lists the generic names of the configuration parameters used so far in the course and the names of the corresponding parameters in the Festo Power Factor Controller module. Furthermore, the configuration parameters in the Festo Power Factor Controller module are accessed via three different operating modes of the unit called PROGRAMMING, EXPERT MODE 1, and MANUAL MODE 2. Access to a specific configuration parameter in the Festo Power Factor Controller module is possible via only one of the three aforementioned operating modes. The cross-reference table indicates which operating mode allows access to each specific configuration parameter in the Festo Power Factor Controller module.

Some of the generic configuration parameters of PF controllers introduced in the course are implemented using two configuration parameters in the Festo Power Factor Controller module. For instance, generic configuration parameter "Current transformer ratio" is implemented with the "I-CONVERTER PRIM" and "I-CONVERTER SEC" configuration parameters in the Festo Power Factor Controller module.

Table 8: Generic names of the configuration parameters used in the course and names of the corresponding parameters in the Festo Power Factor Controller module.

Parameter group	Generic parameter name	Parameter name in Festo Power Factor Controller module	Access mode in Festo Power Factor Controller module
General	Targeted power factor ($\cos \phi_{\text{Targeted}}$)	TARGET COS PHI	PROGRAMMING
	Phase shift	PHASE I and PHASE V	EXPERT MODE 1

Parameter group	**Generic parameter name**	**Parameter name in Festo Power Factor Controller module**	**Access mode in Festo Power Factor Controller module**
	Current transformer ratio	I-CT PRIMARY and I-CT SECONDARY	PROGRAMMING
	Measured voltage	MEAS. VOLTAGE	PROGRAMMING
	Voltage transformer ratio	MEAS. VOLTAGE and V-CONVERTER	PROGRAMMING
Capacitor banks	Number of capacitor banks	END STOP	PROGRAMMING
	Reactive-power step size (Q_{Step})	POWER 1.STAGE	PROGRAMMING
	Bank sequence	CONT. SERIES	PROGRAMMING
	Output/bank status	C1 to C12	MANUAL MODE 2
Capacitor bank switching control	Switching control mode	CONTROL MODE	PROGRAMMING
	Maximum one-step power switching	SWITCH. POWER max	EXPERT MODE 1
	Integration time	INTEGRATION-TIME	EXPERT MODE 1
	Bank switching trigger point	TRIGGER VALUE IND and TRIGGER VALUE CAP	EXPERT MODE 1
Capacitor bank switching control delays	Switch-on delay	SWITCH-IN-TIME	PROGRAMMING
	Switch-off delay	SWITCH-OFF-TIME	PROGRAMMING
	Discharge time	DISCHARGE TIME	PROGRAMMING

Procedure outline

The procedure is divided into the following sections:

- Setup and connections
- Capacitor bank power ratings and capacitor bank sequence
- Setting the configuration parameters in the PF controller of the APFC system, with reversed CT connections and one capacitor bank disabled
- Confirming correct operation of the APFC system, with reversed CT connections and one capacitor bank disabled
- Setting the configuration parameters in the PF controller of the APFC system, with correct CT connections and no capacitor bank disabled
- Confirming correct operation of the APFC system, with correct CT connections and no capacitor bank disabled
- Observing automatic power factor correction by the APFC system

⚠ 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 setup a circuit in which a three-phase ac power source supplies power to a three-phase resistive-inductive load. The circuit also includes an APFC system to correct the power factor at the ac power source (i.e., at the power entrance). You will then set the equipment to measure the voltage, current, power, and power factor at the power entrance and at the load.

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

   Install the equipment required in the Workstation.

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

   Connect the Power Input of the Data Acquisition and Control Interface module 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.

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

   In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface is detected. Make sure that the Computer-Based Instrumentation function for the Data Acquisition and Control Interface is available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the OK button to close the LVDAC-EMS Start-Up window.

5. Connect the equipment to implement the circuit shown in the following three figures. However, reverse the connections at the secondary of the current transformer (i.e., connect terminals X1 and X2 of the current transformer to terminals l and k of the power factor controller, respectively).

   In this circuit, a three-phase ac power source supplies power to a three-phase resistive-inductive load. To correct the power factor, an APFC system is connected between the ac power source (i.e., the power entrance) and the three-phase resistive-inductive load.

   Use a Resistive Load module and an Inductive Load module to implement the three-phase resistive-inductive load. For now, set all switches on these two modules to the O (open) position. This makes the resistance and reactance of the three-phase resistive-inductive load infinite.

   Use the Power Factor Controller module and the Power Factor Correction Capacitor Banks module to implement the APFC system.

