Electricity and New Energy

Thyristor Power Electronics

Courseware Sample

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By the staff of Festo Didactic

Internet: www.festo-didactic.com
e-mail: did@de.festo.com

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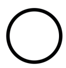
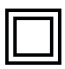
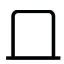
Safety and Common Symbols

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

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

Safety and Common Symbols

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

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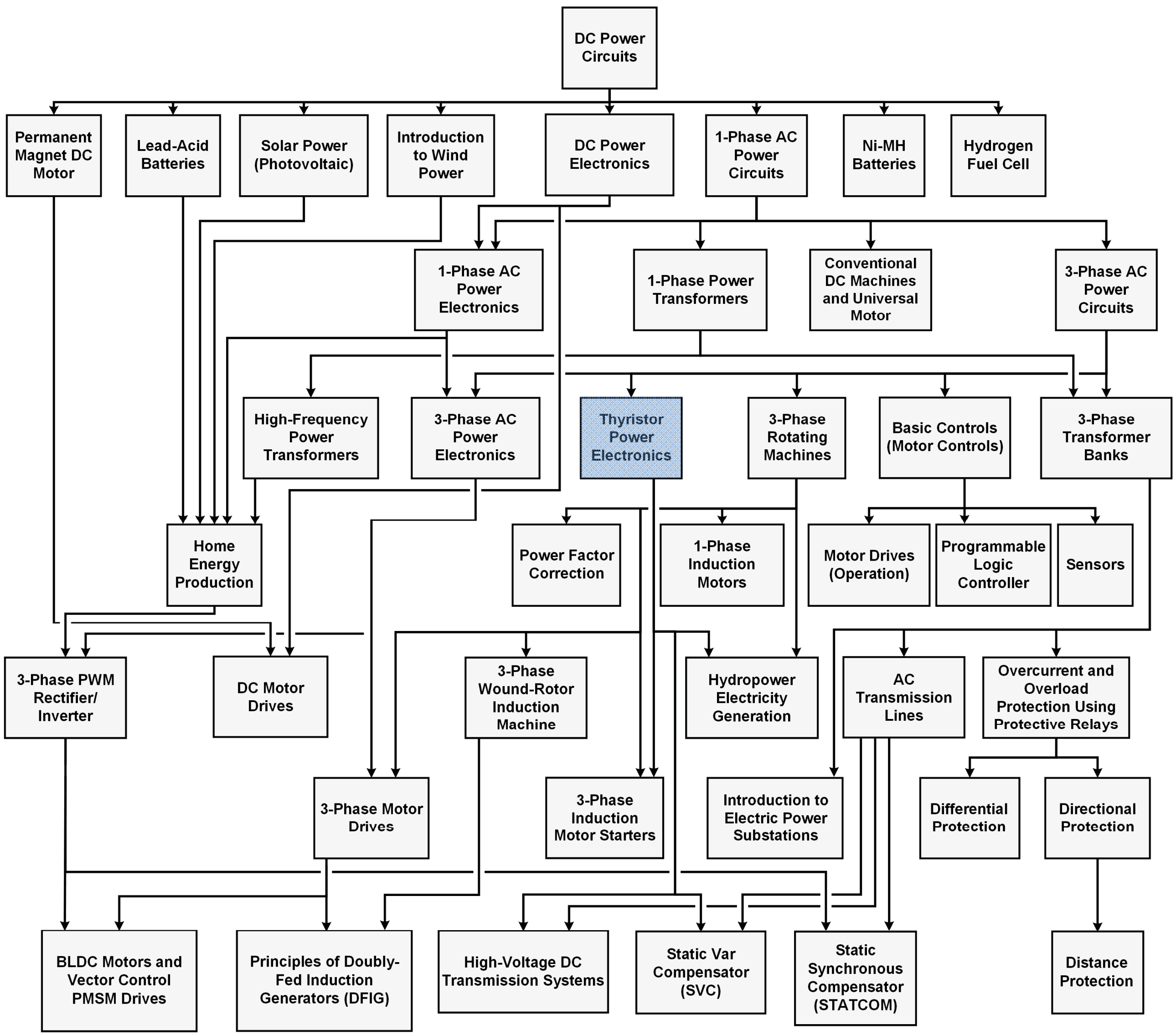
Preface

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

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



The Electric Power Technology Training Program.

Preface

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

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

This manual, *Thyristor Power Electronics*, introduces the student to the power diode, power thyristor, solid state relay, and zero-voltage switched (ZVS) SSR, four components that are widely used in power electronics circuits to achieve switching and control of electrical power. The course provides in-depth coverage of typical circuits using these components and their applications in power control and switching. The course begins with the study of both the single-phase and three-phase power diode rectifiers. The student is then introduced to the thyristor operation. The remainder of the course deals with the following applications of the power thyristor: solid state relay, single-phase and three-phase ac power control circuits using either phase angle control or burst fire control, and three-phase thyristor bridge. Both the rectifier and inverter modes of operation are discussed when studying the three-phase thyristor bridge.

The equipment for the course mainly consists of the Power Thyristors module and the Data Acquisition and Control Interface. The operation of the power thyristors is controlled by using the LVDAC-EMS software, which also provides the instrumentation required to measure, analyze, and record the experimental data. The Resistive Load module, Filtering Inductors/Capacitors module, and Capacitive Load module are used to provide various circuit loads and perform the exercises in this manual.

Safety considerations

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

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

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

Prerequisite

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

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

Accuracy of measurements

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

Equipment installation

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

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

Exercise 6

Three-Phase AC Power Control

EXERCISE OBJECTIVE

When you have completed this exercise, you will know how to perform ac power control in three-phase ac circuits, using thyristors. You will know the four topologies commonly used in three-phase ac power control circuits. You will be familiar with circuit operation and thyristor firing control for each topology.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to three-phase ac power control
- Topologies of three-phase ac power control circuits
- Circuit operation and thyristor firing control in three-phase ac power control circuits with 4S and 6D load configurations
  Phase angle modulation. Burst fire control.
- Circuit operation and thyristor firing control in three-phase ac power control circuits with 3S and 3D load configurations
  Phase angle modulation. Burst fire control.
- Applications of three-phase ac power control

DISCUSSION

Introduction to three-phase ac power control

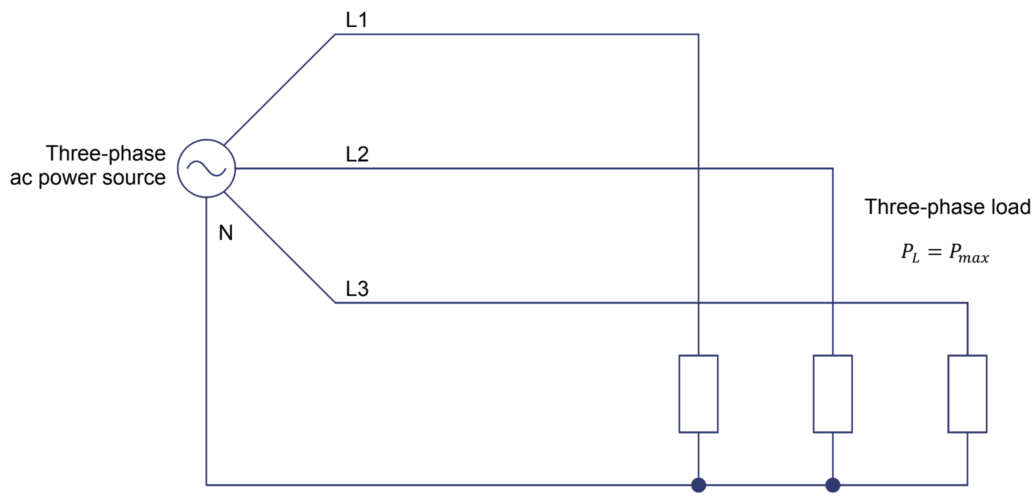
Like single-phase ac power control, **three-phase ac power control** allows adjustment of the amount of electrical power (generally active power) which an ac power source delivers to a load. The main difference is that both the source and the load are three-phase in nature.

Like single-phase ac power control, three-phase ac power control is achieved by decreasing the power delivered to the load, as Figure 76 shows.

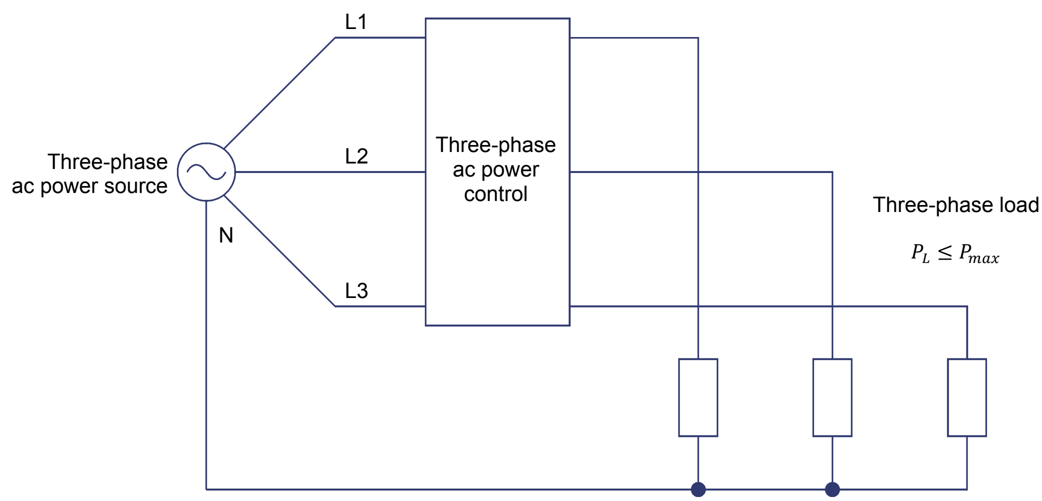
– In Figure 76a, the three-phase ac power source is connected directly to the load. Therefore, the amount of power P_L delivered to the load is equal to the maximum amount of power P_{max} delivered by the source.

– In Figure 76b, the three-phase ac power source is connected to the load via an ac power control circuit that permits adjustment of the power P_L delivered to the load to a value lower than or equal to P_{max}.

Three-phase ac power control circuits are usually built with thyristors or triacs. This exercise deals with three-phase ac power control circuits built with thyristors.



(a) Without three-phase ac power control



(b) With three-phase ac power control

Figure 76. Three-phase ac power control.

Three-phase ac power control can be performed by using two thyristors connected in inverse parallel (as in a single-phase ac power control circuit) in each branch of the circuit. Therefore, three pairs of thyristors are required to achieve three-phase ac power control, as Figure 77 shows.

In each of the three phases of the circuit in Figure 77, one thyristor allows current to flow through the load during the positive half of the corresponding ac source voltage waveform. The other thyristor allows current to flow in the opposite direction during the negative half of the corresponding ac source voltage waveform.

Through proper control of thyristor firing, the rms value of the current flowing through the load, and thus the amount of power delivered to the load can be adjusted.

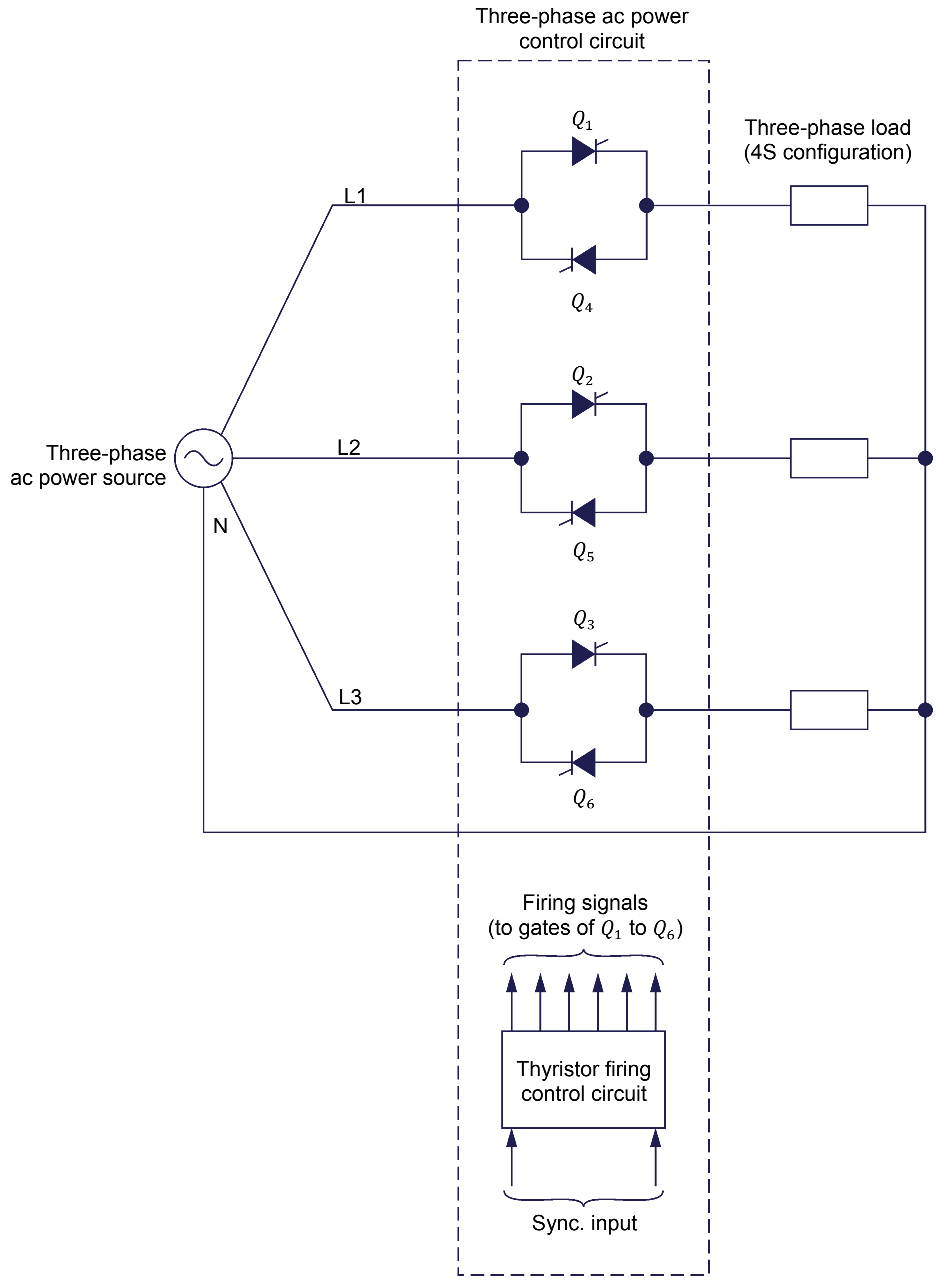


Figure 77. Three-phase ac power control circuit with a 4S load configuration.

Topologies of three-phase ac power control circuits

In the three-phase ac power control circuit shown in Figure 77, the load has a wye (star) configuration with a neutral conductor. This load configuration is commonly referred to as a **4 wire, wye (star) configuration**, and is often abbreviated as **4S** load configuration.

The other three-phase load configurations commonly used are: the **6 wire, delta configuration**, the **3 wire, wye (star) configuration**, and the **3 wire, delta configuration**. Figure 78 shows the topology of a three-phase ac power control circuit with a **6 wire, delta load configuration**, abbreviated as **6D** load configuration.

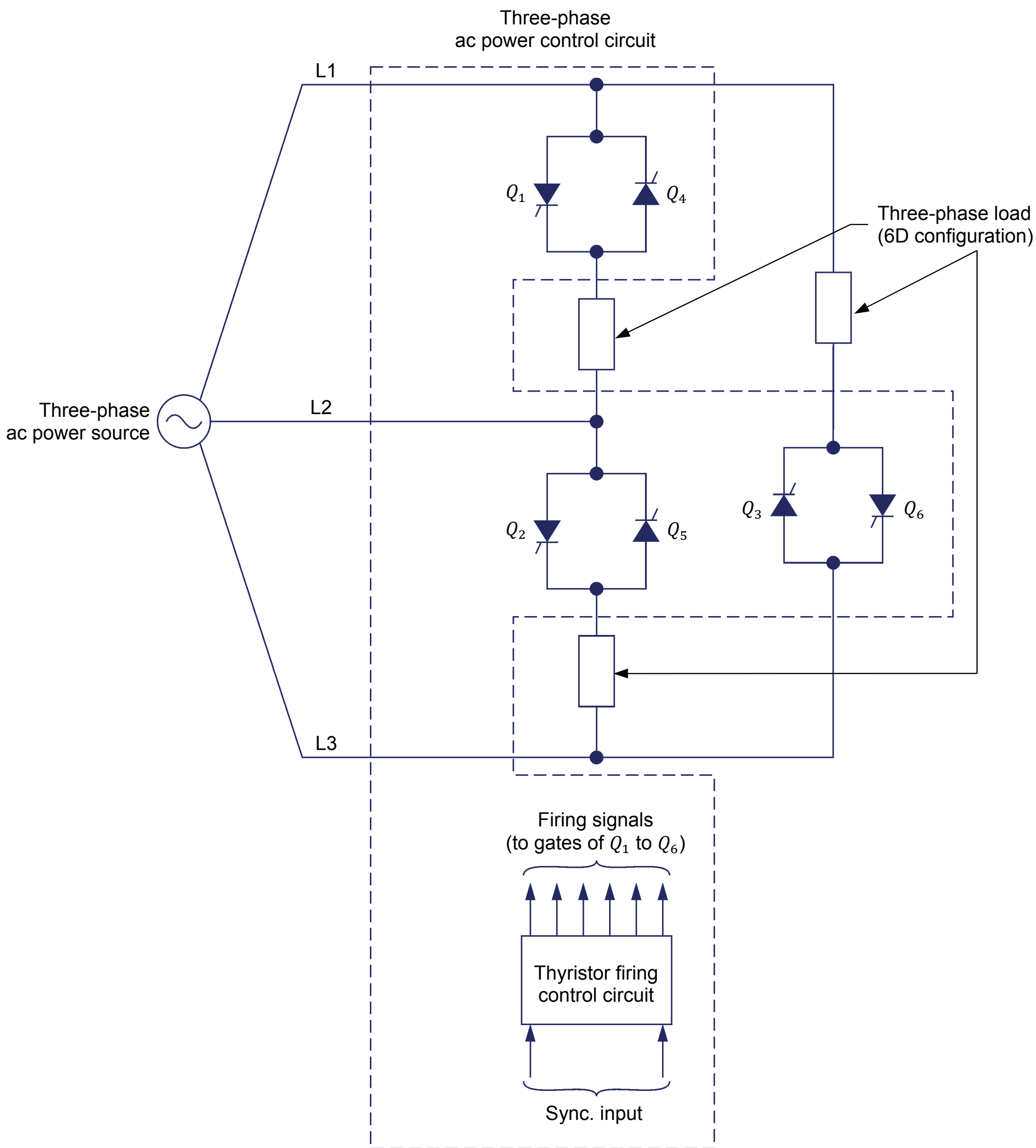


Figure 78. Three-phase ac power control circuit with a 6D load configuration.

Figure 79 shows the topology of a three-phase ac power control circuit with a **3 wire, wye (star)** configuration, abbreviated as **3S** load configuration.

