Electricity and New Energy

Single-Phase Power Transformers

Course Sample

579439

Safety and Common Symbols

The following safety and common symbols may be used in this course 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. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
⎓	Direct current

Safety and Common Symbols

Symbol	Description
∿	Alternating current
∿ (with bar)	Both direct and alternating current
3∿	Three-phase alternating current
⏚	Earth (ground) terminal
⏚ (circled)	Protective conductor terminal
⏚ (frame)	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.
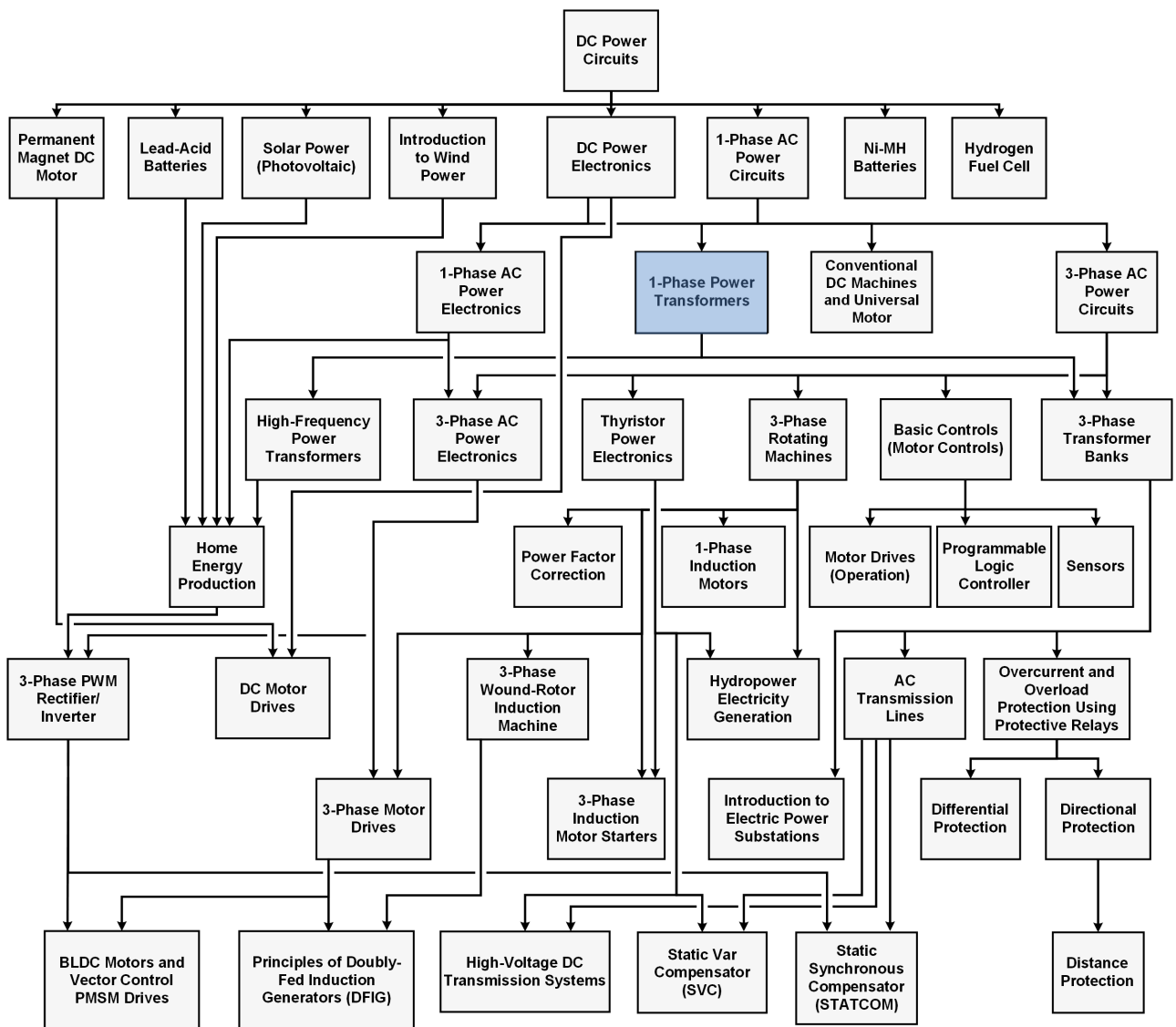
The Electric Power Technology Training Program.

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 motor starters and drives, storage of electrical energy in batteries, home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, protective relaying, and smart-grid technologies (SVC, STATCOM, HVDC transmission systems, etc.).

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

Please send these to services.didactic@festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

Power transformers are one of the most commonly used electrical components. They are found in all types of applications, such as electrical power generation systems, electrical power distribution lines, and home electronic products (microwave ovens, televisions, stereos, computers, grid-tied inverters).

Power transformers are basically electrical devices that transfer electrical power from the primary winding to the secondary winding through electromagnetic induction. While transferring power, power transformers have the ability to either increase or decrease the voltage from the primary winding to the secondary winding. Because of this, power transformers can either be used as step-up transformers or step-down transformers. In either case, the amount of power that is supplied to the power transformer is virtually equal to the amount of power that the power transformer supplies to the load. Power transformers also can provide electrical isolation between the primary winding and the secondary winding, as power transfer is achieved through electromagnetic induction.

Autotransformers are a special type of power transformer whose primary and secondary windings form a single winding. Because of this, autotransformers are smaller, lighter, and cheaper than conventional power transformers for a same power rating. Autotransformers, however, do not provide electrical isolation between the primary and secondary windings.