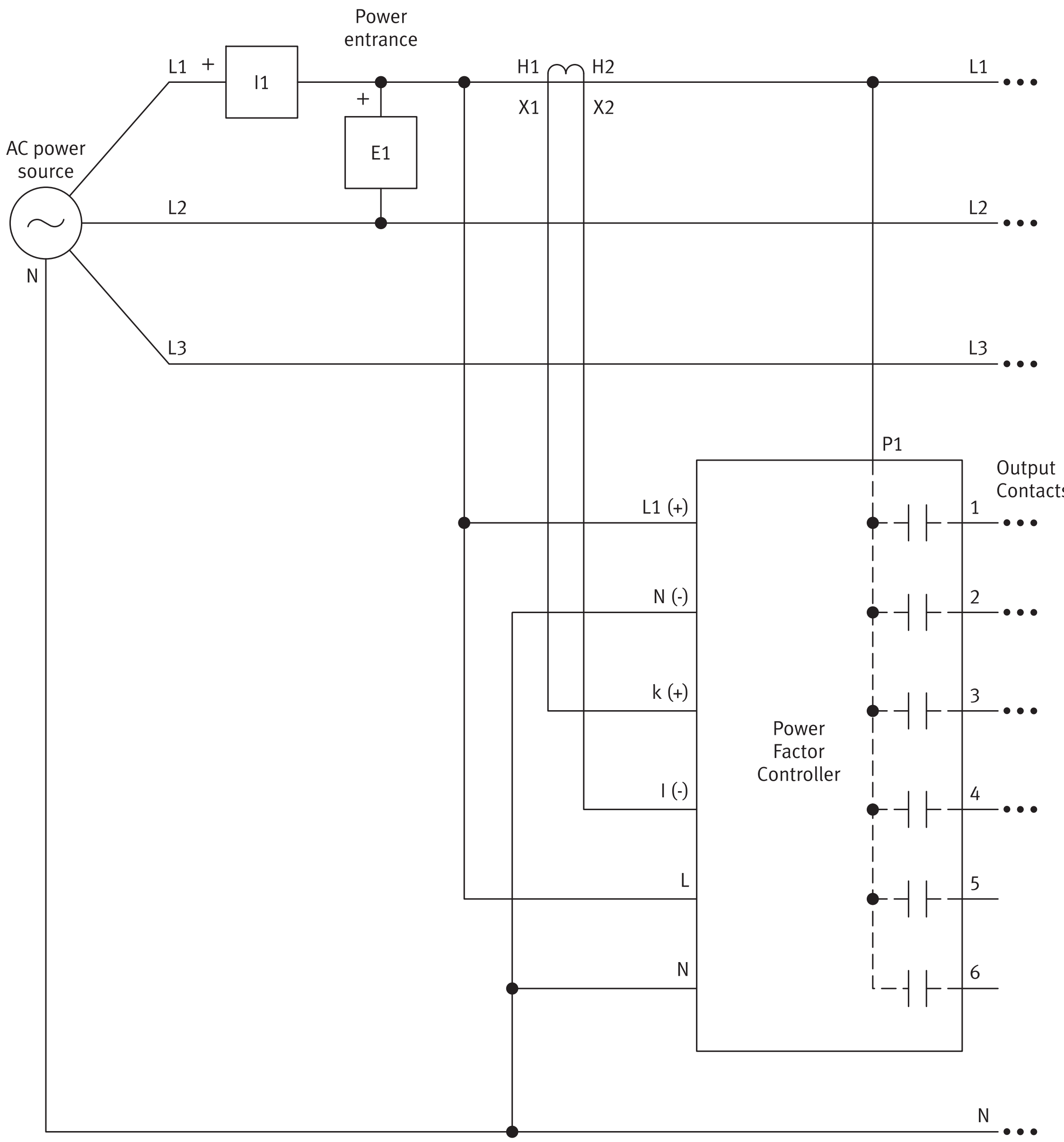


Figure 22: Three-phase resistive-inductive load and APFC system connected to a three-phase ac power source (part I).

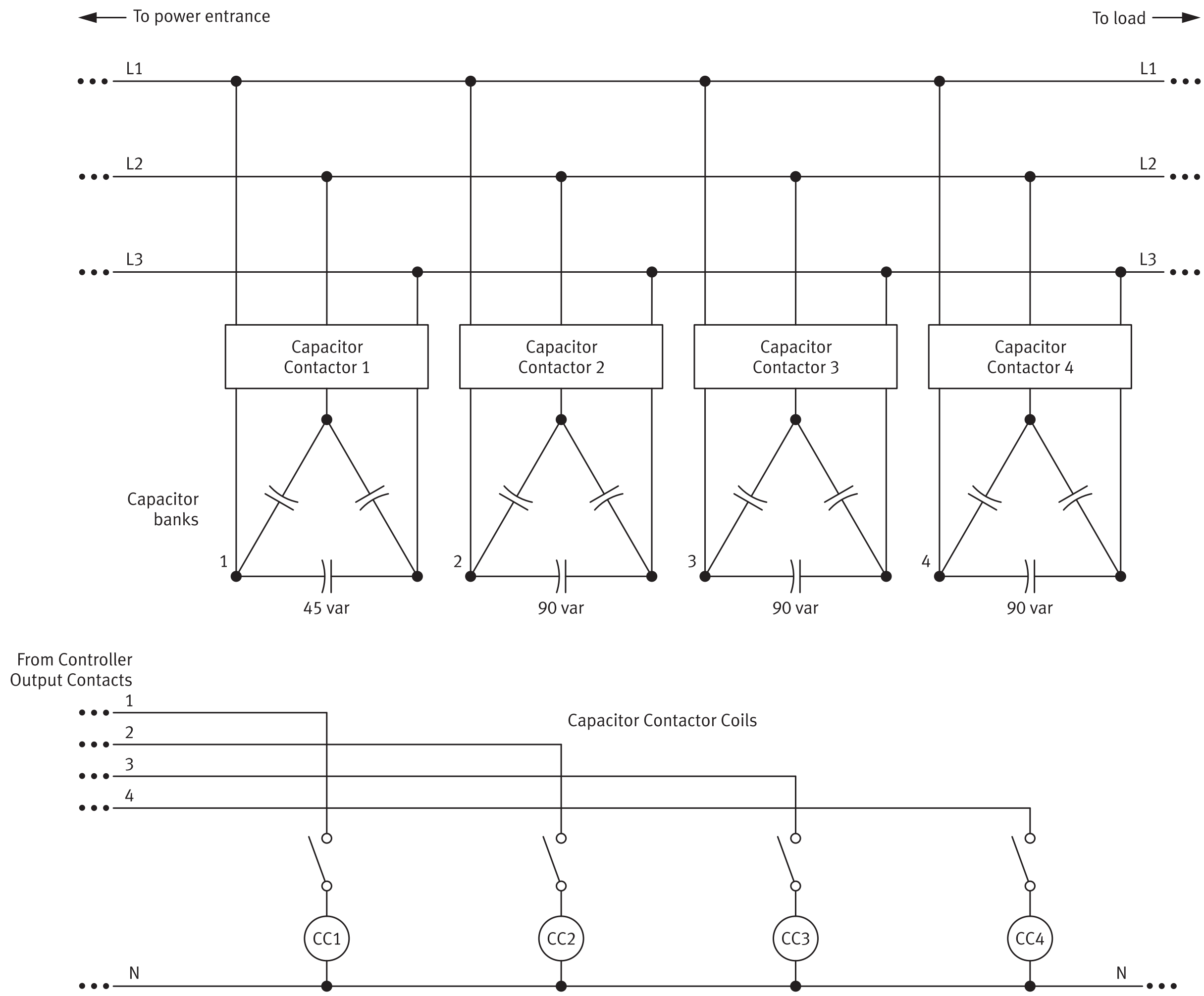


Figure 23: Three-phase resistive-inductive load and APFC system connected to a three-phase ac power source (part II).

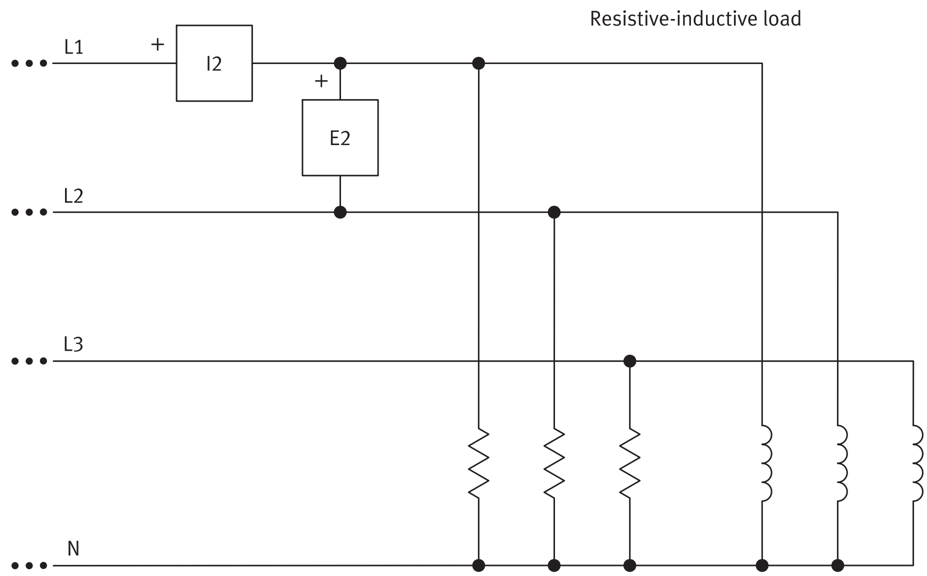


Figure 24: Three-phase resistive-inductive load and APFC system connected to a three-phase ac power source (part III).