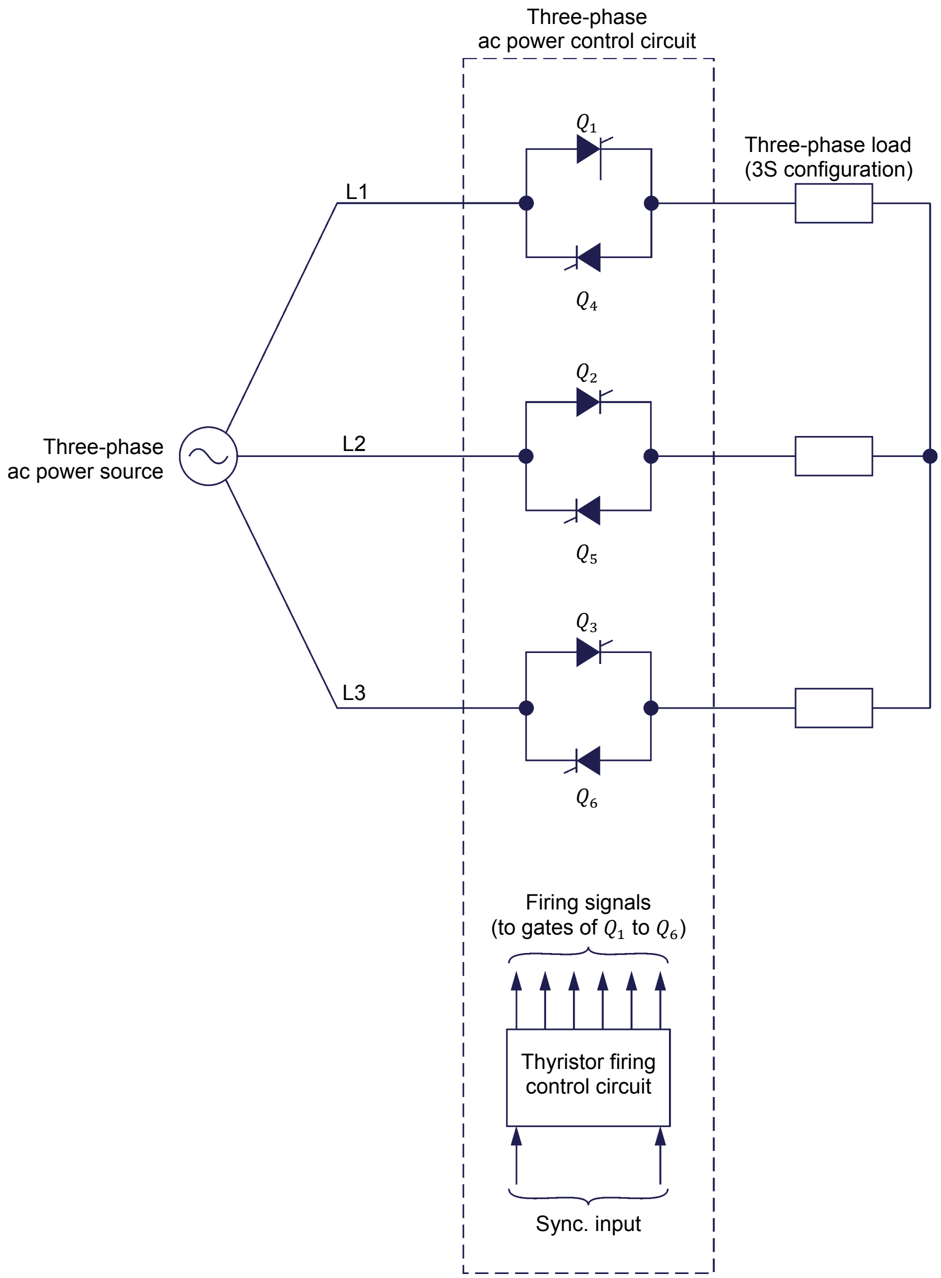


Figure 79. Three-phase ac power control circuit with a 3S load configuration.

Figure 80 shows the topology of a three-phase ac power control circuit with a **3 wire, delta** load configuration, abbreviated as **3D** load configuration.

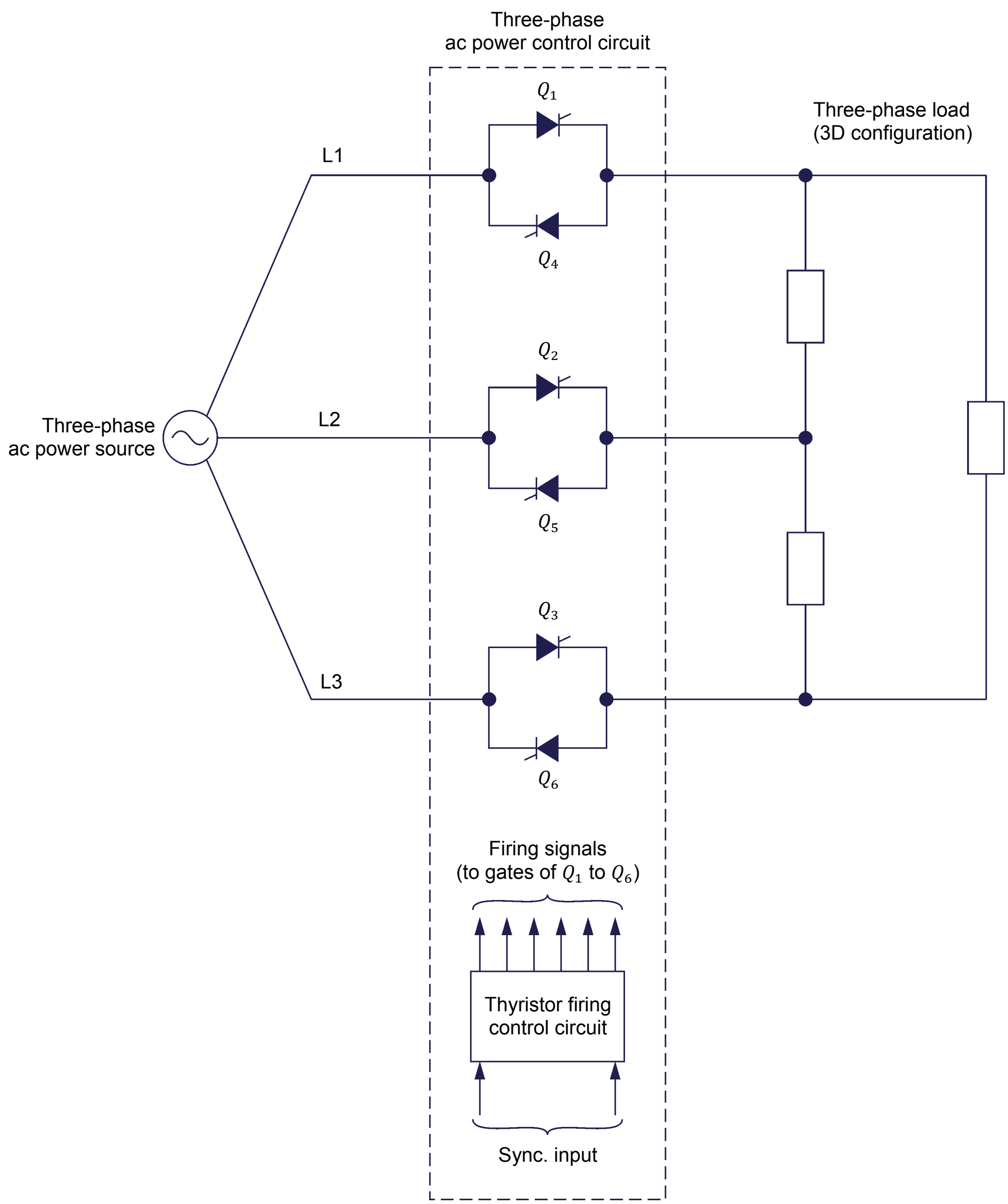


Figure 80. Three-phase ac power control circuit with a 3D load configuration.

Whichever circuit topology is used, thyristor firing control is normally performed using the same techniques as in single-phase ac power control, i.e., phase angle modulation and burst fire control. Consequently, the three-phase ac power control circuits described in this discussion all have a thyristor firing control circuit with a synchronization input to ensure that thyristor firing is properly timed with the ac power source voltage. However, some details of operation vary depending on the topology of the three-phase ac power control circuit and the thyristor firing control technique used, as will be explained in the remainder of this discussion.

Figure 81. Thyristor three-phase ac power control is widely used in soft starters for induction motors. In water stations, soft starters are used to gradually start or stop the pump motors and thus, eliminate water hammers (pressure surges that occur when the water flow is suddenly increased or decreased, which can cause damage to the pumps, valves, and piping infrastructure).

Circuit operation and thyristor firing control in three-phase ac power control circuits with 4S and 6D load configurations

Close observation of the three-phase ac power control circuit with a 4S load configuration (Figure 82) reveals that the circuit consists of three distinct single-phase ac power control circuits, one per phase.

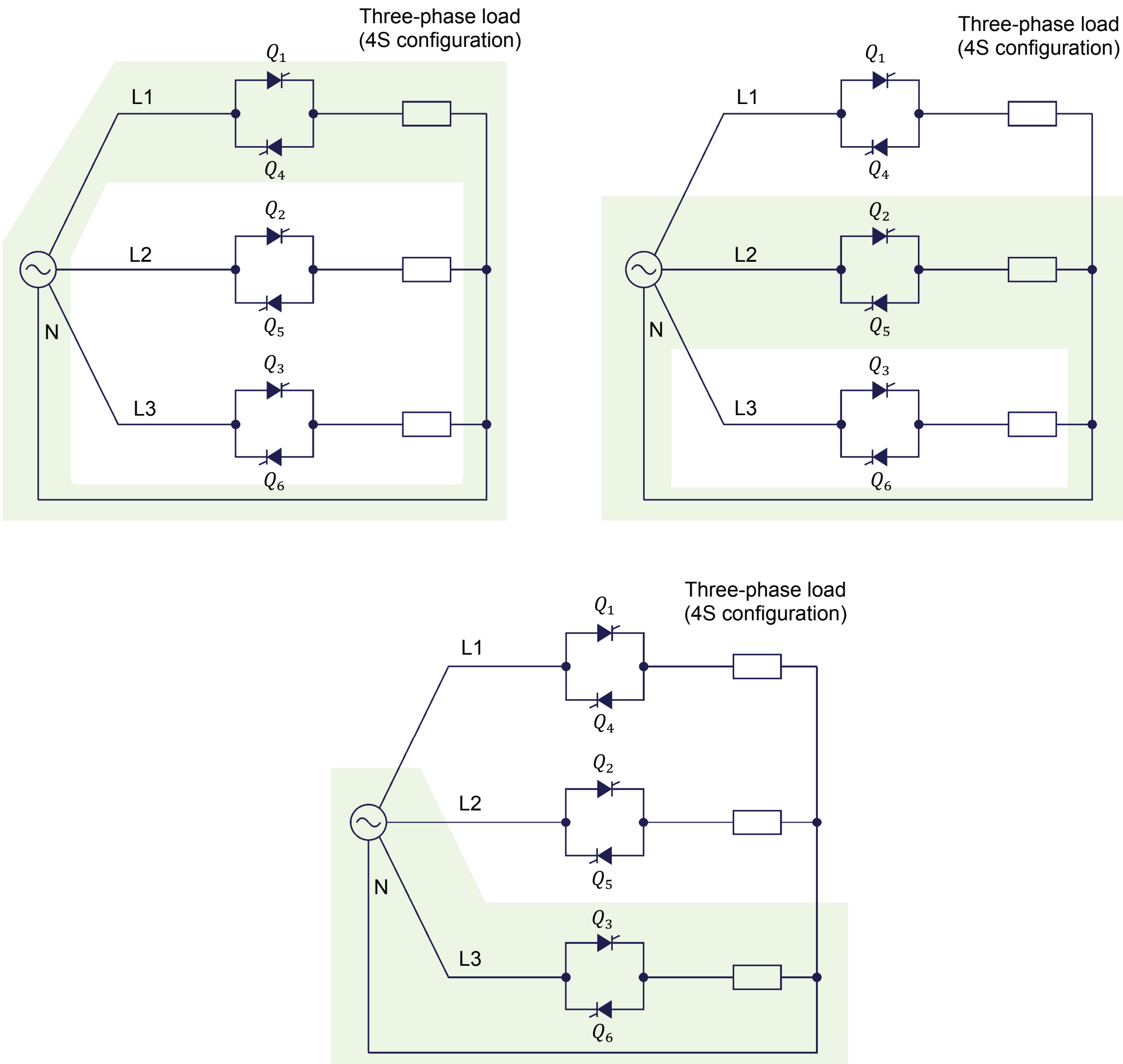


Figure 82. The three-phase ac power control circuit with a 4S load configuration consists of three distinct single-phase ac power control circuits, one per phase.

Similarly, the three-phase control circuit with a 6D load configuration (Figure 83) consists of three distinct single-phase ac power control circuits.

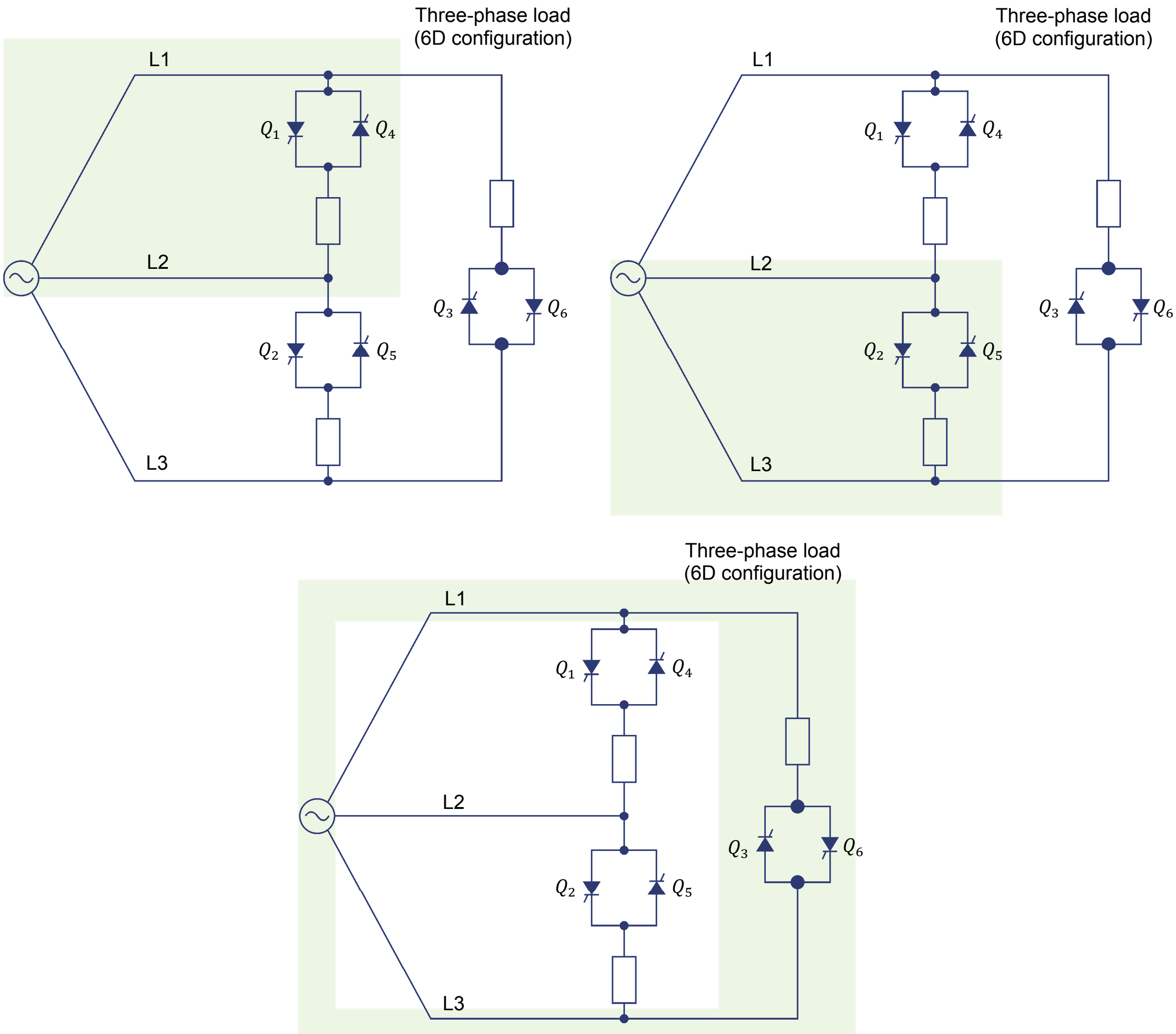


Figure 83. The three-phase ac power control circuit with a 6D load configuration consists of three distinct single-phase ac power control circuits.

Phase angle modulation

When phase angle modulation is used in three-phase ac power control circuits with a 4S or 6D load configuration, circuit operation and thyristor firing control are the same as in single-phase ac power control circuits, except that thyristor firing is delayed by 120° and 240° for the second and third phases of the circuit, respectively. To ensure that the thyristor firing signals are properly timed, the thyristor firing control circuit samples one of the phase voltages of the ac power source when the 4S load configuration is used, while it samples one of the line-to-line voltages of the ac power source when the 6D load configuration is used.

Figure 84 shows an example of typical firing signals in a three-phase ac power control circuit with a **4S** load configuration when phase angle modulation is used. The firing angle α in Figure 84 is 20°. Notice that the firing angle is determined with respect to the instant when phase voltage E_{1-N} crosses zero and becomes positive. Consequently:

The firing angle could also have been determined with respect to the instant when voltage E_{2-N} or E_{3-N} crosses zero and becomes positive.

– Thyristor Q_1 is fired "α" degrees after the instant when voltage E_{1-N} crosses zero and becomes positive, i.e., at phase angle 20°.

– The firing signal of thyristor Q_4 is delayed by 180° with respect to the firing signal of thyristor Q_1. Therefore, thyristor Q_4 is fired at phase angle 200°, i.e., 20° after the beginning of the negative half of phase voltage E_{1-N}.

– The firing signals of the thyristors (Q_2 and Q_5) in the second phase are delayed by 120° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase. Therefore, thyristor Q_2 is fired at phase angle 140° (i.e., 20° after the beginning of the positive half of phase voltage E_{2-N}), while thyristor Q_5 is fired at phase angle 320° (i.e., 20° after the beginning of the negative half of phase voltage E_{2-N}).

– The firing signals of the thyristors (Q_3 and Q_6) in the third phase are delayed by 240° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase. Therefore, thyristor Q_3 is fired at phase angle 260°, (i.e., 20° after the beginning of the positive half of phase voltage E_{3-N}), while thyristor Q_6 is fired at phase angle 80° (i.e., 20° after the beginning of the negative half of phase voltage E_{3-N}).

The width of the rectangular pulses in all firing signals is 120°.

When phase angle modulation is used in a three-phase ac power control circuit with a **6D** load configuration, the firing signals are the same as those shown in Figure 84 for a 4S load configuration, except that the firing angle α is determined with respect to the instant when line-to-line voltage E_{1-2} (or voltage E_{2-3} or E_{3-1}) crosses zero and becomes positive.