6. On the Power Factor Correction Capacitor Banks module, make the following settings:

   - Set the switches of capacitor contactor coils CC1, CC2, and CC3 to the I (closed) position. This connects capacitor contactor coils CC1, CC2, and CC3 to output contacts 1, 2, and 3 of the Power Factor Controller module, respectively. This allows the PF controller to control capacitor banks 1, 2, and 3 of the APFC system.

   - Set the switch of capacitor contactor coil CC4 to the O (open) position. This leaves capacitor contactor coil CC4 disconnected from output contact 4 of the Power Factor Controller module. This prevents the PF controller from controlling capacitor bank 4 of the APFC system.

   - Set the Fault 1 switch to the O position. This disables Fault 1 in capacitor contactor 4.

   - Set the switch at the secondary of the current transformer to the O (open) position. This allows the Power Factor Controller module to measure the line current at the power entrance.

In the remainder of this exercise, the Power Factor Controller module is referred to as the PF controller.

7. In LVDAC-EMS, open the Metering window. In the Metering window, set meters to measure the following parameters:

- The rms (ac) value of the line-to-line voltage at the power entrance (measured via input E1).
- The rms (ac) value of the line current at the power entrance (measured via input I1).
- The three-phase active power at the power entrance (determined from the voltage and current measured via inputs E1 and I1).
- The three-phase reactive power at the power entrance (determined from the voltage and current measured via inputs E1 and I1).
- The three-phase apparent power at the power entrance (determined from the voltage and current measured via inputs E1 and I1).
- The power factor at the power entrance (determined from the voltage and current measured via inputs E1 and I1).
- The rms (ac) value of the line-to-line voltage at the load (measured via input E2).
- The rms (ac) value of the line current at the load (measured via input I2).
- The three-phase active power at the load (determined from the voltage and current measured via inputs E2 and I2).
- The three-phase reactive power at the load (determined from the voltage and current measured via inputs E2 and I2).
- The three-phase apparent power at the load (determined from the voltage and current measured via inputs E2 and I2).
- The power factor at the load (determined from the voltage and current measured via inputs E2 and I2).

Make sure that you select the power factor measurement function for three-phase power systems when configuring the meters in LVDAC-EMS that measure the power factor at the power entrance and the load.

Capacitor bank power ratings and capacitor bank sequence

In this section, you will record the power ratings of the capacitor banks in the APFC system. You will then determine the corresponding bank sequence considering that capacitor bank 4 is disabled.

8. Observe the front panel of the Power Factor Correction Capacitor Banks module. Notice that it contains four capacitor banks numbered 1 to 4.

Record the power ratings of capacitor banks 1 to 4 in the spaces below.

Power rating of capacitor bank 1: ____________ var

Power rating of capacitor bank 2: ____________ var

Power rating of capacitor bank 3: ____________ var

Power rating of capacitor bank 4: ____________ var

Power rating of capacitor bank 1: 45 var

Power rating of capacitor bank 2: 90 var

Power rating of capacitor bank 3: 90 var

Power rating of capacitor bank 4: 90 var

9. Which one of the following bank sequences corresponds to the sequence of the capacitor banks in the APFC system, considering that capacitor bank 4 is disabled?

   a. 1, 2, 2

   b. 4.5, 9, 9

   c. 1, 2, 3

   d. 4.5, 9, 9, 0

a

Setting the parameters in the PF controller, with reversed CT connections and one capacitor bank disabled

In this section, you will use the automatic initialization function of the PF controller to set the key configuration parameters of the APFC system while the connections at the current transformer secondary are reversed and one of the capacitor banks is disabled. You will observe how the PF controller manages this situation. You will finally set the targeted power factor to 0.95, inductive, in the PF controller of the APFC system.

10. On the Power Supply, turn the three-phase ac power source on and let the PF controller complete its start-up routine (this takes a few seconds).

    Observe that the PF controller selects the AUTO-MODE (automatic correction of the power factor) after completion of the start-up routine.

    The selected mode of operation is shown at the top of the front panel display of the PF controller.

Also observe that the PF controller indicates an undercurrent condition. This is normal because the three-phase resistive-inductive load currently has infinite resistance and reactance.

11. Make the necessary switch settings on the Resistive Load and Inductive Load modules so that the active power and reactive power at the three-phase resistive-inductive load are as close as possible to the values indicated in the following table. This sets the power factor (at the load as well as at the power entrance) to a value between 0.90 and 0.95 (inductive). This can be confirmed by reading the values indicated by the two power factor meters in the Metering window of LVDAC-EMS.

The three-phase resistive-inductive load must remain balanced when adjusting the resistance and reactance to obtain the required values of active power and reactive power. When changing the switch settings on the Resistive Load module, make sure that each one of the three resistor sections is set to the same value of resistance. Similarly, when changing the switch settings on the Inductive Load module, make sure that each one of the three inductor sections is set to the same value of reactance.

Setting the reactive power at the three-phase resistive-inductive load to the value indicated in the table causes a noticeable increase of the active power at the load. This is normal because the inductors in the Inductive Load module are not purely inductive. Consequently, the value at which the active power at the three-phase resistive-inductive load can be set slightly exceeds the value indicated in the table.

Observe that the PF controller no longer indicates an undercurrent condition.

Table 9: Values of active power and reactive power at the three-phase resistive-inductive load.

Local ac power network		Three-phase, resistive-inductive load	
Voltage (V)	Frequency (Hz)	Active power (W)	Reactive power (var)
120	60	72	36
220	50	66	33
240	50	72	36
220	60	66	33

12. On the PF controller, go to the PROGRAMMING mode and display the BASIC SETTINGS parameter. Set this parameter to [Yes], then press the Enter button to reset all configuration parameters to the basic setting values, i.e., the factory default values defined by the manufacturer.

    In the PROGRAMMING mode, successively display the various configuration parameters. While doing so, verify that these configuration parameters have effectively been reset to the factory default values. The factory default values of the configuration parameters are provided in an appendix of the instruction manual of the PF controller. You can access the instruction manual of the PF controller using the following link.

    Instruction manual of the PF controller.

13. On the PF controller, go to the AUTO-MODE.

    The PF controller may indicate that the power factor at the power entrance is overcompensated. Disregard this indication because the APFC system has not yet been configured.

    The PF controller automatically returns to the AUTO-MODE when no action is detected (i.e., when no push-button is depressed) during about 2 minutes.

14. Observe the front panel of the Power Factor Correction Capacitor Banks module. Record the primary current rating and secondary current rating of the current transformer (CT) used to measure the line current at the power entrance.

    Primary current rating of CT: ____________ A

    Secondary current rating of CT: ____________ A

    Primary current rating of CT: 2.5 A

    Secondary current rating of CT: 5 A

15. On the PF controller, go to the PROGRAMMING mode and press the up-arrow button to display the AUTO-INIT parameter. Set this parameter to [Yes], then press the Enter button to begin the automatic initialization.

    To start the automatic initialization function, you must enter in the PF controller the ratio of the current transformer measuring the line current at the power entrance or the power rating of the smallest capacitor bank in the APFC system. Continue the procedure by entering in the PF controller the primary current rating and secondary current rating of the current transformer measuring the line current at the power entrance, considering the information below.

The values of active power, reactive power, and apparent power measured by the PF controller are expressed in kW, kvar, and kVA, respectively. On the other hand, the values of active power, reactive power, and apparent power at the power entrance of the circuit used in the exercise are less than 300 W, 250 var, and 400 VA, respectively. These values of power are small compared with the units of power used in the PF controller, thereby resulting in fractional values of power. For instance, when the reactive power at the power entrance is 108 var, the PF controller displays 0.108 kvar. To avoid having to work with fractional values of power, multiply by 1000 the primary current rating of the current transformer measuring the line current at the power entrance and enter the value in the PF controller. This has the effect of multiplying by 1000 all values of current and power that the PF controller measures. For instance, the PF controller displays 108 kvar (instead of 0.108 kvar) when the actual value of reactive power at the power entrance is 108 var. Of course, the displayed value of 108 kvar must be interpreted as 108 var.

16. Observe that once the primary current rating and secondary current rating of the current transformer have been entered in the PF controller, the automatic initialization function starts. Notice that the PF controller performs the following actions during the automatic initialization.

    - The PF controller switches capacitor bank 1 on momentarily, then determines the phase shift value required according to the actual connection of the current and voltage measurement inputs.
    - The PF controller briefly displays the phase shift value required.
    - The PF controller switches each one of its output contacts on and off to detect the presence of the capacitor banks in the APFC system. While doing so, the PF controller determines and displays the reactive power of each capacitor bank in the APFC system.
    - The PF controller repeats the previous step several times.

    The PF controller generally takes a few minutes to complete the automatic initialization, then returns to the AUTO-MODE.

17. Once the PF controller has completed the automatic initialization, go to EXPERT MODE 1. A password is required to access EXPERT MODE 1. The default password to be entered is 6343.

    Once you accessed EXPERT MODE 1, display the "Phase shift" parameter (PHASE I and PHASE V parameters) and record its value below.

    The generic names of the configuration parameters are used in this course. When the generic name of a configuration parameter is stated in the hands-on exercises of the course, the name(s) of the corresponding configuration parameter(s) in the PF controller is(are) generally provided once within parentheses following the generic name of the configuration parameter, as in the previous paragraph. This helps making the cross-reference between the generic names of the configuration parameters and the names of the corresponding configuration parameters in the PF controller.

"Phase shift": ____________________°

"Phase shift": 180°

Is the "Phase shift" parameter set correctly considering the actual connection of the current and voltage measurement inputs of the PF controller? Why?

a. Yes, because it is set to 0°.

b. No, because it is set to 0°.

c. Yes, because it is set to 180°.

d. No, because it is set to 180°.

c

18. On the PF controller, go to the PROGRAMMING mode and successively display the "Number of capacitor banks" (END STOP), "Bank sequence" (CONT. SERIES), "Reactive-power step size" (POWER 1.STAGE), and "Measured voltage" (MEAS. VOLTAGE) parameters. Record the values of these parameters below.

Do not use commas when recording the "bank sequence" parameter (e.g., 1234).

"Number of capacitor banks": ____________________

"Bank sequence": ____________________

"Reactive-power step size": ____________________ var

"Measured voltage": ____________________ V

"Number of capacitor banks": 3

"Bank sequence": 122

"Reactive-power step size": 45 var ± 10%

"Measured voltage": 120 V ± 10%

19. Are the "Number of capacitor banks" and "Bank sequence" parameters set correctly? Why?

a. Yes, because the PF controller presently controls capacitor banks 1, 2, and 3 (3 banks) in the APFC system, and consequently, the bank sequence is 1, 2, 2.

b. Yes, because the PF controller presently controls capacitor banks 1, 2, 3, and 4 (4 banks) in the APFC system, and consequently, the bank sequence is 1, 2, 2, 2.

c. No, because there are 4 capacitor banks in the APFC system having a sequence of 1, 2, 2, 2.

d. No, because there are 4 capacitor banks in the APFC system having a sequence of 4.5, 9, 9, 9.

a

20. Is the "Reactive-power step size" parameter (i.e., the "Q_{Step} " parameter) set to the proper value? Why?

a. Yes, because the smallest capacitor bank in the APFC system has a nominal power rating of 45 var.

b. Yes, because the smallest capacitor bank in the APFC system has a nominal power rating of 90 var.

c. No, because the smallest capacitor bank in the APFC system has a nominal power rating of 90 var.

d. No, because the combined nominal power rating of the capacitor banks presently in use in the APFC system is 225 var.

a

21. Is the "Measured voltage" parameter set to the proper value? Why?

a. Yes, because its value is close to the nominal value of the line-to-neutral voltage at the power entrance.

b. Yes, because its value is close to the nominal value of the line-to-line voltage at the power entrance.

c. No, because its value differs significantly from the nominal value of the line-to-neutral voltage at the power entrance.

d. No, because its value differs significantly from the nominal value of the line-to-line voltage at the power entrance.

a

22. Do the observations you made so far confirm that the key configuration parameters in the PF controller of the APFC system are set properly?

☐ Yes ☐ No

Yes

23. On the PF controller, go to MANUAL MODE 2, then use the Enter button to successively display the "Output/bank status" parameter of each control output of the PF controller (parameters C1, C2, etc.). Observe that the "Output/bank status" parameter of each control output of the PF controller that is presently used to control a capacitor bank (i.e., C1 to C3 in the present case) is set to "automatic" (AUTO). This allows the APFC system to perform automatic correction of the power factor at the power entrance using these capacitor banks.

24. On the PF controller, go to the PROGRAMMING mode and display the "Targeted power factor" (TARGET COS PHI) parameter. Set the value of this parameter to 0.95, inductive.

Confirming correct operation of the APFC system, with reversed CT connections and one capacitor bank disabled

In this section, you will start automatic correction of the power factor by the APFC system. You will then observe whether the APFC system correct the power factor properly, even if the connections at the current transformer are reversed and one capacitor bank is disabled.

25. Make the necessary switch settings on the Inductive Load module so that the reactive power at the three-phase resistive-inductive load is as close as possible to the value indicated in the following table. Observe that this makes the power factor (at the load as well as at the power entrance) decrease to a value below 0.80 (inductive). This can be confirmed by reading the values indicated by the two power factor meters in the Metering window of LVDAC-EMS.

Table 10: Values of active power and reactive power at the three-phase resistive-inductive load.

Local ac power network		Three-phase, resistive-inductive load	
Voltage (V)	**Frequency (Hz)**	**Active power (W)**	**Reactive power (var)**
120	60	72	72
220	50	66	66
240	50	72	72
220	60	66	66

26. On the PF controller, go to the AUTO-MODE. This starts automatic correction of the power factor by the APFC system. Notice that the PF controller displays the power factor measured at the power entrance. The value of the power factor should initially be below 0.80 because the APFC system takes some time to correct the power factor.

Let the APFC system switch the capacitor bank(s) required to correct the power factor (this should take about 1 minute). During this time, calculate the value of the reactive power Q_{Targeted} required at the power entrance to make the power factor equal to the targeted value. To do so, use the value (0.95) of the "Targeted power factor" (TARGET COS PHI) parameter set in the PF controller and the value of the three-phase active power at the power entrance (P_{Entrance}) indicated by the corresponding meter in LVDAC-EMS. Record the value below.