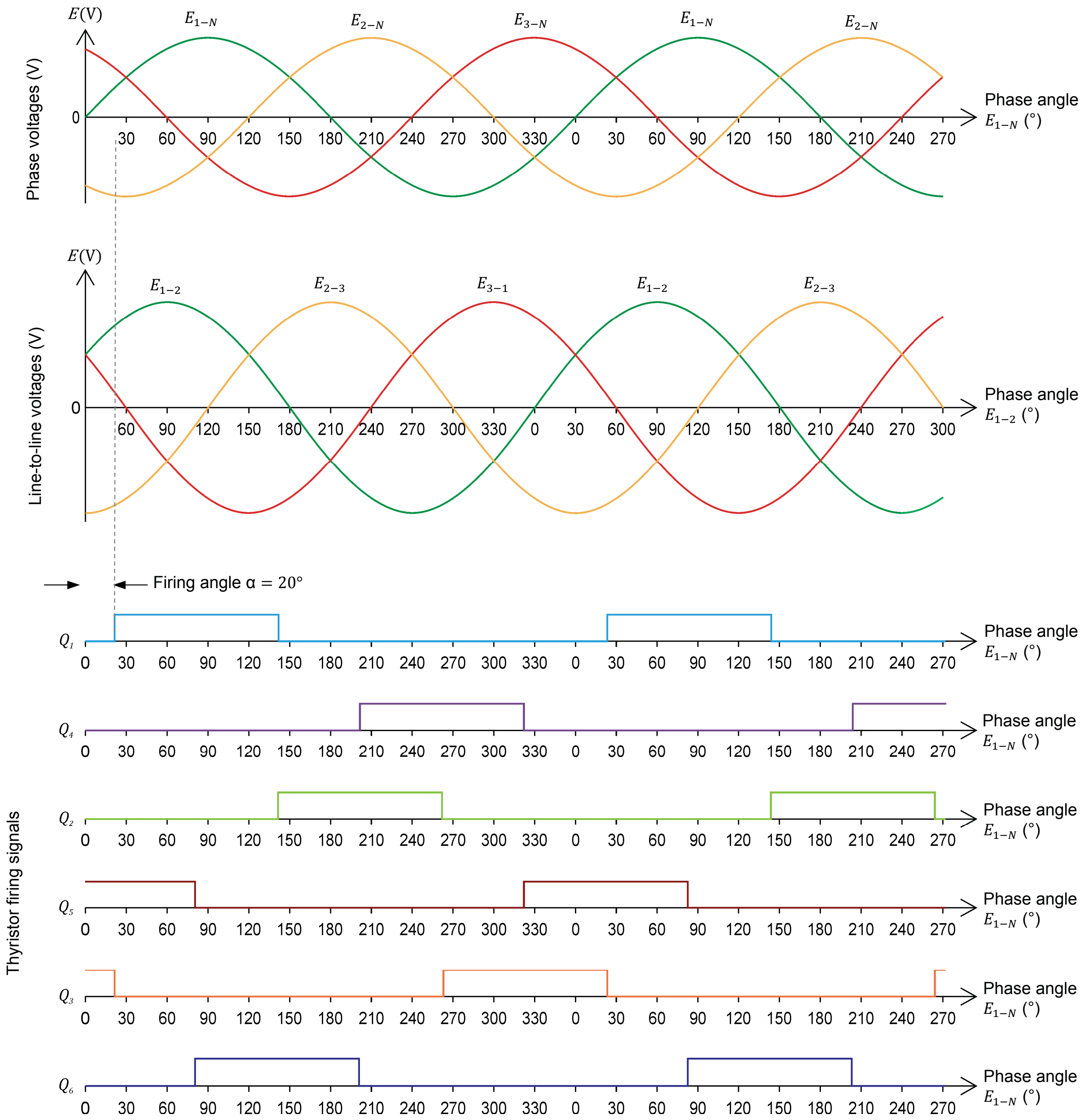


Figure 84. Typical firing signals in a three-phase ac power control circuit with a 4S load configuration when phase angle modulation is used (firing angle α set to 20°).

Burst fire control

When burst fire control is used in three-phase ac power control circuits with a 4S or 6D load configuration, the synchronous mode is generally used.

– With the 4S load configuration, the on-time interval starts at the instant when one of the phase voltages of the ac power source passes through zero.

– With the 6D load configuration, the on-time interval starts at the instant when one of the line-to-line voltages of the ac power source passes through zero.

Figure 85 shows an example of typical firing signals in a three-phase ac power control circuit with 4S and 6D load configurations when synchronous burst fire control is used, for an on-time interval of one cycle.

– With the **4S load configuration** (Figure 85a), the on-time interval starts at the instant when phase voltage E_{1-N} crosses zero and becomes positive. At this instant, the thyristors in this branch of the circuit (Q_1 and Q_4) are fired. 60° later, phase voltage E_{3-N} crosses zero, and the thyristors in this branch of the circuit (Q_3 and Q_6) are fired. 120° after the beginning of the on-time interval, phase voltage E_{2-N} crosses zero and the thyristors in this branch of the circuit (Q_2 and Q_5) are fired. The duration of the firing pulses is equal to ¾ of a period (i.e., 270°) of the ac power source voltage to ensure that thyristor conduction does not exceed one cycle. If the on-time interval were set to two cycles, the duration of the firing pulses would be set to 1 ¾ periods of the ac power source voltage to ensure that thyristor conduction does not exceed two cycles and so on.

– With the **6D load configuration** (Figure 85b), the firing signals are the same as those used for the 4S load configuration, except that the on-time interval starts at the instant when line-to-line voltage E_{1-2} crosses zero and becomes positive. At this instant, the thyristors in the corresponding branch of the circuit (Q_1 and Q_4) are fired. 60° after the beginning of the on-time interval, line-to-line voltage E_{3-1} crosses zero and the thyristors in the corresponding branch of the circuit (Q_3 and Q_6) are fired. 120° later, line-to-line voltage E_{2-3} crosses zero and the thyristors in the corresponding branch of the circuit (Q_2 and Q_5) are fired.

Notice that the burst firing control strategy described above works well when the three-phase load is purely resistive.

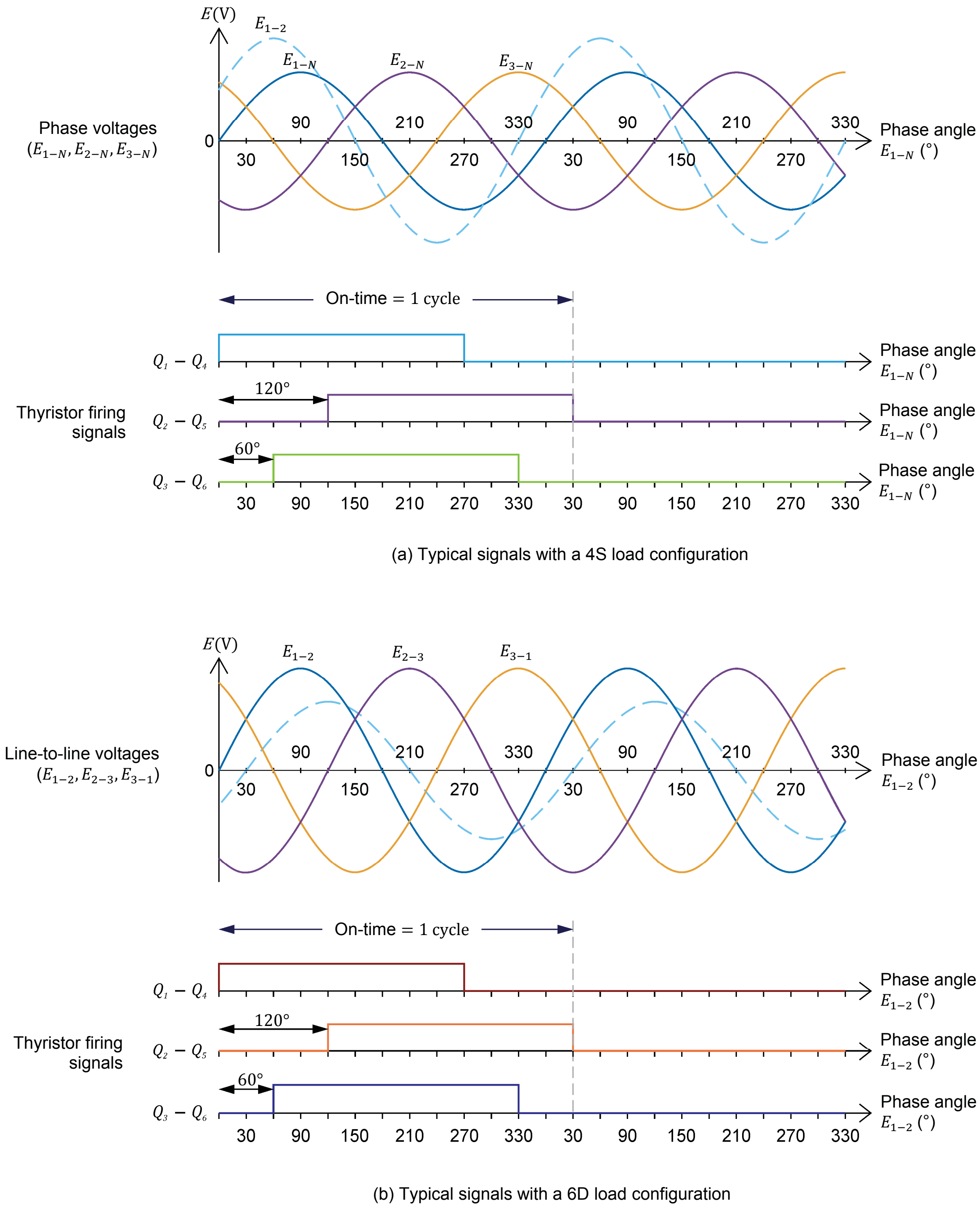


Figure 85. Typical thyristor firing signals in a three-phase ac power control circuit with a 4S or 6D load configuration when burst fire control is used.

In three-phase ac power control circuits with a 4S or 6D load configuration, firing a single thyristor is sufficient to turn it on and create a path for current to flow through one of the load elements. Figure 86 shows the current flow created when thyristor Q_1 is fired in three-phase ac power control circuits with a 4S (Figure 86a) and a 6D (Figure 86b) load configuration. As usual, thyristor Q_1 must be fired when it is forward biased (i.e., during the positive half of the ac power source voltage waveform) for current to flow through the load element.

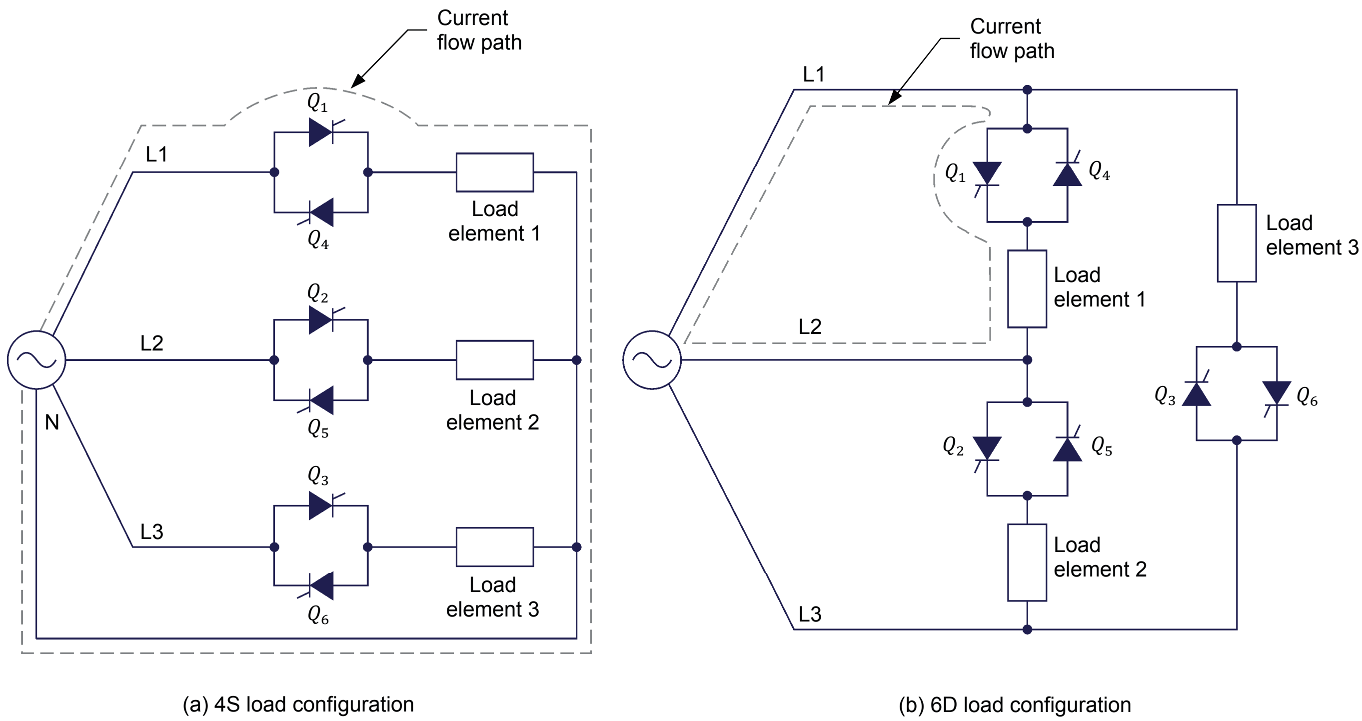


Figure 86. In three-phase ac powe r control circuits with a 4S or 6D load configuration, firing a single thyristor is sufficient to turn it on and create a path for current to flow.

Circuit operation and thyristor firing control in three-phase ac power control circuits with 3S and 3D load configurations

In the case of three-phase ac power control circuits with a 3S or 3D load configuration, firing a single thyristor is not sufficient to create a path for current to flow through the load. In fact, at least two thyristors (for instance, Q_1 and Q_5) must be fired to create a path for current to flow through the load, as Figure 87 shows. Because of this, the operation of three-phase ac power circuits with a 3S or 3D load configuration differs slightly from the operation of three-phase ac power circuits with a 4S or 6D load configuration.

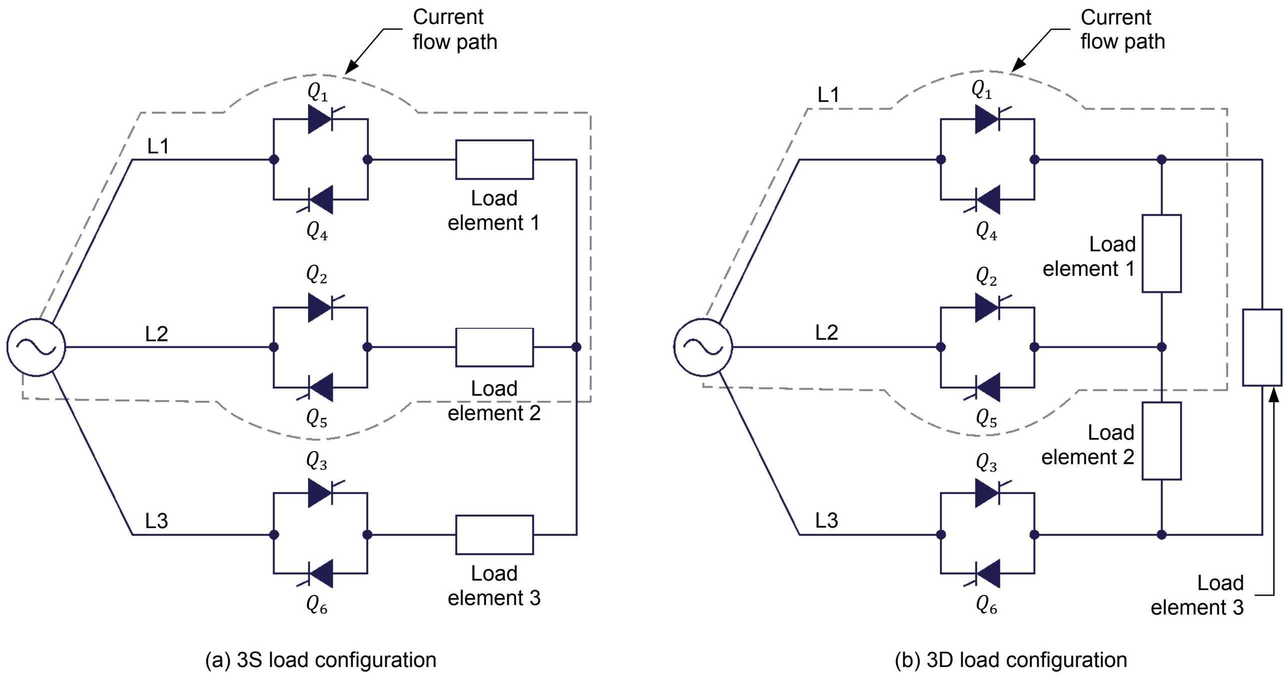


Figure 87. In three-phase ac power control circuits with a 3S or 3D load configuration, at least two thyristors must be simultaneously fired to create a path for current to flow.

Phase angle modulation

When phase angle modulation is used in three-phase ac power control circuits with a 3S or 3D load configuration, the firing signals are identical to those used in three-phase ac power control circuits with a 4S or 6D load configuration. However, the circuit operation differs slightly since current can only flow when at least two thyristors are on. In fact, the number of thyristors that are on at any instant of the ac power source cycle depends on the firing angle α.

Since the number of thyristors that are on at any instant of the ac power source cycle depends on the firing angle α, the waveforms of the load voltage and current can have various shapes, depending on whether the firing angle α is between 0° and 60° (mode 1), 60° and 90° (mode 2), or 90° and 150° (mode 3).

Figure 88, Figure 89, and Figure 90 show examples of the load voltage and current waveforms at a 3S load for firing angles of 30° (mode 1), 75° (mode 2), and 120° (mode 3), respectively. The firing angle α is determined with respect to the instant when phase voltage E_{1-N} crosses zero and becomes positive.

In Figure 88, the firing angle is 30°, i.e., between 0° and 60° (mode 1). In this mode, two or three thyristors are on simultaneously (e.g., between phase angles 90° and 150°, current initially flows through thyristors Q_1, Q_5, and Q_6 then through thyristors Q_1 and Q_6).

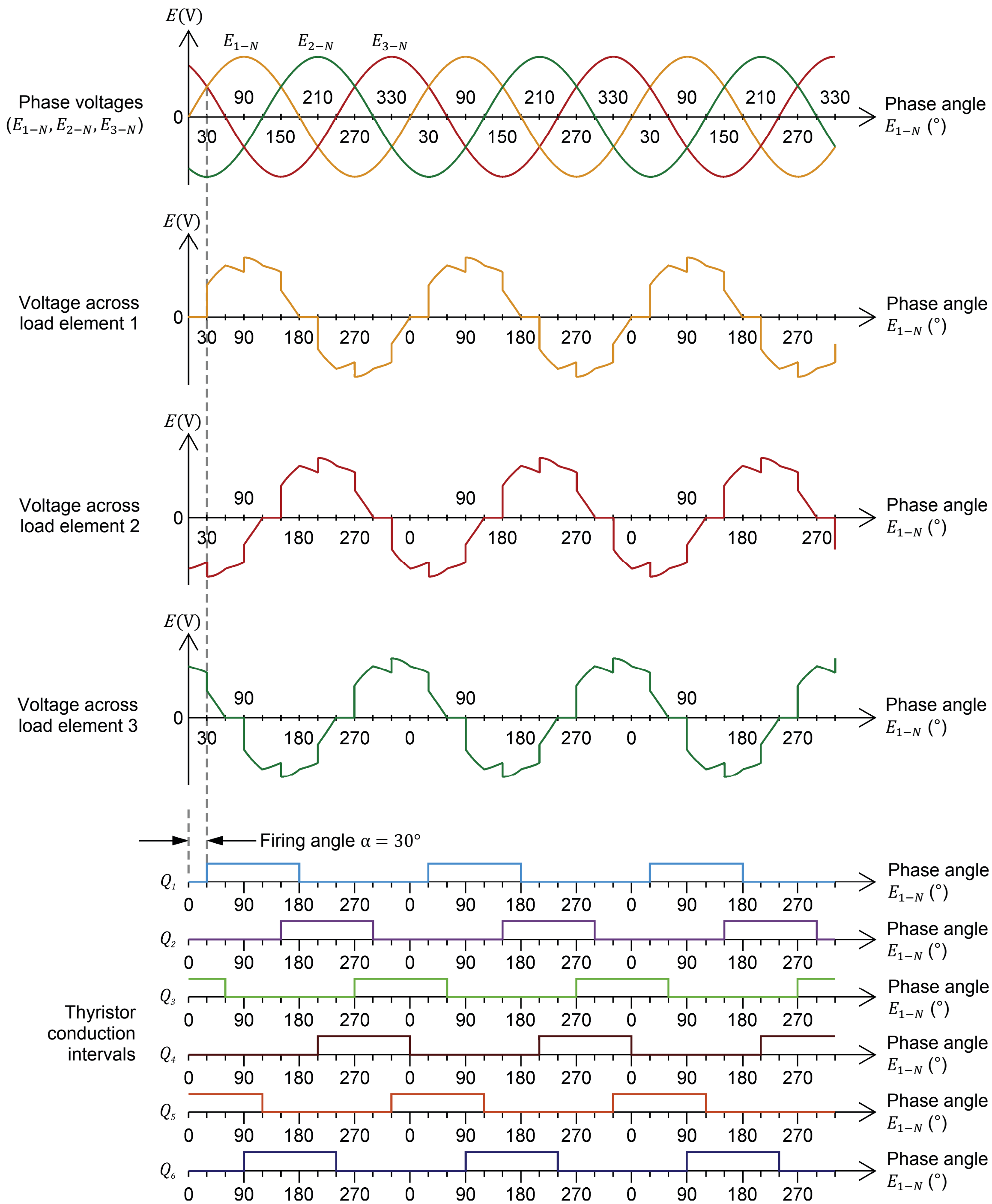


Figure 88. Example of the load voltage and current waveforms at a 3S load when the firing angle is 30° (mode 1).