Q_{Targeted} : ________________ var

The output contacts that the PF controller closes to switch capacitor banks on are shown at the bottom of the front panel display of the unit. Also, LEDs on the front panel of the Power Factor Correction Capacitor Banks module light up to indicate which capacitor banks are switched on.

Q_{Targeted} : 26 var ± 15%

27. Which capacitor bank(s) did the PF controller switch on to correct the power factor at the power entrance?

a. Either one of capacitor banks 2, 3, and 4 (90 var each).

b. Capacitor bank 1 (45 var).

c. Capacitor bank 1 (45 var) and either one of capacitor banks 2, 3, and 4 (90 var each).

d. Capacitor bank 1 (45 var) and two banks among capacitors banks 2, 3, and 4 (90 var each).

b

28. How does the amount of reactive power provided by the capacitor bank(s) that is(are) switched on compare with the amount of reactive power at the resistive-inductive load?

a. The amount of reactive power (225 var) provided by the capacitor banks that are switched on largely exceeds the amount of reactive power (72 var) at the resistive-inductive load.

b. The amount of reactive power (135 var) provided by the capacitor banks that are switched on significantly exceeds the amount of reactive power (72 var) at the resistive-inductive load.

c. The amount of reactive power (90 var) provided by the capacitor bank that is switched on slightly exceeds the amount of reactive power (72 var) at the resistive-inductive load.

d. The amount of reactive power (45 var) provided by the capacitor bank that is switched on is slightly less than the amount of reactive power (72 var) at the resistive-inductive load.

d

29. Measure the value of the three-phase reactive power at the power entrance (Q_{Entrance}) indicated by the corresponding meter in LVDAC-EMS. Record the value below.

Q_{Entrance} : ________________ var

Q_{Entrance} : 27 var ± 15%

Is reactive power Q_{Entrance} recorded above close to reactive power Q_{Targeted} that you calculated earlier in this section of the exercise?

☐ Yes ☐ No

Yes

30. What is the value of the power factor measured at the power entrance by the PF controller?

a. About 0.95, inductive

b. About 0.97, capacitive

c. About 0.75, capacitive

d. About 0.45, capacitive

a

Is the power factor at the power entrance close to the targeted value (0.95, inductive)?

☐ Yes ☐ No

Yes

31. On the PF controller, display the values of voltage, current, reactive power, active power, and apparent power that the unit measures at the power entrance.

Do the values measured by the PF controller correspond to the values measured at the power entrance by the meters in LVDAC-EMS?

☐ Yes ☐ No

Yes

Displaying the values of voltage, current, active power, reactive power, and apparent power that the PF controller measures at the power entrance is useful to monitor what happens at the power entrance when commissioning an APFC system in the field (i.e., without using additional measuring instruments like the meters in LVDAC-EMS).

32. Do the observations you made confirm that the APFC system operates correctly even if the connections at the current transformer are reversed and one capacitor bank is disabled?

☐ Yes ☐ No

Yes

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

Setting the parameters in the PF controller, with correct CT connections and no capacitor bank disabled

In this section, you will use the automatic initialization function of the PF controller to set the key configuration parameters of the APFC system while the connections at the current transformer secondary are correct and all capacitor banks are connected. You will observe how the PF controller manages this situation.

34. Modify the equipment connections so that the secondary of the current transformer is connected properly (i.e., connect terminals X1 and X2 of the current transformer to terminals k and l of the PF controller, respectively, as shown in the following figure).

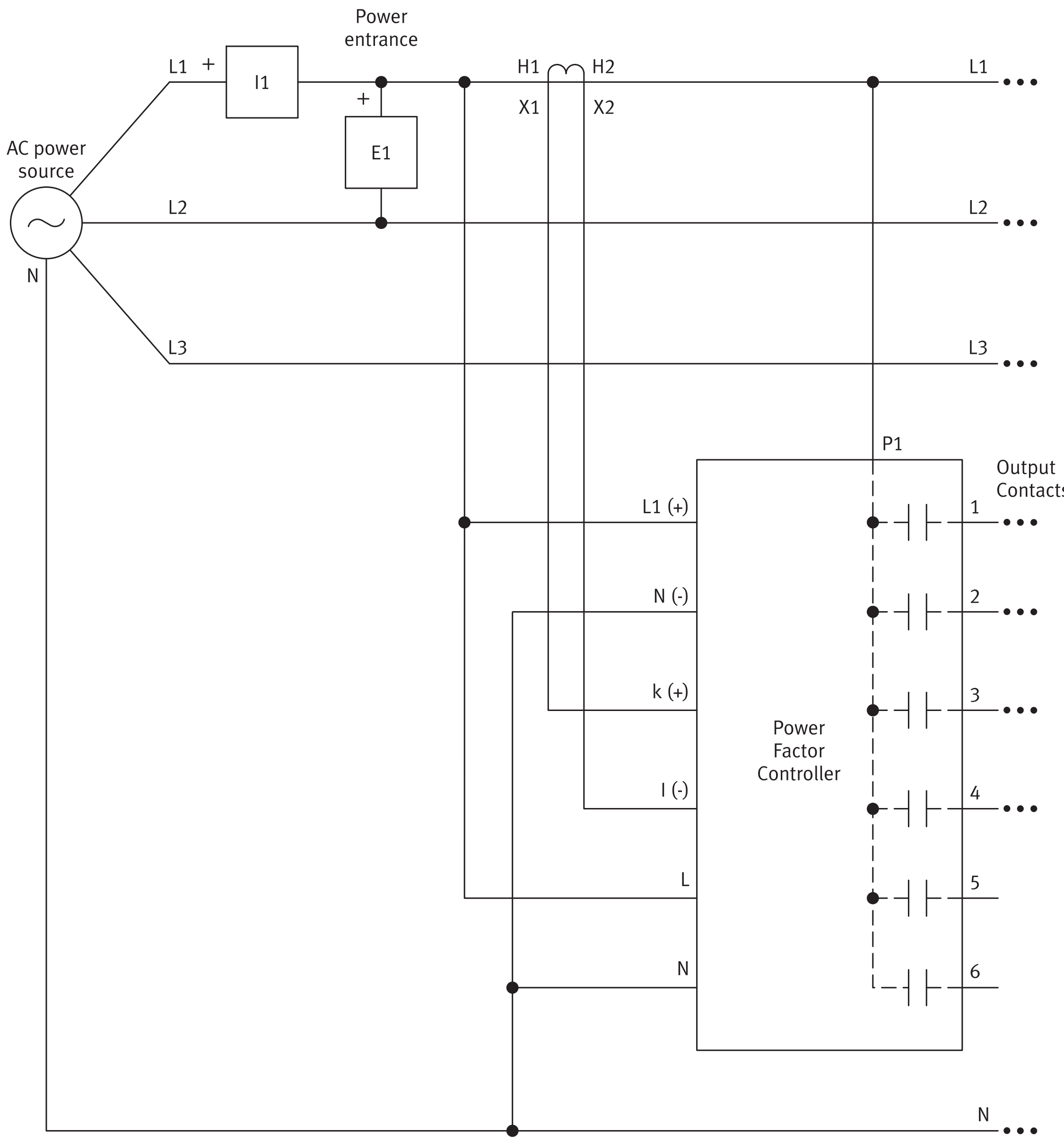


Figure 25: Proper connection of the CT secondary to the current measurement input of the PF controller.