In Figure 89, the firing angle is 75°, i.e., between 60° and 90° (mode 2). In this mode, only two thyristors are on simultaneously (e.g., between phase angles 135° and 195°, current flows through thyristors Q_1 and Q_6).

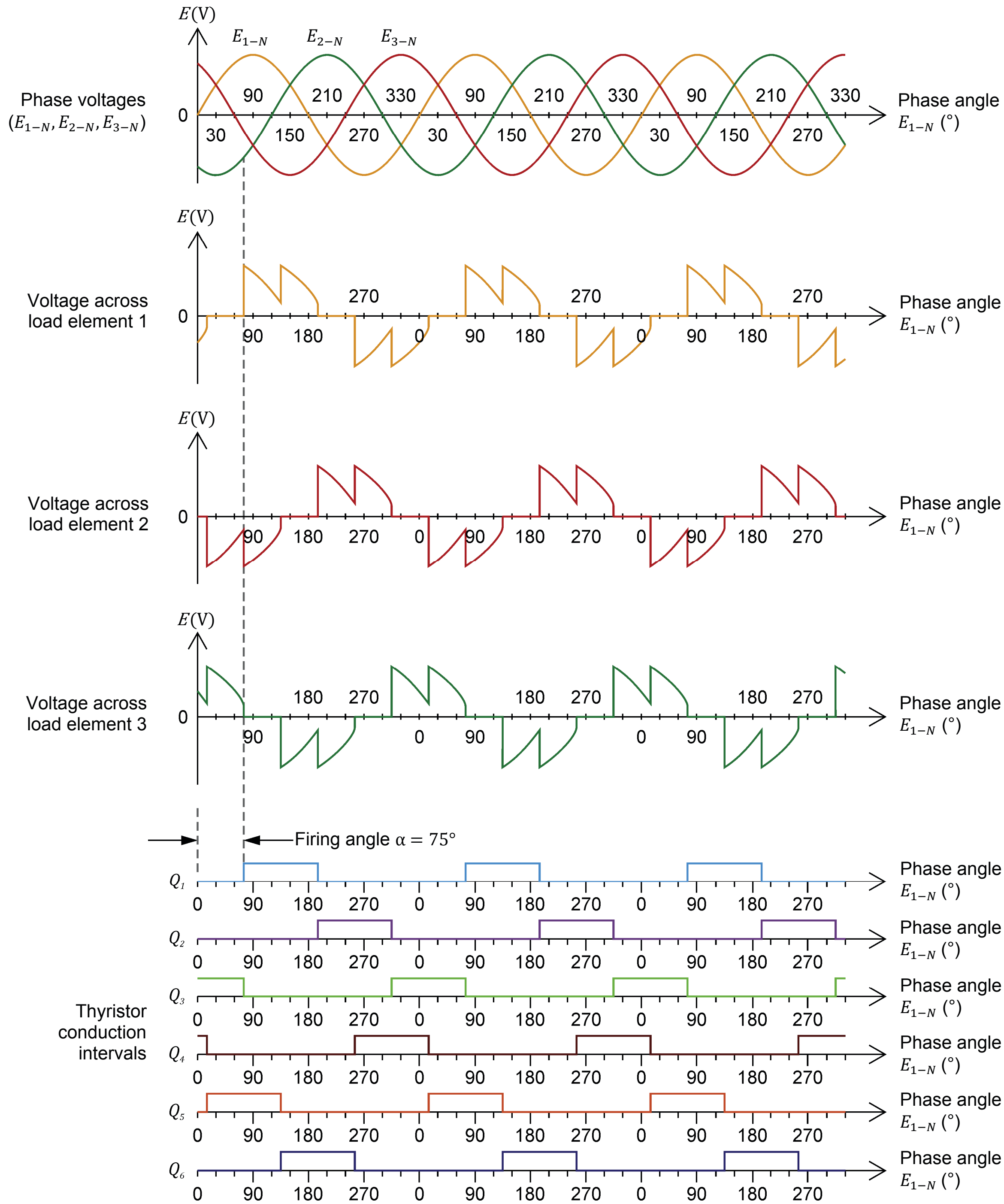


Figure 89. Example of the load voltage and current waveforms at a 3S load when the firing angle is 75° (mode 2).

In Figure 90, the firing angle is 120°, i.e., between 90° and 150° (mode 3). In this mode, two thyristors are on simultaneously or all the thyristors are off (e.g., between phase angles 120° and 180°, current initially flows through thyristors Q_1 and Q_5 for a 30° interval then both thyristors turn off, thereby interrupting current flow). When the firing angle α is greater than 150°, no thyristor can enter into conduction. Therefore, the firing angle can be varied between 0° and 150°.

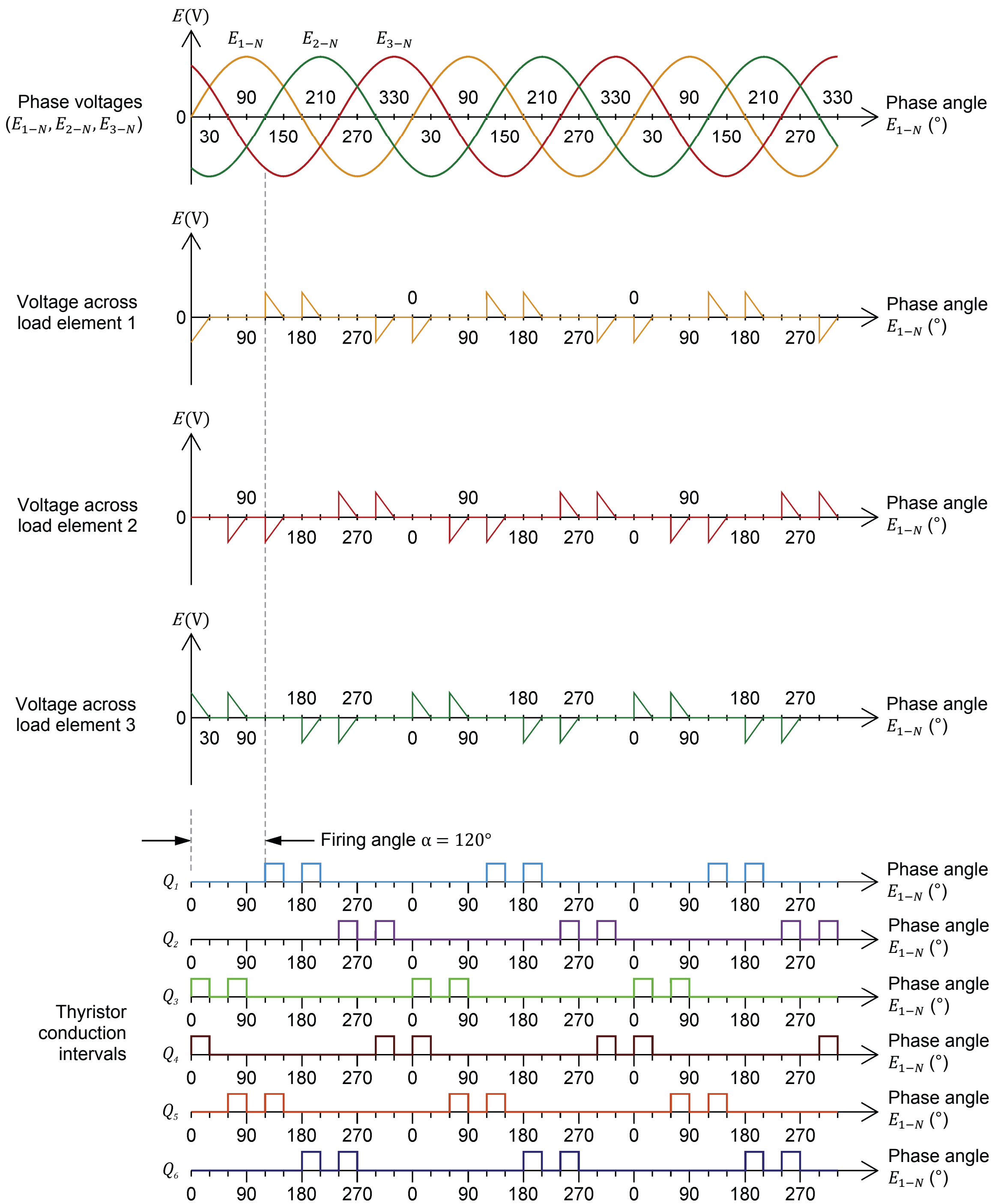


Figure 90. Example of the load voltage and current waveforms at a 3S load when the firing angle is 120° (mode 3).

Three-phase ac power control with phase angle modulation can be used to implement a **variable inductor** [also called **thyristor-controlled reactor (TCR)** in a static var compensator (SVC). An SVC is a fast-acting device used to regulate voltage over three-phase ac power transmission lines or regulate the power factor at the main power input of industrial plants operating with highly inductive loads. The SVC works by adjusting the amount of reactive power it supplies to the ac power system to quickly adapt to variations in power demand.

Figure 91. SVCs can be used near electric arc furnaces to reduce the voltage fluctuations caused by the flicker (sudden and erratic variations in the length of the furnace arc).

Burst fire control

When thyristor firing is performed with burst fire control in three-phase ac power control circuits with 3S or 3D load configurations, each pair of thyristors (i.e., Q_1 and Q_4, Q_2 and Q_5, and Q_3 and Q_6) is controlled (fired) so that it operates like a zero-voltage switched (ZVS) SSR.

Figure 92 shows waveforms of the line-to-line voltage and line current at the load of a three-phase ac power control circuit when burst fire control is used. Notice that the slight imperfection of the waveforms during the first and last 90° of conduction is due to temporary circuit imbalance, as two of the three SSRs are on.

The waveforms of Figure 92 show that:

– At the beginning of each on-time interval, i.e., when power has to be applied to the three-phase load, each ZVS SSR (i.e., each pair of thyristors) is enabled.

– As soon as one of the line-to-line voltages of the power source passes through zero, the two ZVS SSRs connected between these two lines turn on (i.e., two thyristors in these ZVS SSRs turn on).

– 90° later, the voltage across the third ZVS SSR passes through zero and this SSR turns on, thereby completing the connection of the ac power source and three-phase load.

– At the end of each on-time interval, i.e., when power has to be removed from the three-phase load, each ZVS SSR is disabled.

– As soon as one of the line currents passes through zero, the corresponding ZVS SSR turns off (i.e., the two thyristors in this SSR turn off).

– 90° later, the current in the two other lines becomes zero and the other two ZVS SSRs turn off.

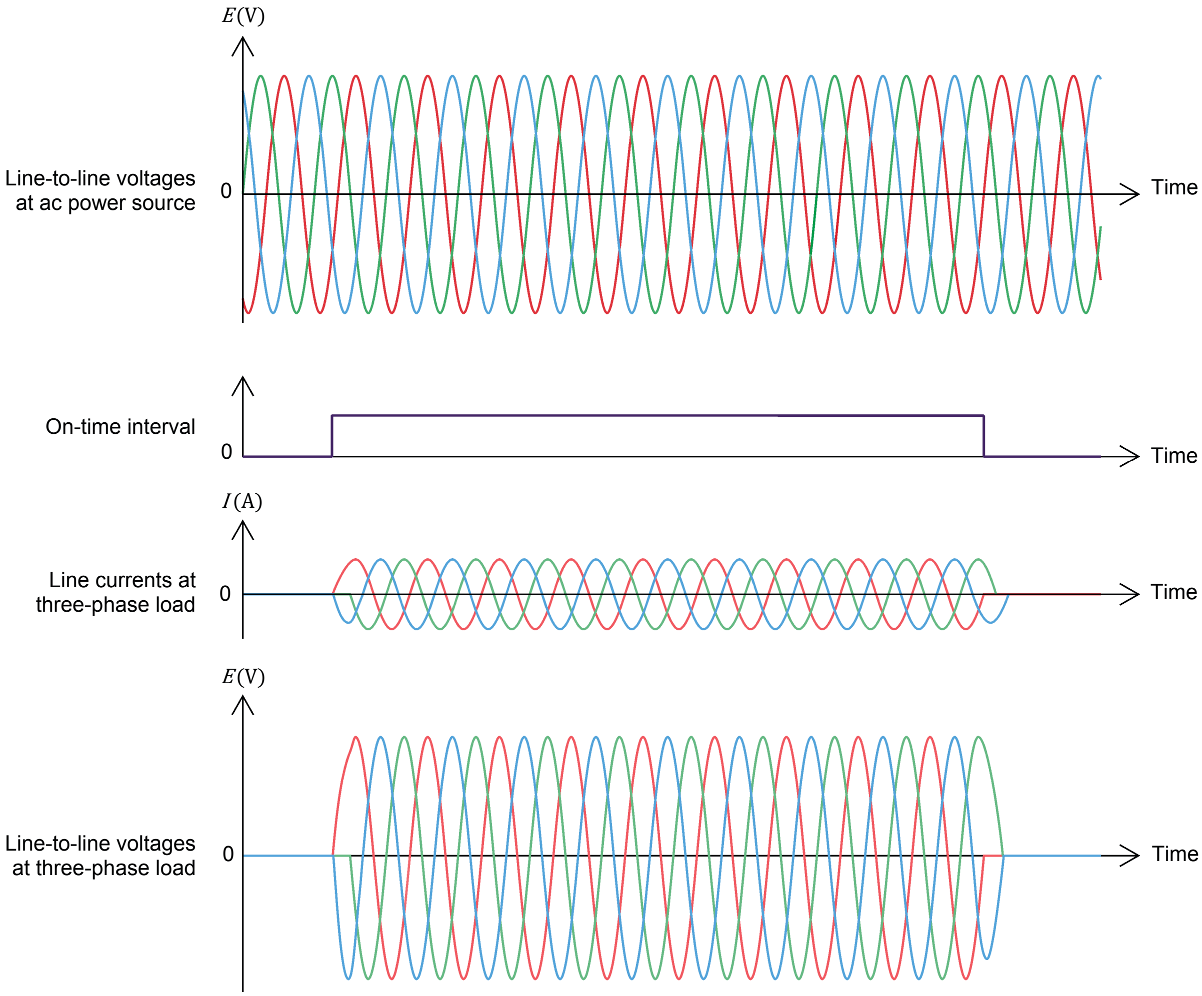


Figure 92. Waveforms of the line-to-line voltages and line currents at the 3S or 3D load when burst fire control is used.

Applications of three-phase ac power control

Three-phase ac power control with phase angle modulation is widely used in three-phase soft starters. These starters are used to start and stop three-phase induction motors smoothly. They limit the current drawn when starting the device or machine, as well as mechanical shocks and noise.

Figure 93. Three-phase soft starters are used to start and stop conveyor motors smoothly.

Figure 94. Three-phase soft starters are also used in wind turbines equipped with asynchronous generators to achieve smooth connection of the generator to the grid.

Three-phase ac power control with burst fire control is commonly used to control the amount of power supplied to three-phase heater elements. In this case, burst fire control is often preferable because it reduces the large, sudden variations in load current, while allowing operation at unity power factor.

Figure 95. Three-phase ac power control using burst fire control is used in industrial ovens.

Figure 96. Three-phase ac power control using burst fire control is typically used for high power heating and ventilating (HVAC) systems in commercial and industrial installations.

Procedure Outline

The Procedure is divided into the following sections:

- Set up and connections
- Thyristor three-phase ac power control using phase angle modulation (4S load configuration)
  Observation of the thyristor firing signals. Observation of the load voltage and current waveforms and measurement of the load voltage, current, and power.
- Thyristor three-phase ac power control using burst fire control (4S load configuration)
  Observation of the thyristor firing signals. Observation of the load voltage and current waveforms and measurement of the load voltage, current, and power.
- Thyristor three-phase ac power control using phase angle modulation (3S load configuration)
  Observation of the thyristor firing signals. Observation of the load voltage and current waveforms and measurement of the load voltage, current, and power.

Procedure

⚠ WARNING

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

Set up and connections

In this part of the exercise, you will set up and connect the equipment.

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

   Install the equipment in the Workstation.

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

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

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

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

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

In the LVDAM-EMS Start-Up window, make sure that the Data Acquisition and Control Interface is detected. Make sure that the *Computer-Based Instrumentation* and *Thyristor Bridge Control* functions for the Data Acquisition and Control Interface are 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 LVDAM-EMS Start-Up window.

Thyristor three-phase ac power control using phase angle modulation (4S load configuration)

In this part of the exercise, you will perform thyristor three-phase ac power control using phase angle modulation and a 4S load configuration. You will observe the firing signals as well as the waveforms of circuit voltages and currents, and explain how the circuit operates. You will observe the effect that varying the firing angle of the thyristors has on the amount of active power delivered to the three-phase load.

Observation of the thyristor firing signals

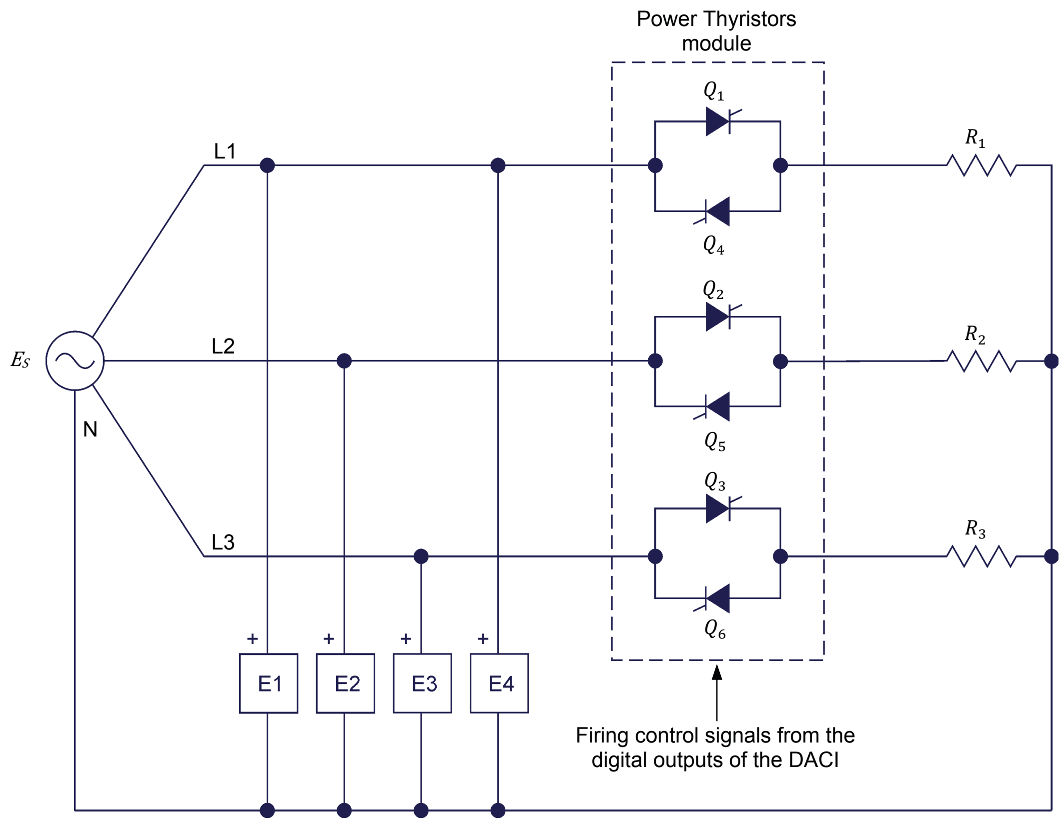
6. On the Power Thyristors module, make sure that switches S_1 and S_2 are set to the O (off) position.

Set up the circuit shown in Figure 97. In this circuit, E_S is the three-phase ac power source of the Power Supply (Model 8823). *E1*, *E2*, *E3*, and *E4* are voltage inputs of the Data Acquisition and Control Interface (DACI). The thyristors (Q_1 through Q_6) are those in the Power Thyristors module. The load resistors R_1, R_2, and R_3 are implemented with the Resistive Load module. The resistance value to be used for each load resistor depends on your local ac power network voltage (see table in the diagram).

Input E4 of the DACI is used for synchronization of the firing signals of the thyristors in the Power Thyristors module. This input must be connected across the line 1 (L1) and neutral (N) terminals of the three-phase ac power source in the Power Supply.

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

Also, perform the following connections to be able to observe the firing control signals applied to thyristors Q_1 through Q_6: connect *Firing Control Inputs 1* through *6* of the Power Thyristors module to *Analog Inputs 1* through *6*, respectively, of the DACI, using 2 mm leads. Connect the common (white) terminal of the *Firing Control Inputs* on the Power Thyristors module to one of the two analog common (white) terminals of the DACI using a 2 mm lead.



Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	**Frequency (Hz)**	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 97. Thyristor three-phase ac power control using phase angle modulation (4S load configuration). Observation of the thyristor firing signals.

8. In LVDAC-EMS, open the Thyristor Control window, and make the following settings:

– Set the *Function* parameter to *Thyristor Three-Phase AC Power Control*.

– Set the *Load Configuration* parameter to *4 wires, star (4S)*. This selects the wye (star) load configuration with a neutral conductor.

– Make sure that the *Control Mode* parameter is set to *Phase Control*. This sets the thyristor firing control to the phase angle modulation mode.

– Make sure that the *Firing Angle Control* parameter is set to *Knob*. This allows the *Firing Angle* parameter to be controlled manually.

– Set the *Firing Angle* parameter to 30° by entering 30 in the field next to this parameter or by using the control knob in the lower left corner of the window. This sets the firing angle α to 30°.

– Make sure that parameters Q_1 through Q_6 are all set to *Active*. This makes the firing signals of these thyristors depend on the *Firing Angle Control* and *Firing Angle* parameters.

– Start the *Thyristor Three-Phase AC Power Control* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

9. On the Power Supply, turn the three-phase ac power source on by setting the corresponding switch to I (on).

10. Start the Oscilloscope.

In the Data Acquisition and Control Settings window of LVDAC-EMS, set the *Range* of voltage inputs *E1*, *E2*, and *E3* to *High*.

On the Oscilloscope, display the phase voltages of the ac power source (*E1*, *E2*, and *E3*) and the firing signals of thyristors Q_1 through Q_5 (*Analog Inputs 1* through *5* of the DACI) on channels, 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Set the Oscilloscope in the continuous refresh mode. Set the time base to display at least two cycles of the source voltage waveform.

Observe that each pulse in the firing signal of thyristor Q_1 (*Channel 4*) occurs 30° after the instant when voltage $E_{1\text{-}N}$ crosses zero and becomes positive, i.e. 30° after the beginning of the positive half of this voltage. Briefly explain why.

This is because the firing angle α is currently set to 30°

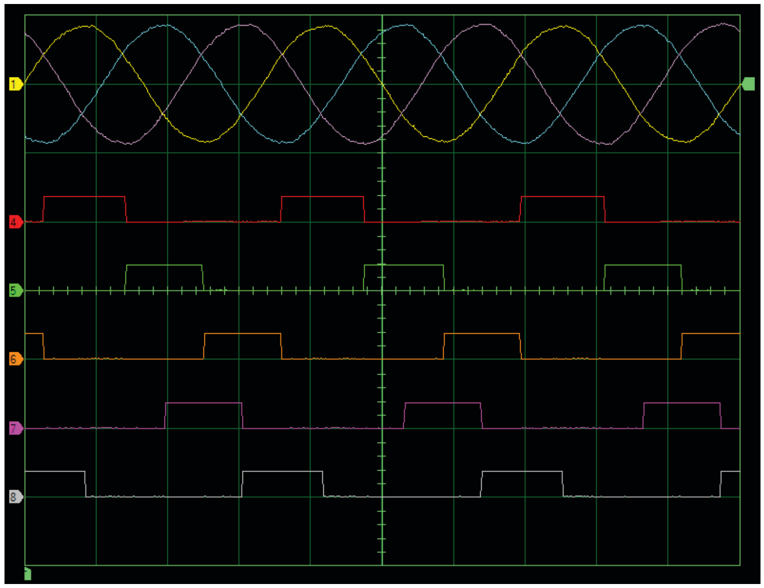
Does each pulse in the firing signal of thyristor Q_4 (*Channel 7*) occur 180° after the corresponding pulse in the firing signal of thyristor Q_1, i.e., 30° after the beginning of the negative half of voltage $E_{1\text{-}N}$?

❑ Yes ❑ No

Yes. The following figure shows an example of the waveforms displayed on the Oscilloscope.

Oscilloscope Settings

Channel-1 Input E1
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input E2
Channel-2 Scale ....200 V/div
Channel-2 Coupling ....DC
Channel-3 Input E3
Channel-3 Scale ....200 V/div
Channel-3 Coupling ....DC
Channel-4 Input AI-1
Channel-4 Scale .... 10 V/div
Channel-4 Coupling ....DC
Channel-5 Input AI-2
Channel-5 Scale .... 10 V/div
Channel-5 Coupling ....DC
Channel-6 Input AI-3
Channel-6 Scale .... 10 V/div
Channel-6 Coupling ....DC
Channel-7 Input AI-4
Channel-7 Scale .... 10 V/div
Channel-7 Coupling ....DC
Channel-8 Input AI-5
Channel-8 Scale .... 10 V/div
Channel-8 Coupling ....DC
Time Base .... 5 ms/div
Trigger Type ....Software
Trigger Source Ch1
Trigger Level .... 0 V
Trigger Slope ....Rising



Phase voltages of the ac power source and firing signals of thyristors Q_1 through Q_5 (firing angle α set to 30°).

11. Compare the firing signals of the thyristors (Q_2 and Q_5) in the second phase of the circuit to the firing signals of the thyristors (Q_1 and Q_4) in the first phase of the circuit. What is the phase relationship between these two pairs of firing signals? Explain.

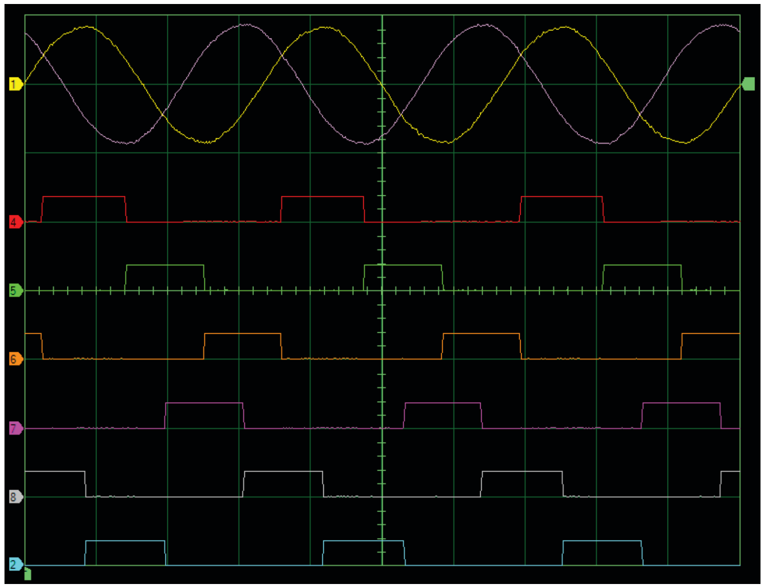
The firing signals of the thyristors (Q_2 and Q_5) in the second phase of the circuit are delayed by 120° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase. Consequently, each pulse in the firing signal of thyristor Q_2 occurs 30° after the beginning of the positive half of voltage E_{2-N}, and each pulse in the firing signal of thyristor Q_5 occurs 30° after the beginning of the negative half of voltage E_{2-N}.

12. On the Oscilloscope, set *Channel 2* to display the firing signal of thyristor Q_6 (instead of voltage $E_{2\text{-}N}$).

Compare the firing signals of the thyristors (Q_3 and Q_6) in the third phase of the circuit to the firing signals of the thyristors (Q_1 and Q_4) in the first phase of the circuit. What is the phase relationship between these two pairs of firing signals?

The firing signals of the thyristors (Q_3 and Q_6) in the third phase of the circuit are delayed by 240° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase. Consequently, each pulse in the firing signal of thyristor Q_3 occurs 30° after the beginning of the positive half of voltage E_{3-N}, and each pulse in the firing signal of thyristor Q_6 occurs 30° after the beginning of the negative half of phase voltage E_{3-N}. The following figure shows an example of the waveforms displayed on the Oscilloscope.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input AI-6
Channel-2 Scale .... 10 V/div
Channel-2 Coupling ....DC
Channel-3 Input E3
Channel-3 Scale ....200 V/div
Channel-3 Coupling ....DC
Channel-4 Input AI-1
Channel-4 Scale .... 10 V/div
Channel-4 Coupling ....DC
Channel-5 Input AI-2
Channel-5 Scale .... 10 V/div
Channel-5 Coupling ....DC
Channel-6 Input AI-3
Channel-6 Scale .... 10 V/div
Channel-6 Coupling ....DC
Channel-7 Input AI-4
Channel-7 Scale .... 10 V/div
Channel-7 Coupling ....DC
Channel-8 Input AI-5
Channel-8 Scale .... 10 V/div
Channel-8 Coupling ....DC
Time Base .... 5 ms/div
Trigger Type ....Software
Trigger Source Ch1
Trigger Level .... 0 V
Trigger Slope ....Rising



Phase voltages E_{1-N} and E_{3-N}, and firing signals of thyristors Q_1 through Q_6 (firing angle α set to 30°).

13. By using the *Firing Angle* control knob in the Thyristor Control window, slowly vary the firing angle α while observing the firing signals of thyristors Q_1 through Q_6. Describe what happens when the firing angle is varied.

When the firing angle α increases, the pulses in the thyristor firing signals become increasingly delayed, and vice versa.

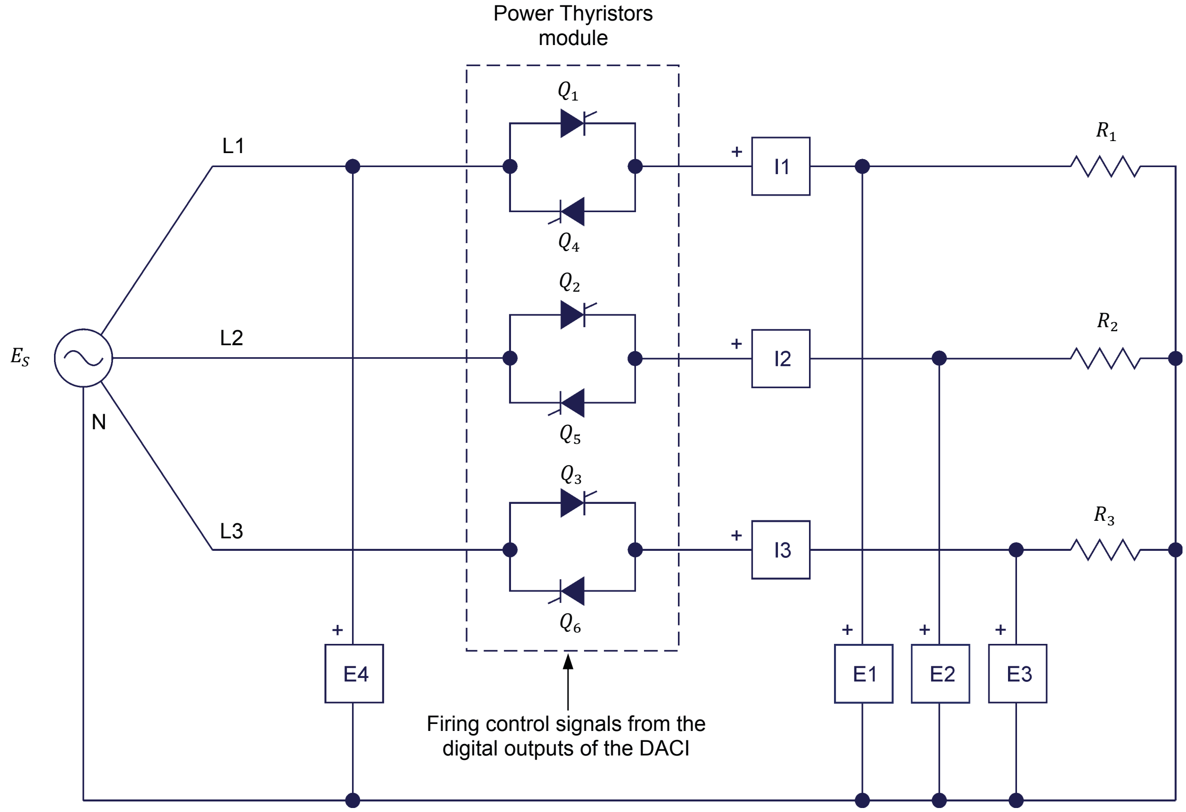
14. In the Thyristor Control window, stop the *Thyristor Three-Phase AC Power Control* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

On the Power Supply, turn the three-phase ac power source off by setting the corresponding switch to O (off).

Observation of the load voltage and current waveforms and measurement of the load voltage, current, and power

15. Modify the circuit connections as shown in Figure 98. The resistance value for the load resistors R_1, R_2, and R_3 depends on your local ac power network voltage (see table in the diagram).

Input E4 of the DACI is used for synchronization of the firing signals of the thyristors in the Power Thyristors module. This input must be connected across the line 1 (L1) and neutral (N) terminals of the three-phase ac power source in the Power Supply.



Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 98. Thyristor three-phase ac power control using phase angle modulation (4S load configuration). Observation of the load current and voltage waveforms and measurement of the load voltage, current, and power.

16. In the Thyristor Control window, start the *Thyristor Three-Phase AC Power Control* function. Set the *Firing Angle* parameter to 30°.

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

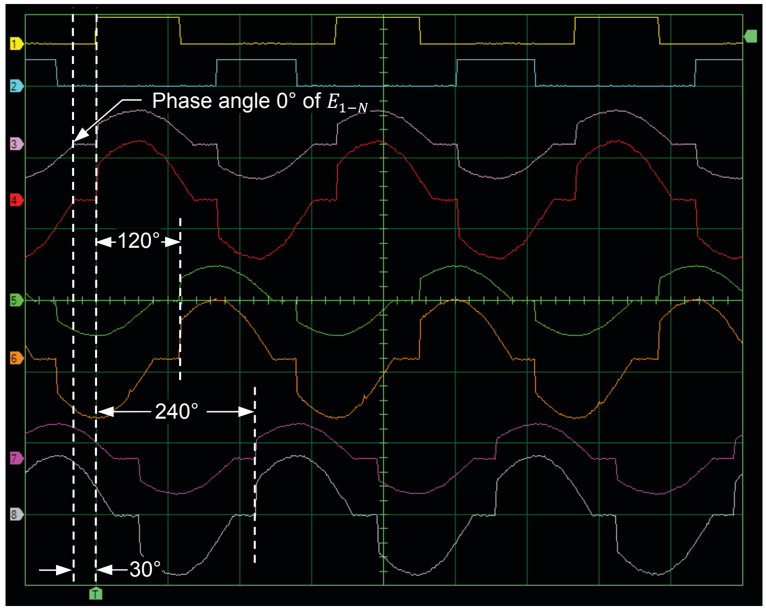
17. On the Oscilloscope, make the settings required to display the firing signals of thyristors Q_1 and Q_4 (*Analog Inputs 1* and *4* of the DACI), and the load current and voltage waveforms (*I1*, *E1*, *I2*, *E2*, *I3*, and *E3*) on channels 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Set the Oscilloscope in the continuous refresh mode. Set the time base to display at least two cycles of the source voltage waveform.

Observe the relationship between the firing signals of thyristors Q_1 and Q_4 and the waveforms of the load current and voltage (*Channels 3* and *4*, respectively) in the corresponding phase (E_{1-N}) of the circuit. Describe these waveforms and explain why they follow voltage E_{1-N} during some portions of the voltage cycle only.

At phase angle 30°, thyristor Q_1 enters into conduction, allowing current to flow through the load (resistor R_1) in the first phase ($E_{1\text{-}N}$) of the circuit. Therefore, the waveforms of the load current and voltage (*Channels 3* and *4*, respectively) follow voltage $E_{1\text{-}N}$ between phase angle 30° and the end of the positive half of voltage $E_{1\text{-}N}$. Between phase angles 180° and 210°, thyristors Q_1 and Q_4 are off, so the load current and voltage are null. At phase angle 210°, thyristor Q_4 enters into conduction. Therefore, the waveforms of the load current and voltage follow voltage $E_{1\text{-}N}$ between phase angle 210° and the end of the negative half of voltage $E_{1\text{-}N}$. Between 0° and 30°, thyristors Q_1 and Q_4 are off, so the load current and voltage in the first phase are null.

The following figure shows an example of the waveforms displayed on the Oscilloscope.

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-4
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input I1
Channel-3 Scale .... 2 A/div
Channel-3 Coupling .... DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input I2
Channel-5 Scale .... 2 A/div
Channel-5 Coupling .... DC
Channel-6 Input E2
Channel-6 Scale .... 200 V/div
Channel-6 Coupling .... DC
Channel-7 Input I3
Channel-7 Scale .... 2 A/div
Channel-7 Coupling .... DC
Channel-8 Input E3
Channel-8 Scale .... 200 V/div
Channel-8 Coupling .... DC
Time Base .... 5 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 1 V
Trigger Slope .... Rising



Firing signals of thyristors Q_1 and Q_4 and waveforms of the load currents and voltages (firing angle α set to 30°).

18. Are the waveforms of the load current and voltage (*Channels 5* and *6*, respectively) in the second phase (E_{2-N}) of the circuit identical to those in the first phase of the circuit, except that they are delayed by 120°? Why?

Yes. This is because the firing signals of the thyristors (Q_2 and Q_5) in the second phase of the circuit are delayed by 120° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase of the circuit.

Are the waveforms of the load current and voltage (*Channels 7* and *8*, respectively) in the third phase (E_{3-N}) of the circuit identical to those in the first phase of the circuit, except that they are delayed by 240°? Why?

Yes. This is because the firing signals of the thyristors (Q_3 and Q_6) in the third phase of the circuit are delayed by 240° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase of the circuit.

19. Open the Metering window. Set three meters to measure the rms values of the load voltages (*E1*, *E2*, and *E3*). Set three meters to measure the rms values of the load currents (*I1*, *I2*, and *I3*). Finally, set a meter to measure the total active power supplied to the load (*PQS1 + PQS2 + PQS3*).

Disable meter *E4*. Select the *Continuous Refresh* mode by clicking the *Continuous Refresh* button.

When the Thyristor Control window is in use, meter E4 in the Metering window must be disabled for the Continuous Refresh mode to be operational. This is because input E4 of the Data Acquisition and Control Interface is dedicated to the thyristor control function which uses this input for the synchronization of the thyristor firing signals.

20. By using the *Firing Angle* control knob in the Thyristor Control window, slowly vary the firing angle α while observing the waveforms on the Oscilloscope and the values of the load voltages, load currents, and active load power indicated by the meters. From your observations, briefly explain how the circuit operates.

When the firing angle α increases, the pulses in the firing signals of the thyristors become increasingly delayed. This decreases the conduction intervals of the thyristors and thus, the values of the load voltages, load currents, and active load power. Conversely, when the firing angle α decreases, the pulses in the firing signals of the thyristors become less and less delayed. This increases the conduction intervals of the thyristors and thus, the values of the load voltages, load currents, and active load power.

Is circuit operation the same in each of the three phases? Explain.

Yes. In each of the three phases of the circuit, one thyristor allows current to flow through the load during the positive half of the corresponding phase voltage, while the other thyristor allows current to flow through the load during the negative half of the corresponding phase voltage. Furthermore, the conduction interval of the thyristors in each phase of the circuit decreases when the firing angle α increases, and vice versa.

Can the amount of active power delivered to the three-phase load be varied smoothly by varying the firing angle?