35. On the Power Factor Correction Capacitor Banks module, set the switch of capacitor contactor coil CC4 to the I (closed) position. This connects capacitor contactor coil CC4 to output contact 4 of the Power Factor Controller module. This allows the PF controller to control capacitor bank 4 of the APFC system.

36. On the Power Supply, turn the three-phase ac power source on and let the PF controller complete its start-up routine (this takes a few seconds). Observe that the PF controller selects the AUTO-MODE (automatic correction of the power factor) after completion of the start-up routine.

The PF controller may indicate that the power factor at the power entrance is overcompensated. Disregard this indication because the APFC system has not yet been configured.

37. Make the necessary switch settings on the Inductive Load module so that the reactive power at the three-phase resistive-inductive load is as close as possible to the value indicated in the following table. This sets the power factor (at the load as well as at the power entrance) to a value between 0.90 and 0.95 (inductive). This can be confirmed by reading the values indicated by the two power factor meters in the Metering window of LVDAC-EMS.

Table 11: Values of active power and reactive power at the three-phase resistive-inductive load.

Local ac power network		Three-phase, resistive-inductive load	
Voltage (V)	Frequency (Hz)	Active power (W)	Reactive power (var)
120	60	72	36
220	50	66	33
240	50	72	36
220	60	66	33

38. On the PF controller, go to the PROGRAMMING mode and display the BASIC SETTINGS parameter. Set this parameter to [Yes], then press the Enter button to reset all configuration parameters to the basic setting values, i.e., the factory default values defined by the manufacturer.

In the PROGRAMMING mode, successively display the various configuration parameters. While doing so, verify that these configuration parameters have effectively been reset to the factory default values. The factory default values of the configuration parameters are provided in an appendix of the instruction manual of the PF controller. You can access the instruction manual of the PF controller using the following link.

Instruction manual of the PF controller.

39. On the PF controller, go to the AUTO-MODE.

The PF controller automatically returns to the AUTO-MODE when no action is detected (i.e., when no push-button is depressed) during about 2 minutes.

40. On the PF controller, go to the PROGRAMMING mode and press the up-arrow button to display the AUTO-INIT parameter. Set this parameter to [Yes], then press the Enter button to begin the automatic initialization.

To start the automatic initialization function, continue the procedure by entering in the PF controller the primary current rating and secondary current rating of the current transformer measuring the line current at the power entrance, considering the information below.

To avoid having to work with fractional values of power, multiply by 1000 the primary current rating of the current transformer measuring the line current at the power entrance and enter the value in the PF controller. This has the effect of multiplying by 1000 all values of current and power that the PF controller measures. For instance, the PF controller displays 108 kvar (instead of 0.108 kvar) when the actual value of reactive power at the power entrance is 108 var. Of course, the displayed value of 108 kvar must be interpreted as 108 var.

41. Observe that once the primary current rating and secondary current rating of the current transformer have been entered in the PF controller, the automatic initialization function starts. The PF controller generally takes a few minutes to complete the automatic initialization, then returns to the AUTO-MODE.

42. Once the PF controller has completed the automatic initialization, go to EXPERT MODE 1. A password is required to access EXPERT MODE 1. The default password to be entered is 6343.

Once you accessed EXPERT MODE 1, display the "Phase shift" parameter (PHASE I and PHASE V parameters) and record its value below.

"Phase shift": ________________°

"Phase shift": 0°

Is the "Phase shift" parameter set correctly considering the actual connection of the current and voltage measurement inputs of the PF controller? Why?

a. Yes, because it is set to 0°.

b. No, because it is set to 0°.

c. Yes, because it is set to 180°.

d. No, because it is set to 180°.

a

43. On the PF controller, go to the PROGRAMMING mode and successively display the "Number of capacitor banks" (END STOP), "Bank sequence" (CONT. SERIES), "Reactive-power step size" (POWER 1.STAGE), and "Measured voltage" (MEAS. VOLTAGE) parameters. Record the values of these parameters below.

Do not use commas when recording the "bank sequence" parameter (e.g., 1234).

"Number of capacitor banks": ____________________

"Bank sequence": ____________________

"Reactive-power step size": ____________________ var

"Measured voltage": ____________________ V

"Number of capacitor banks": 4

"Bank sequence": 1222

"Reactive-power step size": 45 var ± 10%

"Measured voltage": 120 V ± 10%

44. Are the "Number of capacitor banks" and "Bank sequence" parameters set correctly? Why?

a. Yes, because the PF controller presently controls capacitor banks 1, 2, and 3 (3 banks) in the APFC system, and consequently, the bank sequence is 1, 2, 2.

b. Yes, because the PF controller presently controls capacitor banks 1, 2, 3, and 4 (4 banks) in the APFC system, and consequently, the bank sequence is 1, 2, 2, 2.

c. No, because there are 4 capacitor banks in the APFC system having a sequence of 1, 2, 2, 2.

d. No, because there are 4 capacitor banks in the APFC system having a sequence of 4.5, 9, 9, 9.

b

45. Is the "Reactive-power step size" parameter (i.e., the "Q_{Step}" parameter) set to the proper value? Why?

a. Yes, because the smallest capacitor bank in the APFC system has a nominal power rating of 45 var.

b. Yes, because the smallest capacitor bank in the APFC system has a nominal power rating of 90 var.

c. No, because the smallest capacitor bank in the APFC system has a nominal power rating of 90 var.

d. No, because the combined nominal power rating of the capacitor banks presently in use in the APFC system is 225 var.

a

46. Is the "Measured voltage" parameter set to the proper value? Why?

a. Yes, because its value is close to the nominal value of the line-to-neutral voltage at the power entrance.

b. Yes, because its value is close to the nominal value of the line-to-line voltage at the power entrance.

c. No, because its value differs significantly from the nominal value of the line-to-neutral voltage at the power entrance.

d. No, because its value differs significantly from the nominal value of the line-to-line voltage at the power entrance.

a

47. Do the observations you made so far confirm that the key configuration parameters in the PF controller of the APFC system are set properly?

☐ Yes ☐ No

Yes

48. On the PF controller, go to MANUAL MODE 2, then use the Enter button to successively display the "Output/bank status" parameter of each control output of the PF controller (parameters C1, C2, etc.). Observe that the "Output/bank status" parameter of each control output of the PF controller that is presently used to control a capacitor bank (i.e., C1 to C4 in the present case) is set to "automatic" (AUTO). This allows the APFC system to perform automatic correction of the power factor at the power entrance using these capacitor banks.

49. On the PF controller, go to the PROGRAMMING mode and display the "Targeted power factor" (TARGET COS PHI) parameter. Set the value of this parameter to 0.95, inductive.

Confirming correct operation of the APFC system, with correct CT connections and no capacitor bank disabled

In this section, you will start automatic correction of the power factor by the APFC system. You will then observe whether the APFC system correct the power factor properly.

50. Make the necessary switch settings on the Inductive Load module so that the reactive power at the three-phase resistive-inductive load is as close as possible to the value indicated in the following table. Observe that this makes the power factor (at the load as well as at the power entrance) decrease to a value below 0.80 (inductive). This can be confirmed by reading the values indicated by the two power factor meters in the Metering window of LVDAC-EMS.