❑ Yes ❑ No

Yes

21. In the Thyristor Control window, stop the *Thyristor Three-Phase AC Power Control* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

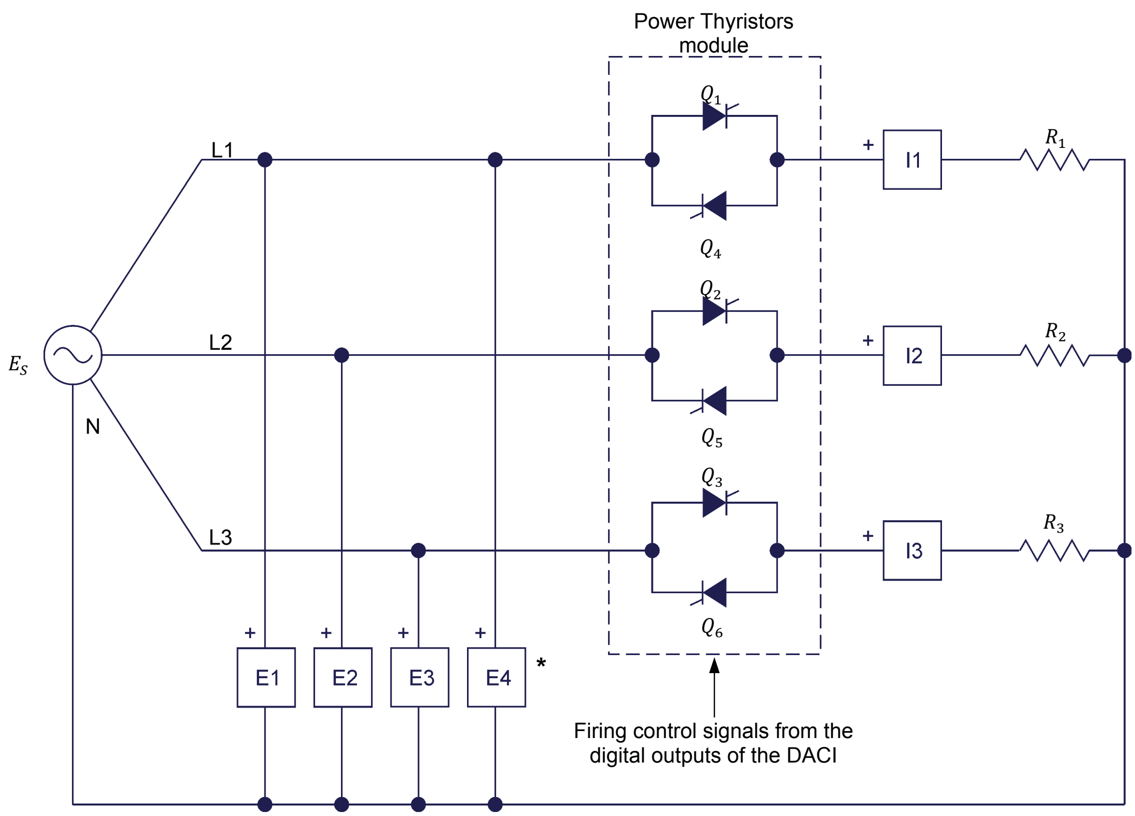
On the Power Supply, turn the three-phase ac power source off.

Thyristor three-phase ac power control using burst fire control (4S load configuration)

In this part of the exercise, you will perform thyristor three-phase ac power control using burst fire control and a 4S load configuration. You will observe the firing signals as well as the waveforms of circuit voltages and currents, and explain how the circuit operates. You will observe the effect that varying the on *time and period (i.e., the duty cycle) has on the amount of active power delivered to the three-phase load.*

Observation of the thyristor firing signals

22. Modify the circuit connections in order to obtain the circuit shown in Figure 99. The resistance value for the load resistors R_1, R_2, and R_3 depends on your local ac power network voltage (see table in the diagram).



* Input *E4* of the DACI is used for synchronization of the firing signals of the thyristors in the Power Thyristors module. This input must be connected across the line 1 (*L1*) and neutral (*N*) terminals of the three-phase ac power source in the Power Supply.

Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	**Frequency (Hz)**	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 99. Thyristor three-phase ac power control using burst fire control (4S load configuration). Observation of the thyristor firing signals.

23. In the Thyristor Control window, make the following settings:

– Make sure that the *Function* parameter is set to *Thyristor Three-Phase AC Power Control*.

– Make sure the *Load Configuration* parameter is set to *4 wires, star (4S)*.

– Set the *Control Mode* parameter to *Burst Fire Control (synchronous)*. This sets the thyristor firing control to the burst fire control (synchronous) mode.

– Make sure that the *On-Time Control* parameter is set to *Knob*. This allows the *On Time* parameter to be controlled manually.

– Set the *Period* and *On Time* parameters to 10 and 3 cycles, respectively. This sets the duty cycle to 30%.

– Make sure that the Q_1 through Q_6 parameters are set to *Active*. This makes the firing signals of these thyristors depend on the *Period* and *On Time* parameters.

– Start the *Thyristor Three-Phase AC Power Control* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

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

25. On the Oscilloscope, display phase voltage $E_{1\text{-}N}$ (*E1*), as well as the firing signals of thyristors Q_1 through Q_6 (*Analog Inputs 1* through *6* of the DACI) on channels, 1, 2, 3, 4, 5, 6, and 7, respectively. Set the Oscilloscope in the continuous refresh mode. Make sure the *Trigger* type is set to *Software*. Select the firing signal of thyristor Q_1 (*Channel 2*) as the trigger source and set the trigger level and slope to 1 V and *Rising*, respectively. Set the time base to display one or two cycles of the thyristor firing signals.

Observe that the firing signals of thyristors Q_1 and Q_4 are identical: they are at high level during nearly three cycles of phase voltage $E_{1\text{-}N}$ and at low level during the seven subsequent cycles of this voltage.

Are the firing signals of thyristors Q_2 and Q_5 identical but delayed 120° with respect to the firing signals of thyristors Q_1 and Q_4?

❑ Yes ❑ No

Yes

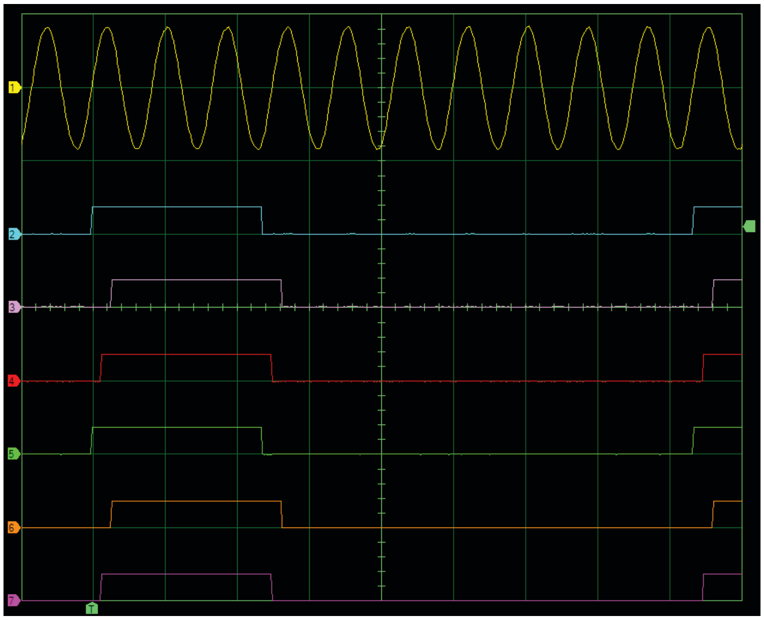
Are the firing signals of thyristors Q_3 and Q_6 identical but delayed 60° with respect to the firing signals of thyristors Q_1 and Q_4?

❑ Yes ❑ No

Yes

The following figure shows an example of the waveforms displayed on the Oscilloscope.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input AI-1
Channel-2 Scale .... 10 V/div
Channel-2 Coupling ....DC
Channel-3 Input AI-2
Channel-3 Scale .... 10 V/div
Channel-3 Coupling ....DC
Channel-4 Input AI-3
Channel-4 Scale .... 10 V/div
Channel-4 Coupling ....DC
Channel-5 Input AI-4
Channel-5 Scale .... 10 V/div
Channel-5 Coupling ....DC
Channel-6 Input AI-5
Channel-6 Scale .... 10 V/div
Channel-6 Coupling ....DC
Channel-7 Input AI-6
Channel-7 Scale .... 10 V/div
Channel-7 Coupling ....DC
Time Base .... 20 ms/div
Trigger Type ....Software
Trigger Source Ch2
Trigger Level .... 1 V
Trigger Slope ....Rising



Firing signals of thyristors Q_1 through Q_6 (on time and period set to 3 cycles and 10 cycles, respectively).

26. On the Oscilloscope, make the settings required to display phase voltages *E1*, *E2*, and *E3*, as well as the firing signals of thyristors Q_1, Q_2, and Q_3 (*Analog Inputs 1*, *2*, and *3* of the DACI, respectively).

Observe that the on-time interval of thyristor Q_1 starts at the instant when voltage $E_{1\text{-}N}$ crosses zero, thereby indicating that the thyristors ($Q_1$and Q_4) in the first phase of the circuit are fired at this instant.

Stop and start the *Thyristor Three-Phase AC Power Control* function a couple of times by clicking the *Start/Stop* button in the Thyristor Control window. Observe that the on-time interval of thyristor Q_1 can start when voltage $E_{1\text{-}N}$ crosses zero and becomes either positive or negative, depending on the phase angle of voltage $E_{1\text{-}N}$ when the *Thyristor Three-Phase AC Power Control* function is started. Is this your observation?

❑ Yes ❑ No

Yes

Does the on-time interval of thyristor Q_3 start 60° after the beginning of the on-time interval for voltage $E_{1\text{-}N}$, i.e., when voltage $E_{3\text{-}N}$ crosses zero and becomes either positive or negative, thereby indicating that the thyristors (Q_3 and Q_6) in the third phase of the circuit are fired at this instant?

❑ Yes ❑ No

Yes

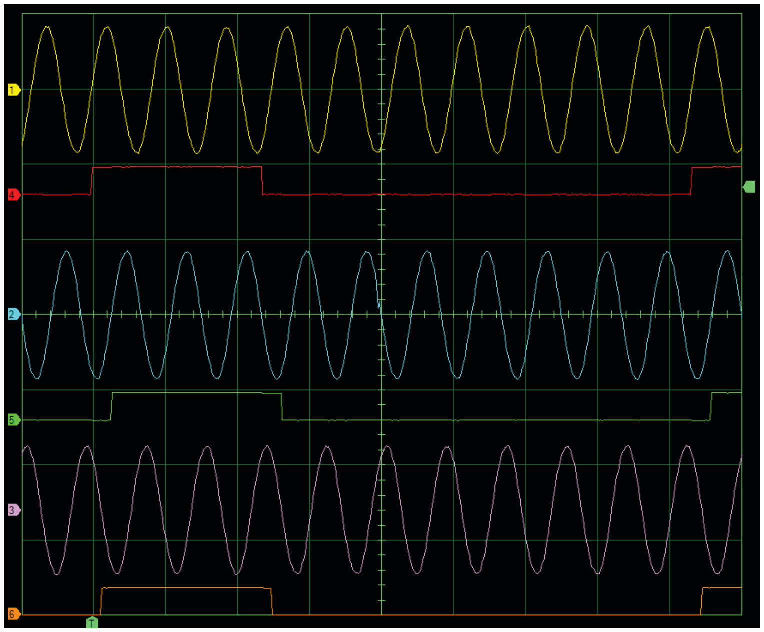
Does the on-time interval of thyristor Q_2 start 120° after the beginning of the on-time interval for voltage $E_{1\text{-}N}$, i.e., when voltage $E_{2\text{-}N}$ crosses zero and becomes either positive or negative, thereby indicating that the thyristors (Q_2 and Q_5) in the second phase of the circuit are fired at this instant?

❑ Yes ❑ No

Yes. The first of the two following figures shows an example of the waveforms displayed on the Oscilloscope when the on-time interval of thyristor Q_1 starts at the instant when voltage E_{1-N} crosses zero and becomes positive. The second figure shows an example of the waveforms displayed on the Oscilloscope when the on-time interval of thyristor Q_1 starts at the instant when voltage E_{1-N} crosses zero and becomes negative.

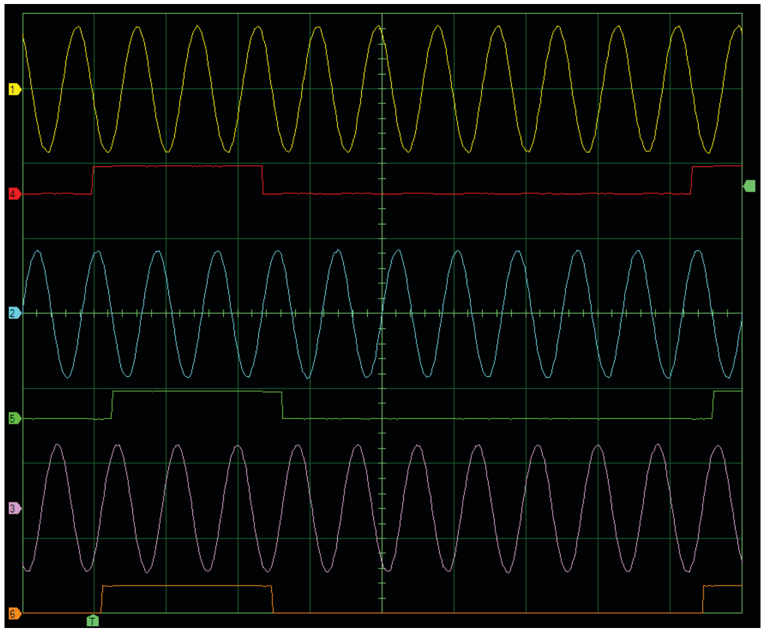
Oscilloscope Settings

Channel-1 Input	E1
Channel-1 Scale	200 V/div
Channel-1 Coupling	DC
Channel-2 Input	E2
Channel-2 Scale	200 V/div
Channel-2 Coupling	DC
Channel-3 Input	E3
Channel-3 Scale	200 V/div
Channel-3 Coupling	DC
Channel-4 Input	AI-1
Channel-4 Scale	10 V/div
Channel-4 Coupling	DC
Channel-5 Input	AI-2
Channel-5 Scale	10 V/div
Channel-5 Coupling	DC
Channel-6 Input	AI-3
Channel-6 Scale	10 V/div
Channel-6 Coupling	DC
Time Base	20 ms/div
Trigger Type	Software
Trigger Source	Ch4
Trigger Level	1 V
Trigger Slope	Rising



Phase voltages of the ac power source and firing signals of thyristors Q_1, Q_2, and Q_3 (the on-time interval of thyristor Q_1 starts when voltage E_{1-N} crosses zero and becomes positive).

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale ....200 V/div
Channel-1 Coupling ....DC
Channel-2 Input E2
Channel-2 Scale ....200 V/div
Channel-2 Coupling ....DC
Channel-3 Input E3
Channel-3 Scale ....200 V/div
Channel-3 Coupling ....DC
Channel-4 Input AI-1
Channel-4 Scale ....10 V/div
Channel-4 Coupling ....DC
Channel-5 Input AI-2
Channel-5 Scale ....10 V/div
Channel-5 Coupling ....DC
Channel-6 Input AI-3
Channel-6 Scale ....10 V/div
Channel-6 Coupling ....DC
Time Base .... 20 ms/div
Trigger Type ....Software
Trigger Source Ch4
Trigger Level .... 1 V
Trigger Slope ....Rising



Phase voltages of the ac power source and firing signals of thyristors Q_1, Q_2, and Q_3 (the on-time interval of thyristor Q_1 starts when voltage E_{1-N} crosses zero and becomes negative).

27. In the Thyristor Control window, successively set the *On Time* parameter to 4, 5, 6, 7, 8, 9, and 10 while observing the signals displayed on the Oscilloscope. Does changing the on time interval change the width of the pulses in the thyristor firing signals?

❑ Yes ❑ No

Yes

Also, observe that, no matter the value of the *On Time* parameter, the on time interval of each pair of thyristors is always a bit shorter (by 1/6 of a cycle) than the value set for this parameter. Explain why.

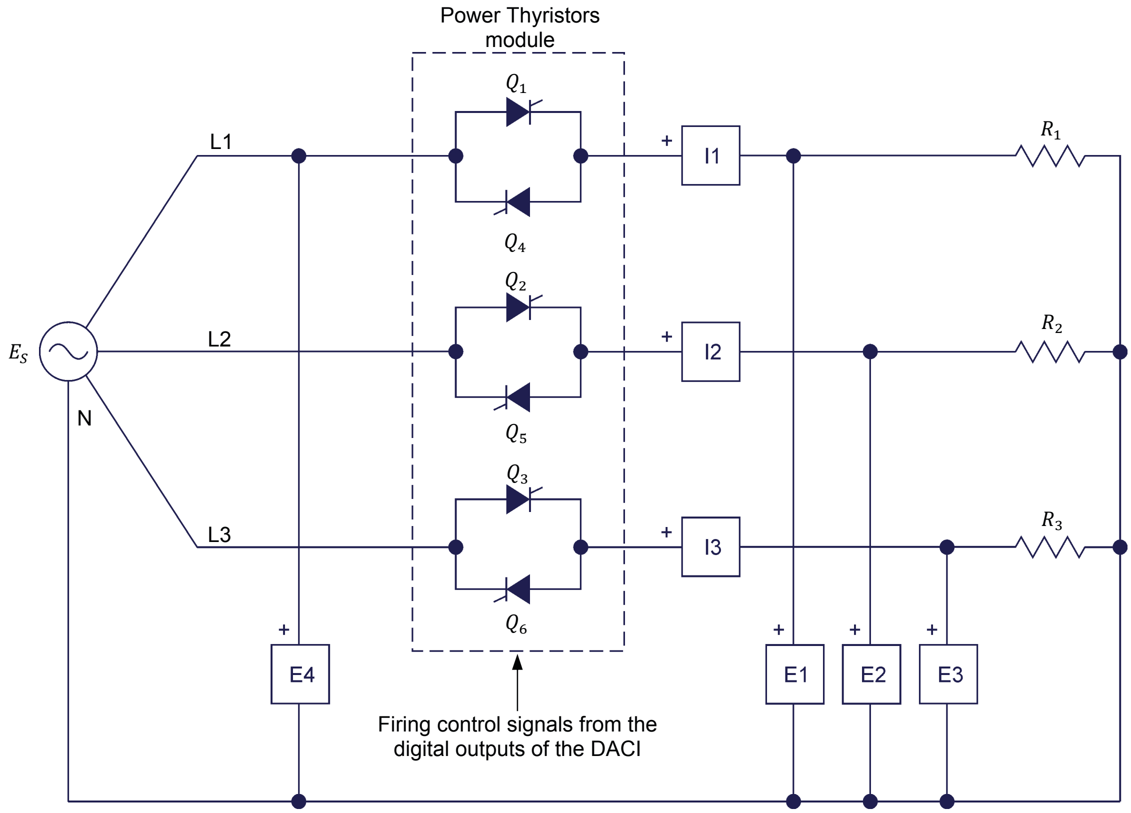
Yes. The on time interval is always a bit shorter (by 1/6 of a cycle) than the value set for the *On Time* parameter in order to prevent undesired firing of the thyristors for an additional half cycle.

28. In the Thyristor Control window, stop the *Thyristor Three-Phase AC Power Control* function.

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

Observation of the load voltage and current waveforms and measurement of the load voltage, current, and power

29. Modify the circuit connections as shown in Figure 100. The resistance value for the load resistors R_1, R_2, and R_3 depends on your local ac power network voltage (see table in the diagram).



Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 100. Thyristor three-phase ac power control using burst fire control (4S load configuration). Observation of the load current and voltage waveforms and measurement of the load voltage, current, and power.

30. In the Thyristor Control window, start the *Thyristor Three-Phase AC Power Control* function. Set the *On Time* parameter to 3 cycles. Set the *Period* parameter to 8 cycles.

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

31. On the Oscilloscope, make the settings required to display the firing signals of thyristors Q_1, Q_2, and Q_3, as well as the load current and voltage waveforms (*I1*, *E1*, *I2*, *E2*, and *I3*) on channels, 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Set the Oscilloscope in the continuous refresh mode. Set the time base to display one or two cycles of the thyristor firing signals.

32. In the Metering window, open the Acquisition Settings dialog box, set the *Sampling Window* to *8 cycles*, and close the dialog box.

Make sure that the meters are set to measure the rms values of the load voltages (*E1*, *E2*, and *E3*) and load currents (*I1*, *I2*, and *I3*), as well as the total active power supplied to the load (*PQS1 + PQS2 + PQS3*). Make sure meter *E4* is disabled. Select the *Continuous Refresh* mode by clicking the *Continuous Refresh* button.

33. In the Thyristor Control window, vary the value of the *On Time* parameter while observing the waveforms on the Oscilloscope, the duty cycle indicated by meter *T1* in the Thyristor Control window, and the values of the load voltages, currents, and power indicated by the meters. Does changing the on time change the duty cycle and thus, the amount of power delivered to the three-phase load by steps?

❑ Yes ❑ No

Yes

The following figure shows an example of the waveforms displayed on the Oscilloscope when the duty cycle is 75% (on time and period set to 6 cycles and 8 cycles, respectively).

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-2
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input AI-3
Channel-3 Scale .... 10 V/div
Channel-3 Coupling .... DC
Channel-4 Input I1
Channel-4 Scale .... 2 A/div
Channel-4 Coupling .... DC
Channel-5 Input E1
Channel-5 Scale .... 200 V/div
Channel-5 Coupling .... DC
Channel-6 Input I2
Channel-6 Scale .... 2 A/div
Channel-6 Coupling .... DC
Channel-7 Input E2
Channel-7 Scale .... 200 V/div
Channel-7 Coupling .... DC
Channel-8 Input I3
Channel-8 Scale .... 2 A/div
Channel-8 Coupling .... DC
Time Base .... 50 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 1 V
Trigger Slope .... Rising

Firing signals of thyristors Q_1, Q_2, and Q_3 and waveforms of load currents and voltages (duty cycle α set to 75%).

34. Set the *On Time* parameter to each of the values listed in Table 4 and for each setting, record the rms load voltages and the total active power delivered to the load indicated by the meters in this table.

Table 4. Load voltage and power as a function of the duty cycle.

On time (number of source voltage cycles)	Duty cycle α (%)	Load voltage E_{R1} (V)	Load voltage E_{R2} (V)	Load voltage E_{R3} (V)	Total active power (W)
0	0				
1	12.5				
2	25.0				
3	37.5				
4	50.0				
5	62.5				
6	75.0				
7	87.5				
8	100				

The results are presented in the following table.

Load voltage and power as a function of the duty cycle.

On time (number of source voltage cycles)	Duty cycle α (%)	Load voltage E_{R1} (V)	Load voltage E_{R2} (V)	Load voltage E_{R3} (V)	Total active power (W)
0	0	0	0	0	0
1	12.5	42	42	42	31
2	25.0	60	60	60	63
3	37.5	72	72	72	94
4	50.0	85	85	85	126
5	62.5	95	95	95	156
6	75.0	103	103	103	189
7	87.5	111	111	111	220
8	100	119	119	119	252

35. From your observations, explain how the circuit operates.

When the value of the *On Time* parameter is changed, the duty cycle changes by steps, causing the values of the load voltages, load currents, and load active power to also change by steps. Thus, when the value of the *On Time* parameter is increased, the pairs of thyristors in each phase of the circuit are on during a greater portion of the on/off cycle, which increases the duty cycle, and thus the values of the load voltages, load currents, and load active power. Conversely, when the value of the *On Time* parameter is decreased, the pairs of thyristors in each phase of the circuit are on during a smaller portion of the on/off cycle, which decreases the duty cycle, and thus the values of the load voltages, load currents, and load active power.

Is circuit operation the same in each of the three phases? Explain.

Yes. In each phase of the circuit, one thyristor allows current to flow through the load during positive halves of the corresponding phase voltage, while the other thyristor allows current to flow through the load during negative halves of the corresponding phase voltage.

36. In the Thyristor Control window, stop the *Thyristor Three-Phase AC Power Control* function.

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

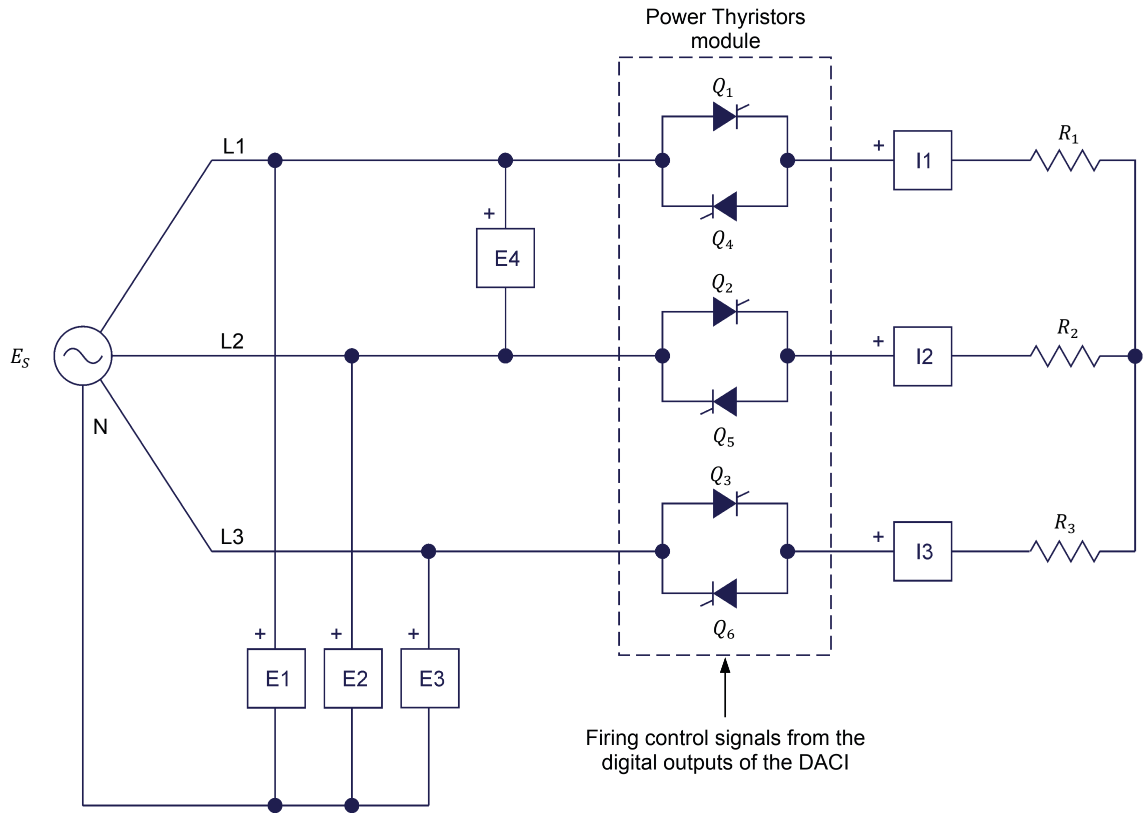
Thyristor three-phase ac power control using phase angle modulation (3S load configuration)

In this part of the exercise, you will perform thyristor three-phase ac power control using phase angle modulation and a 3S load configuration. You will observe the firing signals as well as the waveforms of circuit voltages and currents, and explain how the circuit operates. You will observe the effect that varying the firing angle of the thyristors has on load voltage and current waveforms and the amount of active power delivered to the three-phase load.

Observation of the thyristor firing signals

37. Modify the circuit connections in order to obtain the circuit shown in Figure 101. The resistance value for the load resistors R_1, R_2, and R_3 depends on your local ac power network voltage (see table in the diagram).

Input E4 of the DACI is used for synchronization of the firing signals of the thyristors in the Power Thyristors module. This input must be connected across the line 1 (L1) and line 2 (L2) terminals of the three-phase ac power source in the Power Supply.



Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 101. Thyristor three-phase ac power control using phase angle modulation (3S load configuration). Observation of the thyristor firing signals.

38. In the Thyristor Control window, make the following settings:

– Set the *Function* parameter to *Thyristor Three-Phase AC Power Control*.

– Set the *Load Configuration* parameter to *3 wires, star (3S)*. This selects the wye (star) load configuration without neutral conductor.

– Make sure that the *Fire Angle Control* parameter is set to *Knob*. This allows the *Firing Angle* parameter to be controlled manually.

– Set the *Firing Angle* parameter to 30° by entering 30 in the field next to this parameter or by using the control knob in the lower left corner of the window. This sets the firing angle α to 30°.

– Make sure that parameters Q_1 through Q_6 are all set to *Active*. This makes the firing signals of these thyristors depend on the *Firing Angle Control* and *Firing Angle* parameters.

– Start the *Thyristor Three-Phase AC Power Control* function by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

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

40. On the Oscilloscope, make the settings required to display the phase voltages (*E1*, *E2*, and *E3*) and the firing signals of thyristors Q_1 through Q_5 (*Analog Inputs 1* through *5* of the DACI) on channels 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Set the Oscilloscope in the continuous refresh mode. Set the time base to display at least two cycles of the source voltage waveform.

Observe the firing signals of the thyristors (Q_1 and Q_4) in the first phase of the circuit. Since the firing angle α is currently set to 30°, each pulse in the firing signal of thyristor Q_1 occurs 30° after the instant when voltage $E_{1\text{-}N}$ crosses zero and becomes positive, i.e., 30° after the beginning of the positive half of this voltage. Does each pulse in the firing signal of thyristor Q_4 occurs 180° after the pulses in the firing signal of thyristor Q_1, i.e., 30° after the beginning of the negative half of voltage $E_{1\text{-}N}$?

❑ Yes ❑ No

Yes

Observe that the firing signals of the thyristors (Q_2 and Q_5) in the second phase of the circuit are delayed by 120° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase. Does each pulse in the firing signal of thyristor Q_2 occur 30° after the beginning of the positive half of voltage $E_{2\text{-}N}$, and each pulse in the firing signal of thyristor Q_5 30° after the beginning of the negative half of voltage $E_{2\text{-}N}$?

❑ Yes ❑ No

Yes

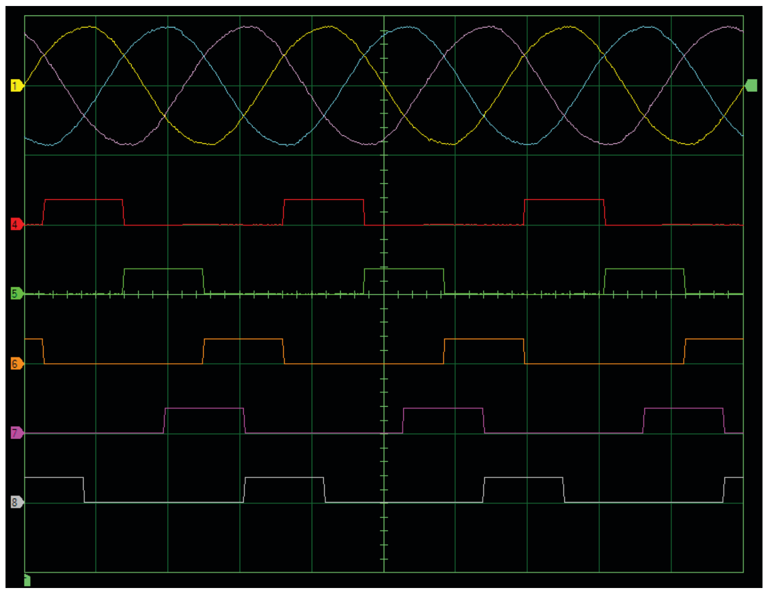
On the Oscilloscope, set *Channel 2* to display the firing signal of thyristor Q_6 (instead of voltage $E_{2\text{-}N}$). Observe that the firing signals of the thyristors (Q_3 and Q_6) in the third phase of the circuit are delayed by 240° with respect to the firing signals of the thyristors (Q_1 and Q_4) in the first phase. Does each pulse in the firing signal of thyristor Q_3 occur 30° after the beginning of the positive half of voltage $E_{3\text{-}N}$, and each pulse in the firing signal of thyristor Q_6 30° after the beginning of the negative half of voltage $E_{3\text{-}N}$?

❑ Yes ❑ No

Yes

The following figure shows an example of the waveforms displayed on the Oscilloscope.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale .... 200 V/div
Channel-1 Coupling .... DC
Channel-2 Input E2
Channel-2 Scale .... 200 V/div
Channel-2 Coupling .... DC
Channel-3 Input E3
Channel-3 Scale .... 200 V/div
Channel-3 Coupling .... DC
Channel-4 Input AI-1
Channel-4 Scale .... 10 V/div
Channel-4 Coupling .... DC
Channel-5 Input AI-2
Channel-5 Scale .... 10 V/div
Channel-5 Coupling .... DC
Channel-6 Input AI-3
Channel-6 Scale .... 10 V/div
Channel-6 Coupling .... DC
Channel-7 Input AI-4
Channel-7 Scale .... 10 V/div
Channel-7 Coupling .... DC
Channel-8 Input AI-5
Channel-8 Scale .... 10 V/div
Channel-8 Coupling .... DC
Time Base .... 5 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 0 V
Trigger Slope .... Rising



Phase voltages of the ac power source and firing signals of thyristors Q_1 through Q_5 (firing angle α set to 30°).

41. By using the *Firing Angle* control knob, slowly vary the firing angle α while observing the firing signals of thyristors Q_1 through Q_6. Notice that as the firing angle α increases, the pulses in the thyristor firing signals become increasingly delayed, and vice versa.

From your observations, are the firing signals identical to those in thyristor three-phase ac power control using phase angle modulation and a 4S load configuration seen in the first part of this exercise?

❑ Yes ❑ No

Yes

42. In the Thyristor Control window, stop the *Thyristor Three-Phase AC Power Control* function.

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

Observation of the load voltage and current waveforms and measurement of the load voltage, current, and power

43. Modify the circuit connections as shown in Figure 102. The resistance value for the load resistors R_1, R_2, and R_3 depends on your local ac power network voltage (see table in the diagram).

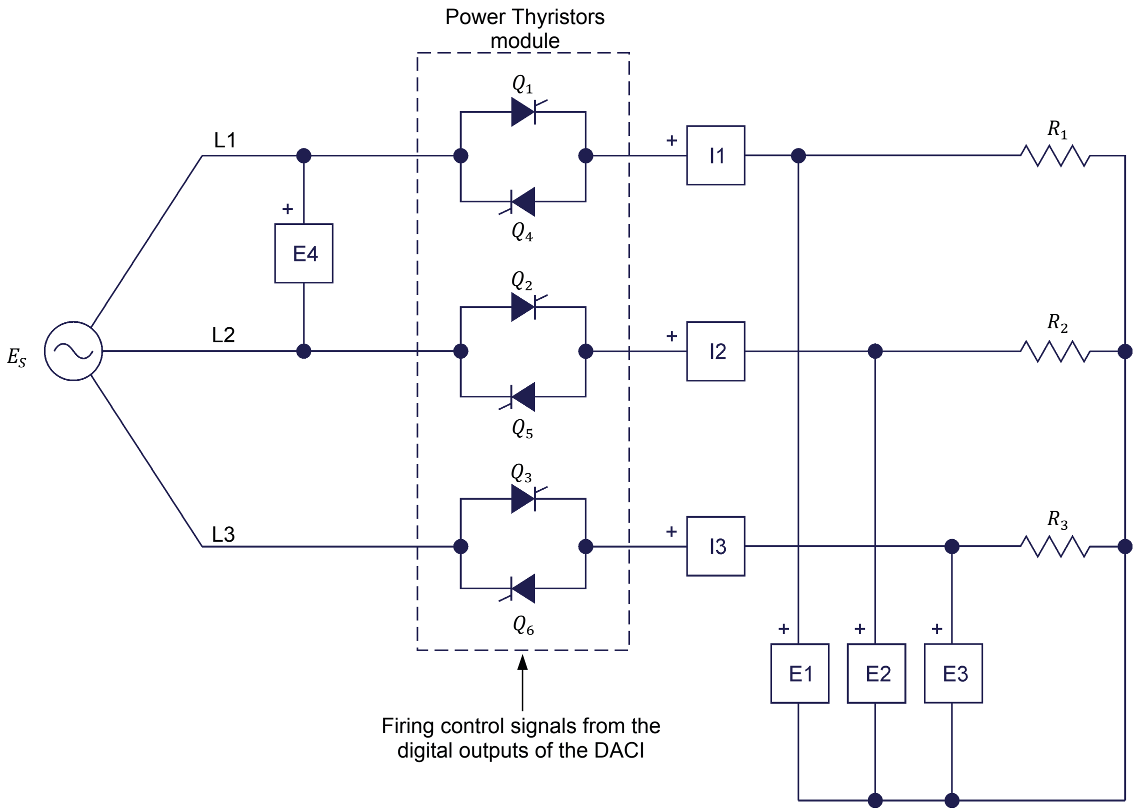
Input E4 of the DACI (input used for synchronization of the firing signals of the thyristors in the Power Thyristors module) must be connected across the line 1 (L1) and line 2 (L2) terminals of the three-phase ac power source in the Power Supply.

44. In the Thyristor Control window, start the *Thyristor Three-Phase AC Power Control* function. Set the *Firing Angle* parameter to 0°.

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

45. On the Oscilloscope, make the settings required to display the firing signals of thyristors Q_1 and Q_4 (*Analog Inputs 1* and *4* of the DACI), and the load current and voltage waveforms (*I1*, *E1*, *I2*, *E2*, *I3*, and *E3*) on channels, 1, 2, 3, 4, 5, 6, 7, and 8, respectively. Set the Oscilloscope in the continuous refresh mode. Set the time base to display at least two cycles of the thyristor firing signals.

In the Metering window, open the *Acquisition Settings* dialog box, set the *Sampling Window* to *Extended* and close the dialog box. Make sure that the meters are set to measure the rms values of the load voltages (*E1*, *E2*, and *E3*) and load currents (*I1*, *I2*, and *I3*), as well as the total active power supplied to the load (*PQS1 + PQS2 + PQS3*). Make sure meter *E4* is disabled. Select the *Continuous Refresh* mode by clicking the *Continuous Refresh* button.



Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 102. Thyristor three-phase ac power control using phase angle modulation (4S load configuration). Observation of the load current and voltage waveforms and measurement of the load voltage, current, and power.

46. Slowly increase the firing angle α and notice that the waveforms of the load currents and voltages change significantly when the firing angle reaches 60°, and change again significantly when the firing angle reaches 90°. Briefly explain why.

This is because the number of thyristors in the circuit which conduct current simultaneously changes depending on the firing angle value.

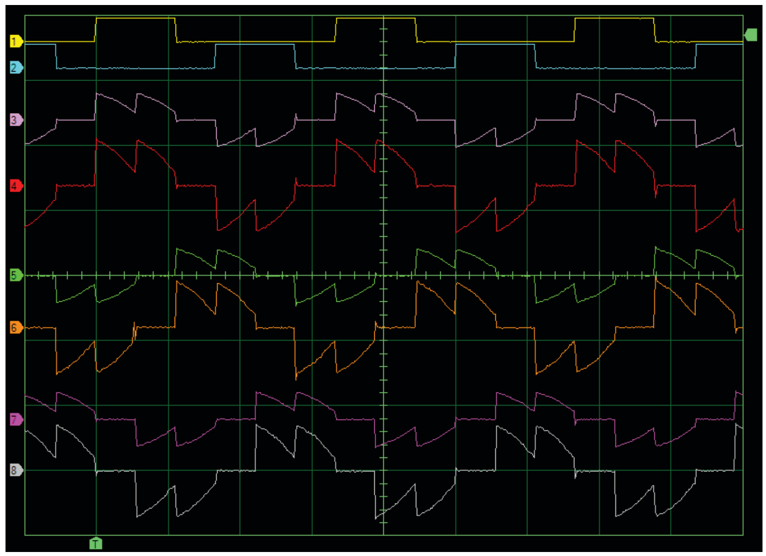
Also, observe that as the firing angle α is increased, the rms values of the load currents and voltages decrease, and that these currents and voltages become null when the firing angle exceeds 150°. Is this your observation?