Table 12: Values of active power and reactive power at the three-phase resistive-inductive load.

Local ac power network		Three-phase, resistive-inductive load	
Voltage (V)	**Frequency (Hz)**	**Active power (W)**	**Reactive power (var)**
120	60	72	72
220	50	66	66
240	50	72	72
220	60	66	66

51. On the PF controller, go to the AUTO-MODE. This starts automatic correction of the power factor by the APFC system. Notice that the PF controller displays the power factor measured at the power entrance. The value of the power factor should initially be below 0.80 because the APFC system takes some time to correct the power factor.

    Let the APFC system switch the capacitor bank(s) required to correct the power factor (this should take about 1 minute). During this time, calculate the value of the reactive power Q_{Targeted} required at the power entrance to make the power factor equal to the targeted value. To do so, use the value (0.95) of the "Targeted power factor" (TARGET COS PHI) parameter set in the PF controller and the value of the active power P_{Entrance} indicated by the corresponding meter in LVDAC-EMS. Record the value below.

    Q_{Targeted} : ________________ var

    Q_{Targeted} : 26 var ± 15%

52. Which capacitor bank(s) did the PF controller switch on to correct the power factor at the power entrance?

a. Either one of capacitor banks 2, 3, and 4 (90 var each).

b. Capacitor bank 1 (45 var).

c. Capacitor bank 1 (45 var) and either one of capacitor banks 2, 3, and 4 (90 var each).

d. Capacitor bank 1 (45 var) and two banks among capacitors banks 2, 3, and 4 (90 var each).

b

53. How does the amount of reactive power provided by the capacitor bank(s) that is(are) switched on compare with the amount of reactive power at the resistive-inductive load?

a. The amount of reactive power (225 var) provided by the capacitor banks that are switched on largely exceeds the amount of reactive power (72 var) at the resistive-inductive load.

b. The amount of reactive power (135 var) provided by the capacitor banks that are switched on significantly exceeds the amount of reactive power (72 var) at the resistive-inductive load.

c. The amount of reactive power (90 var) provided by the capacitor bank that is switched on slightly exceeds the amount of reactive power (72 var) at the resistive-inductive load.

d. The amount of reactive power (45 var) provided by the capacitor bank that is switched on is slightly less than the amount of reactive power (72 var) at the resistive-inductive load.

d

54. Measure the value of reactive power Q_{Entrance} indicated by the corresponding meter in LVDAC-EMS. Record the value below.

Q_{Entrance} : ____________ var

Q_{Entrance} : 27 var ± 15%

Is reactive power Q_{Entrance} recorded above close to reactive power Q_{Targeted} that you calculated earlier in this section of the exercise?

☐ Yes ☐ No

Yes

55. What is the value of the power factor at the power entrance?

a. About 0.95, inductive
b. About 0.97, capacitive
c. About 0.75, capacitive
d. About 0.45, capacitive

a

Is the power factor at the power entrance close to the targeted value (0.95, inductive)?

☐ Yes ☐ No

Yes

56. On the PF controller, display the values of voltage, current, reactive power, active power, and apparent power that the unit measures at the power entrance.

Do the values measured by the PF controller correspond to the values measured at the power entrance by the meters in LVDAC-EMS?

☐ Yes ☐ No

Yes

57. Do the observations you made confirm that the APFC system operates correctly?

☐ Yes ☐ No

Yes

Observing automatic power factor correction by the APFC system

In this section, you will cause the power factor at the power entrance to decrease significantly by increasing the reactive power at the resistive-inductive load. You will observe how the APFC system reacts to maintain the power factor at the power entrance close to the targeted value. You will once again cause the power factor at the power entrance to decrease significantly, this time by decreasing the reactive power at the resistive-inductive load. You will observe how the APFC system reacts to maintain the power factor at the power entrance close to the targeted value.

58. Make the necessary switch settings on the Resistive Load and Inductive Load modules so that the active power and reactive power at the three-phase resistive-inductive load are as close as possible to the values indicated in the following table. This causes the power factor at the power entrance to decrease significantly.

Setting the reactive power at the three-phase resistive-inductive load to the value indicated in the table causes a noticeable increase of the active power at the load. This is normal because the inductors in the Inductive Load module are not purely inductive. Consequently, the value at which the active power at the three-phase resistive-inductive load can be set slightly exceeds the value indicated in the table.

Table 13: Values of active power and reactive power at the three-phase resistive-inductive load.

Local ac power network		Three-phase, resistive-inductive load	
Voltage (V)	Frequency (Hz)	Active power (W)	Reactive power (var)
120	60	108	216
220	50	99	165
240	50	108	216
220	60	99	165

59. Let the APFC system switch the capacitor bank(s) required to correct the power factor (this should take about 1 minute). During this time, calculate the reactive power Q_{Targeted} required at the power entrance to make the power factor equal to the targeted value (0.95, inductive).

Q_{Targeted} : ________________ var

Q_{Targeted} : 41 var ± 15%

60. Which capacitor bank(s) did the PF controller switch on to correct the power factor at the power entrance?

a. Either one of capacitor banks 2, 3, and 4 (90 var each).

b. Capacitor bank 1 (45 var) and either one of capacitor banks 2, 3, and 4 (90 var each).

c. Two banks among capacitors banks 2, 3, and 4 (90 var each).

d. Capacitor bank 1 (45 var) and two banks among capacitors banks 2, 3, and 4 (90 var each).

c

61. How does the amount of reactive power provided by the capacitor bank(s) that is(are) switched on compare with the amount of reactive power at the resistive-inductive load?

a. The amount of reactive power (225 var) provided by the capacitor banks that are switched on slightly exceeds the amount of reactive power (216 var) at the resistive-inductive load.

b. The amount of reactive power (180 var) provided by the capacitor banks that are switched on is slightly less than the amount of reactive power (216 var) at the resistive-inductive load.

c. The amount of reactive power (135 var) provided by the capacitor banks that are switched on is significantly less than the amount of reactive power (216 var) at the resistive-inductive load.

d. The amount of reactive power (90 var) provided by the capacitor bank that is switched on is well below the amount of reactive power (216 var) at the resistive-inductive load.

b

62. Measure the value of reactive power Q_{Entrance} indicated by the corresponding meter in LVDAC-EMS. Record the value below.

Q_{Entrance} : ________________ var

Q_{Entrance} : 36 var ± 20%

Is reactive power Q_{Entrance} recorded above close to reactive power Q_{Targeted} that you calculated earlier in this section of the exercise?

☐ Yes ☐ No

Yes

63. What is the value of the power factor at the power entrance?

a. About 0.99, capacitive
b. About 0.80, inductive
c. About 0.65, inductive
d. About 0.95, inductive

d

64. Is the power factor at the power entrance close to the targeted value (0.95, inductive)?

☐ Yes ☐ No

Yes

65. Make the necessary switch settings on the Resistive Load and Inductive Load modules so that the active power and reactive power at the three-phase resistive-inductive load are as close as possible to the values indicated in the following table. This causes the power factor at the power entrance to decrease significantly and become capacitive.

Setting the reactive power at the three-phase resistive-inductive load to the value indicated in the table causes a noticeable increase of the active power at the load. This is normal because the inductors in the Inductive Load module are not purely inductive. Consequently, the value at which the active power at the three-phase resistive-inductive load can be set slightly exceeds the value indicated in the table.