❑ Yes ❑ No

Yes

The following figure shows an example of the waveforms displayed on the Oscilloscope when the firing angle α is set to 75°.

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-4
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input I1
Channel-3 Scale .... 2 A/div
Channel-3 Coupling .... DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input I2
Channel-5 Scale .... 2 A/div
Channel-5 Coupling .... DC
Channel-6 Input E2
Channel-6 Scale .... 200 V/div
Channel-6 Coupling .... DC
Channel-7 Input I3
Channel-7 Scale .... 2 A/div
Channel-7 Coupling .... DC
Channel-8 Input E3
Channel-8 Scale .... 200 V/div
Channel-8 Coupling .... DC
Time Base .... 5 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 1 V
Trigger Slope .... Rising



Firing signals of thyristors Q_1 and Q_4, and load current and voltage waveforms (firing angle α set to 75°).

47. Set the Oscilloscope time base to display about one cycle of the thyristor firing signals.

48. While observing the waveforms of the load currents and voltages, slowly vary the firing angle between 0° and 60° (mode 1). Notice that two or three thyristors are on simultaneously within this range of firing angles:

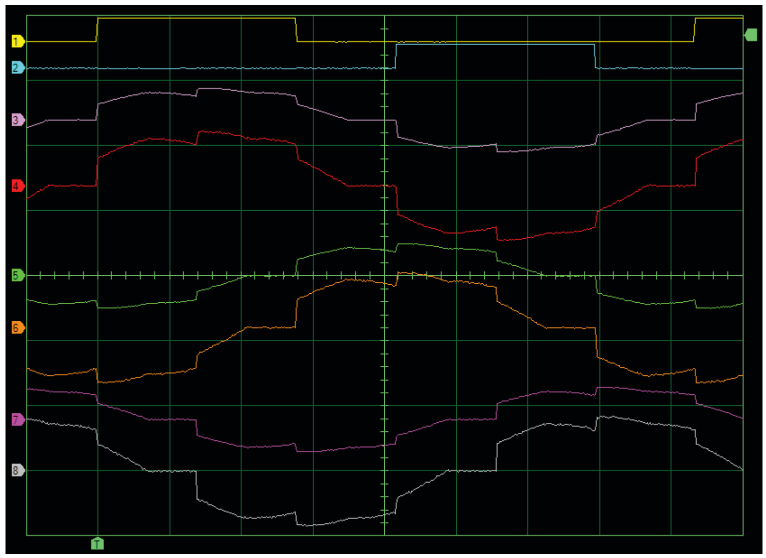
– When two thyristors are on simultaneously, load currents and voltages appear in two phases of the circuit, while the load current and voltage are null in the other phase. Consequently, a brief flat (zero-level) section appears in the waveforms of the load current and voltage in this phase.

– When three thyristors are on simultaneously, load currents and voltages appear in the three phases of the circuit. Consequently, there is no flat (zero-level) section in any of the load current and voltage waveforms when three thyristors are conducting current.

Set the firing angle to 30°. How many thyristors are on simultaneously when the firing pulse of thyristor Q_1 goes from low to high level?

When the firing angle is set to 30°, three thyristors are on simultaneously just after the firing pulse of thyristor Q_1 goes from low to high level. The following figure shows an example of the waveforms displayed on the Oscilloscope when the firing angle α is set to 30°.

Oscilloscope Settings	
Channel-1 Input	AI-1
Channel-1 Scale	10 V/div
Channel-1 Coupling	DC
Channel-2 Input	AI-4
Channel-2 Scale	10 V/div
Channel-2 Coupling	DC
Channel-3 Input	I1
Channel-3 Scale	2 A/div
Channel-3 Coupling	DC
Channel-4 Input	E1
Channel-4 Scale	200 V/div
Channel-4 Coupling	DC
Channel-5 Input	I2
Channel-5 Scale	2 A/div
Channel-5 Coupling	DC
Channel-6 Input	E2
Channel-6 Scale	200 V/div
Channel-6 Coupling	DC
Channel-7 Input	I3
Channel-7 Scale	2 A/div
Channel-7 Coupling	DC
Channel-8 Input	E3
Channel-8 Scale	200 V/div
Channel-8 Coupling	DC
Time Base	2 ms/div
Trigger Type	Software
Trigger Source	Ch1
Trigger Level	1 V
Trigger Slope	Rising

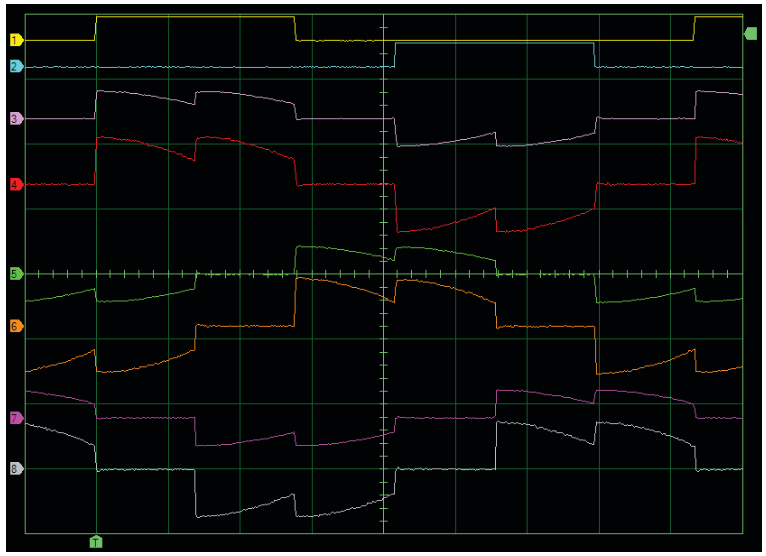


Firing signals of thyristors Q_1 and Q_4, and load current and voltage waveforms (firing angle α set to 30°).

Set the firing angle to 60°. How many thyristors are on simultaneously just after the firing pulse of thyristor Q_1 goes from low to high level?

When the firing angle is 60°, two thyristors are on simultaneously just after the firing pulse of thyristor Q_1 goes from low to high level. The following figure shows an example of the waveforms displayed on the Oscilloscope when the firing angle is 60°.

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-4
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input I1
Channel-3 Scale .... 2 A/div
Channel-3 Coupling .... DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input I2
Channel-5 Scale .... 2 A/div
Channel-5 Coupling .... DC
Channel-6 Input E2
Channel-6 Scale .... 200 V/div
Channel-6 Coupling .... DC
Channel-7 Input I3
Channel-7 Scale .... 2 A/div
Channel-7 Coupling .... DC
Channel-8 Input E3
Channel-8 Scale .... 200 V/div
Channel-8 Coupling .... DC
Time Base .... 2 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 1 V
Trigger Slope .... Rising



Firing signals of thyristors Q_1 and Q_4, and load current and voltage waveforms (firing angle α set to 60°).

Does this confirm that mode 1 (2 or 3 thyristors on simultaneously) is possible for firing angles between 0° and 60°?

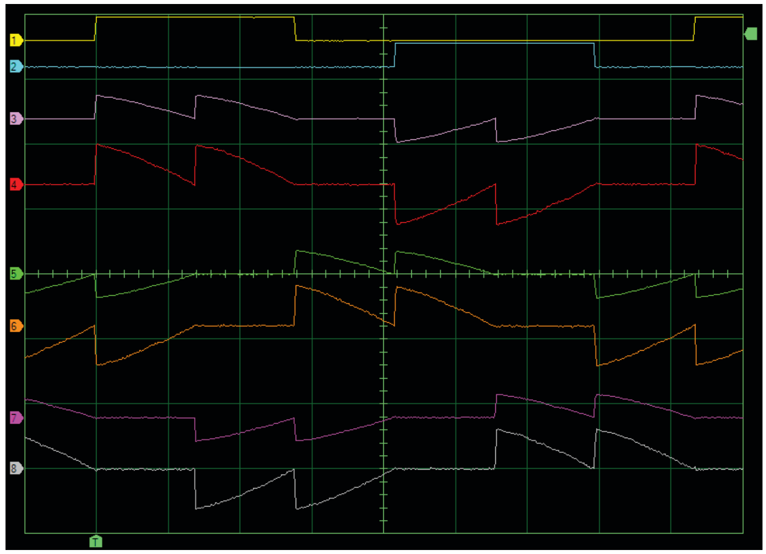
❑ Yes ❑ No

Yes

49. While observing the waveforms of the load currents and voltages, slowly vary the firing angle between 60° and 90° (mode 2). How many thyristors are on simultaneously within this range of firing angles?

When the firing angle is between 60° and 90° (mode 2), two thyristors are on simultaneously. The following figure shows an example of the waveforms displayed on the Oscilloscope when the firing angle is 90°.

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-4
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input I1
Channel-3 Scale .... 2 A/div
Channel-3 Coupling .... DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input I2
Channel-5 Scale .... 2 A/div
Channel-5 Coupling .... DC
Channel-6 Input E2
Channel-6 Scale .... 200 V/div
Channel-6 Coupling .... DC
Channel-7 Input I3
Channel-7 Scale .... 2 A/div
Channel-7 Coupling .... DC
Channel-8 Input E3
Channel-8 Scale .... 200 V/div
Channel-8 Coupling .... DC
Time Base .... 2 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 1 V
Trigger Slope .... Rising

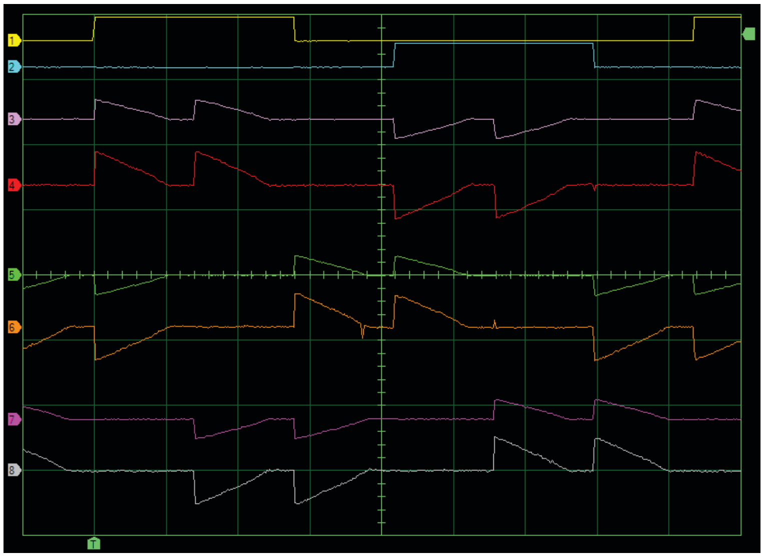


Firing signals of thyristors Q_1 and Q_4, and load current and voltage waveforms (firing angle α set to 90°).

50. While observing the waveforms of the load currents and voltages, slowly vary the firing angle between 90° and 150° (mode 3). How many thyristors are on simultaneously within this range of firing angles?

When the firing angle is between 90° and 150°, there are time intervals during which two thyristors conduct current simultaneously, and time intervals during which all the thyristors are off [(i.e., the load currents and voltages are all null during part of the ac source voltage cycle)]. The following figure shows an example of the waveforms displayed on the Oscilloscope when the firing angle is 105°.

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling ....DC
Channel-2 Input AI-4
Channel-2 Scale .... 10 V/div
Channel-2 Coupling ....DC
Channel-3 Input I1
Channel-3 Scale ....2 A/div
Channel-3 Coupling ....DC
Channel-4 Input E1
Channel-4 Scale ....200 V/div
Channel-4 Coupling ....DC
Channel-5 Input I2
Channel-5 Scale ....2 A/div
Channel-5 Coupling ....DC
Channel-6 Input E2
Channel-6 Scale ....200 V/div
Channel-6 Coupling ....DC
Channel-7 Input I3
Channel-7 Scale ....2 A/div
Channel-7 Coupling ....DC
Channel-8 Input E3
Channel-8 Scale ....200 V/div
Channel-8 Coupling ....DC
Time Base.............................. 2 ms/div
Trigger Type ....Software
Trigger Source Ch1
Trigger Level.................................. 1 V
Trigger Slope ....Rising



Firing signals of thyristors Q_1 and Q_4, and load current and voltage waveforms (firing angle α set to 105°).

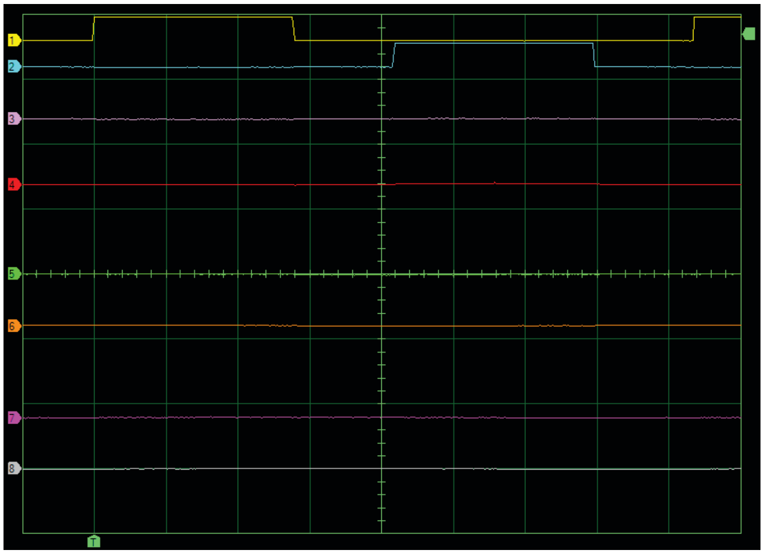
51. In LVDAC-EMS, set the *Range* setting of voltage inputs *E1*, *E2*, and *E3* to *High*.

Slowly vary the firing angle between 150° and 180° while observing the waveforms of the load currents and voltages. Are all thyristors off during the whole cycle when the firing angle is 150° or more?

❑ Yes ❑ No

Yes. The following figure shows an example of the waveforms displayed on the Oscilloscope when the firing angle is 150°.

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-4
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input I1
Channel-3 Scale .... 2 A/div
Channel-3 Coupling .... DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input I2
Channel-5 Scale .... 2 A/div
Channel-5 Coupling .... DC
Channel-6 Input E2
Channel-6 Scale .... 200 V/div
Channel-6 Coupling .... DC
Channel-7 Input I3
Channel-7 Scale .... 2 A/div
Channel-7 Coupling .... DC
Channel-8 Input E3
Channel-8 Scale .... 200 V/div
Channel-8 Coupling .... DC
Time Base .... 2 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level .... 1 V
Trigger Slope .... Rising



Firing signals of thyristors Q_1 and Q_4, and load current and voltage waveforms (firing angle α set to 150°).

52. Slowly vary the firing angle between 0° and 150° while observing the values of the load voltages, load currents, and total load power on the meters in the Metering window. Can the amount of active power delivered to the three-phase load be varied smoothly (rather than by steps) by varying the firing angle?

❑ Yes ❑ No

Yes

53. On the Power Supply, turn the three-phase ac power source off. Close LVDAC-EMS. Disconnect all leads and return them to their storage location.

Conclusion

In this exercise, you learned that three-phase ac power control allows adjustment of the amount of electrical power that a three-phase ac power source delivers to a three-phase load. You became familiar with four of the most common topologies (4S, 6D, 3S, and 3D) of thyristor three-phase ac power control circuits. You learned that thyristor firing control is generally performed using the same techniques as in single-phase ac power control circuits, i.e., phase angle modulation or burst fire control. When phase angle modulation is used with the 4S, 6D, 3S, or 3D load configuration, thyristor firing is the same as in single-phase ac power control circuits, except that thyristor firing is delayed by 120° and 240°, respectively, for the second and third phases of the circuit. When burst fire control is used with the 4S or 6D load configuration, the on-time interval starts at the instant when one of the phase voltages (4S) or line-to-line voltages (6D) passes through zero. At this instant, the thyristors in the corresponding phase of the circuit are fired, while the pairs of thyristors in the third and second phases of the circuit are fired 60° and 120° later, respectively. When burst fire control is used with 3S or 3D load configurations, each pair of thyristors is fired so that it operates like a zero-voltage switched (ZVS) SSR.

Review Questions

1. What are the two topologies of three-phase ac power control circuits for which the firing of a single thyristor is sufficient to create a path for current to flow through one of the load elements? Which topologies of three-phase ac power control circuits require that at least two thyristors be fired for current to flow through one of the load elements?

   In three-phase ac power control circuits with a 4S or 6D load configuration, firing of a single thyristor is sufficient to create a path for current to flow through one of the load elements. On the other hand, three-phase ac power control circuits with a 3S or 3D load configuration require that at least two thyristors be fired for current to flow through one of the load elements.

2. Describe the circuit operation and thyristor firing control in three-phase ac power control circuits with 4S or 6D load configuration and using phase angle modulation.

   The circuit operation and thyristor firing control are the same as in single-phase ac power control circuits, except that thyristor firing is delayed by 120° and 240° for the second and third phases of the circuit, respectively. To ensure that the thyristor firing signals are properly timed, the thyristor firing control circuit samples one of phase voltages of the ac power source when the 4S load configuration is used, while it samples one of the line-to-line voltages of the ac power source when the 6D load configuration is used. The instant when the sampled voltage crosses zero and becomes positive is the instant used to determine the firing angle.

3. Describe the circuit operation and thyristor firing control in three-phase ac power control circuits with a 4S or 6D load configuration and using burst fire control (synchronous).

With the 4S load configuration, the on time interval starts at the instant when one of the phase voltages of the ac power source passes through zero. With the 6D load configuration, the on time interval starts at the instant when one of the line-to-line voltages of the ac power source passes through zero. At this instant, the thyristors in the corresponding phase of the circuit are fired, while the pairs of thyristors in the third and second phases of the circuit are fired 60° and 120° later, respectively.

4. Describe circuit operation and thyristor firing control in three-phase ac power control circuits with a 3S load configuration using phase angle modulation.

When phase angle modulation is used, the firing signals in three-phase ac power control circuits with a 3S load configuration are identical to those used in three-phase ac power control circuits with a 4S load configuration. However, circuit operation with a 3S load configuration differs slightly since current can flow only when at least two thyristors are conducting current simultaneously. In fact, the number of thyristors that conduct current at any instant of the ac power source cycle depends on the firing angle α. When α is between 0° and 60° (mode 1), two or three thyristors are turned on simultaneously. When α is between 60° and 90° (mode 2), only two thyristors are turned on simultaneously. When α is between 90° and 150° (mode 3), two thyristors are turned on simultaneously or all the thyristors are off. When α is greater than 150°, no thyristor can enter into conduction. Since the number of thyristors that are turned on at any instant of the ac power source cycle depends on the firing angle α, the waveforms of the load voltage and current can have various shapes, depending on whether the firing angle α is between 0° and 60°, 60° and 90°, or 90° and 150°.

5. Describe circuit operation and thyristor firing control in three-phase ac power control circuits with 3S or 3D load configurations using burst fire control.

Each pair of thyristors is controlled (fired) so that it operates like a zero-voltage switched (ZVS) SSR. At the beginning of each on-time interval, i.e., when power has to be applied to the three-phase load, each ZVS SSR (i.e., each pair of thyristors) is enabled. As soon as one of the line-to-line voltages of the power source passes through zero, the two ZVS SSRs connected between these two lines turn on (i.e., two thyristors in these ZVS SSRs turn on). 90° later, the voltage across the third ZVS SSR passes through zero and this SSR turns on, thereby completing the path between the ac power source and load. At the end of each on-time interval, i.e., when power has to be removed from the three-phase load, each ZVS SSR is disabled. As soon as one of the line currents passes through zero, the corresponding ZVS SSR turns off (i.e., the two thyristors in this SSR turn off). 90° later, the current in the other two lines becomes zero and the two other ZVS SSRs turn off.

Bibliography

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