Table 14: Values of active power and reactive power at the three-phase resistive-inductive load.

Local ac power network		Three-phase, resistive-inductive load	
Voltage (V)	Frequency (Hz)	Active power (W)	Reactive power (var)
120	60	72	108
220	50	66	99
240	50	72	108
220	60	66	99

66. Let the APFC system switch the capacitor bank(s) required to correct the power factor (this should take about 1 minute). During this time, calculate the reactive power Q_{Targeted} required at the power entrance to make the power factor equal to the targeted value (0.95, inductive).

Q_{Targeted} : ________________ var

Q_{Targeted} : 27 var ± 15%

67. Which capacitor bank(s) did the PF controller switch on to correct the power factor at the power entrance?

a. Capacitor bank 1 (45 var).

b. Either one of capacitor banks 2, 3, and 4 (90 var each).

c. Capacitor bank 1 (45 var) and either one of capacitor banks 2, 3, and 4 (90 var each).

d. Two banks among capacitors banks 2, 3, and 4 (90 var each).

b

68. How does the amount of reactive power provided by the capacitor bank(s) that is(are) switched on compare with the amount of reactive power at the resistive-inductive load?

a. The amount of reactive power (180 var) provided by the capacitor banks that are switched on significantly exceeds the amount of reactive power (108 var) at the resistive-inductive load.

b. The amount of reactive power (135 var) provided by the capacitor banks that are switched on slightly exceeds the amount of reactive power (108 var) at the resistive-inductive load.

c. The amount of reactive power (90 var) provided by the capacitor bank that is switched on is slightly less than the amount of reactive power (108 var) at the resistive-inductive load.

d. The amount of reactive power (45 var) provided by the capacitor bank that is switched on is well below the amount of reactive power (108 var) at the resistive-inductive load.

c

69. Measure the value of reactive power Q_{Entrance} indicated by the corresponding meter in LVDAC-EMS. Record the value below.

Q_{Entrance} : ____________ var

Q_{Entrance} : 18 var ± 20%

Is reactive power Q_{Entrance} recorded above close to reactive power Q_{Targeted} that you calculated earlier in this section of the exercise?

☐ Yes ☐ No

Yes

70. What is the value of the power factor at the power entrance?

a. About 0.71, capacitive

b. About 0.94, capacitive

c. About 0.97, inductive

d. About 0.71, inductive

c

71. Is the power factor at the power entrance close to the targeted value (0.95, inductive)?

☐ Yes ☐ No

Yes

72. Do the observations you made in this section still confirm that the APFC system operates correctly?

☐ Yes ☐ No

Yes

73. From the observations you made in this exercise, select the statement that correctly explains how the APFC system makes the power factor at the power entrance inductive and close to the targeted value.

a. The APFC system switches capacitor banks on so that the amount of reactive power they provide significantly exceeds the amount of reactive power at the resistive-inductive load. This forces the ac power source to absorb some reactive power, thereby ensuring that the power factor at the power entrance is inductive and close to the targeted value.

b. The APFC system switches capacitor banks on so that the amount of reactive power they provide is significantly less than the amount of reactive power at the resistive-inductive load. This forces the ac power source to supply some reactive power, thereby ensuring that the power factor at the power entrance is inductive and close to the targeted value.

c. The APFC system switches capacitor banks on so that the amount of reactive power at the power entrance is as close as possible to the value of the targeted reactive power (Q_{Targeted}). In most cases, this forces the ac power source to supply some reactive power, thereby ensuring that the power factor at the power entrance is inductive and close to the targeted value.

d. The APFC system switches capacitor banks on so that the amount of reactive power they provide is virtually equal to the reactive power at the resistive-inductive load. In most cases, this forces the ac power source to supply a slight amount of reactive power, thereby making the power factor at the power entrance inductive and close to the targeted value.

c

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

Close LVDAC-EMS, then turn the 24 V ac power supply off. Disconnect all leads and return them to their storage location.

Review Questions

1. An APFC system has two 25 kvar capacitor banks, two 50 kvar capacitor banks, and two 100 kvar capacitor banks. What is the sequence related to the capacitor banks of the APFC system?

   a. 25, 50, 100

   b. 25, 25, 50, 50, 100, 100

   c. 1, 1, 2, 2, 4, 4

   d. 2.5, 2.5, 5, 5, 10, 10

c

2. Which of the following statements about APFC systems are true?

   a. In most cases, an APFC can maintain the value of the corrected power factor exactly at the targeted value.

   b. An APFC system achieves power factor correction by switching capacitor banks on and off at the power entrance of an application.

   c. In most cases, the amount of reactive power provided by the capacitor banks that an APFC system switches on to correct the power factor rarely equals the exact amount of reactive power required to make the power factor equal to the targeted value.

   d. The lower the power rating of the smallest capacitor bank in an APFC system, the closer to the targeted value the APFC system can maintain the power factor at the power entrance of an application.

   e. In general, the value of the corrected power factor obtained with an APFC system differs slightly from the targeted value.

   f. The higher the power rating of the smallest capacitor bank in an APFC system, the closer to the targeted value the APFC system can maintain the power factor at the power entrance of an application.

b, c, d, and e

3. An APFC system consists of 4 capacitor banks having power ratings of 5 kvar, 10 kvar, 20 kvar, and 40 kvar. What is the reactive-power step size (Q_{Step}) of the APFC system?

   a. 5 kvar

   b. 10 kvar

   c. 20 kvar

   d. 40 kvar

a

4. Commissioning an APFC system is basically a three-step process. Select the statements in the following list that correspond to these three steps.

   a. Make sure that all inductive loads in the application to which the APFC system is connected operate at full capacity.

   b. Set the various configuration parameters in the PF controller of the APFC system to meet the requirements of the specific application in which the system is used.

   c. Make sure that all inductive loads in the application to which the APFC system is connected are switched off.

   d. Temporarily disconnect all control outputs of the PF controller from the capacitor contactors in the APFC system.

   e. Measure the total harmonic distortion (THD) at the power entrance of the application before connecting the APFC system to the application.

   f. Start automatic correction of the power factor in the APFC system and confirm that the system operates correctly.

   g. Install the APFC system and connect it to the electric power system according to the instructions of the manufacturer.

b, f, and g

5. Select in the following list the configuration parameters of the PF controller that define fundamental characteristics of an APFC system.

   a. Targeted power factor ($\cos\phi_{\text{Targeted}}$)

   b. Switching control mode

   c. Discharge time

   d. Phase shift

   e. Number of capacitor banks

   f. Switch-on delay

   g. Reactive-power step size (Q_{Step})

   h. Switch-off delay

   i. Integration time

   j. Current transformer ratio

   k. Bank sequence

a, d, e, g, j, and k

6. The targeted power factor ($\cos\phi_{\text{Targeted}}$) is set to 0.97 (inductive) in the PF controller of an APFC system. What is the value of the targeted reactive power (Q_{Targeted}), knowing that the active power at the power entrance (P_{Entrance}) of the application in which the APFC system is used is 500 kW?

   a. 0 kvar

   b. 8.47 kvar

   c. 125.3 kvar

   d. 164.3 kvar

c

Appendix D

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