This course, *Single-Phase Power Transformers*, teaches the basic concepts of power transformers. Students are introduced to the different parameters of power transformers, such as turns, voltage, and current ratios, winding polarity, power losses, efficiency, voltage regulation, and operating frequency. Students learn about different transformer connections, such as series-aiding, series-opposing, parallel, and autotransformer connections. Finally, students verify the theory presented in each exercise by performing circuit measurements and calculations.

Typical single-phase power transformer.

About This Course

Safety considerations

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

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 completed the following courses: *DC Power Circuits* and *1-Phase AC Power Circuits*.

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 course should be considered as a guide. Students who correctly perform 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

Extracted from

Instructor Guide

Transformer Winding Polarity and Interconnection

EXERCISE OBJECTIVE   When you have completed this exercise, you will know what the polarity of a power transformer winding is, and how to represent it in a schematic diagram. You will be able to determine the polarity of power transformer windings using either an oscilloscope or a voltmeter. You will also know how to connect transformer windings in series and in parallel, as well as the effects of each type of connection on the transformer voltage, current, and power.

DISCUSSION OUTLINE   The Discussion of this exercise covers the following points:

- Introduction to transformer winding polarity
- Transformer winding polarity in schematic diagrams
- Determining the polarity of transformer windings using an oscilloscope
- Series connection of transformer windings
- Determining the polarity of transformer windings using a voltmeter
- Parallel connection of transformer windings

DISCUSSION   **Introduction to transformer winding polarity**

As seen previously, when the primary winding of a power transformer is energized by an ac power source, an alternating magnetic flux is established in the iron core. This alternating flux links, or couples, the turns of each winding on the transformer and induces ac voltages in the windings. The **polarity** of these induced voltages might seem to be of minor importance for power transformers since they are ac voltages. However, when two or more transformer windings are connected together, their polarities have a significant effect on the resulting voltage. If the voltage in one winding has a positive polarity when it reaches its maximum value while the voltage in another winding has a negative polarity when it reaches its maximum value, i.e., if they are 180° out of phase, the voltages oppose each other and the resulting voltage is equal to the difference between the two when the windings are connected in series.

The polarity of a power transformer winding refers to the polarity of the voltage at one end of the winding relative to the voltage at the opposite end of the winding, at any given instant. The polarity of a power transformer winding has no meaning in itself. It is only meaningful in relation to the polarity of the other windings. When the end of a winding is of the same polarity as the end of another winding of the transformer, it means that the polarity of the voltage at this end of each winding, with respect to the voltage at the other end of each winding, is the same for both windings, and thus, that the ac voltages across these windings are in phase. Conversely, when the end of a winding is of opposite polarity to the end of another winding, it means that the polarity of the voltage at this end for one winding is opposite to that of the voltage at the end of the other winding, and thus, that the ac voltages across these windings are 180° out of phase. The polarity of transformer windings is thus crucial when connecting windings in series or in parallel, as will be seen later in this exercise.

Transformer winding polarity in schematic diagrams

Markings are generally used to identify the polarity of power transformer windings. These markings come in a variety of types, but one of the most common practices in schematic diagrams is to put a dot next to the ends of the transformer windings that have the same polarity. Figure 10 shows an example in which dots are used to mark the ends of the transformer windings that have the same polarity.
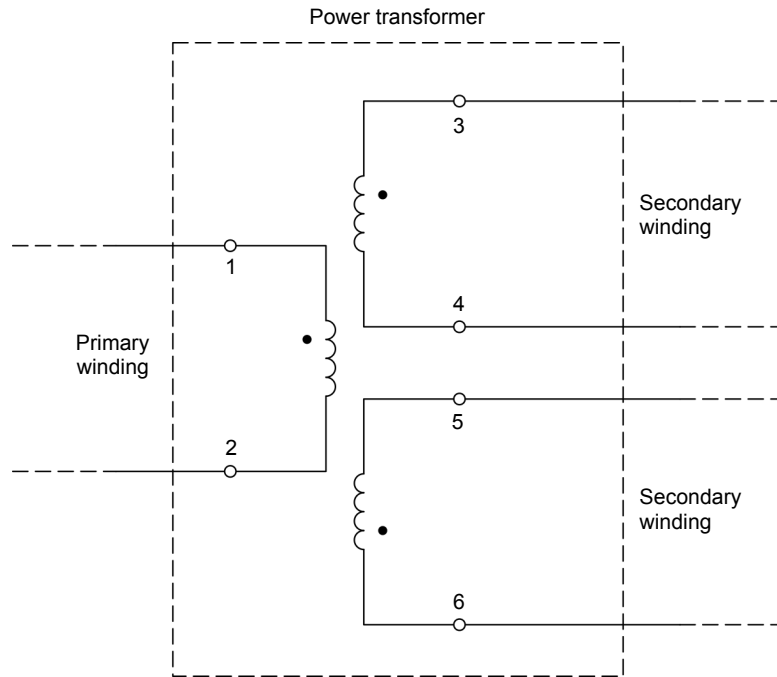
Figure 10. Example of the schematic diagram of a power transformer in which dots mark the windings that have the same polarity.

In Figure 10, when the voltage at terminal 1 is positive with respect to (i.e., higher than) the voltage at terminal 2, the voltages at terminals 3 and 6 are also positive with respect to the voltages at terminals 4 and 5. Conversely, when the voltage at terminal 1 is negative with respect to (i.e., lower than) the voltage at terminal 2, the voltages at terminals 3 and 6 are also negative with respect to the voltages at terminals 4 and 5.

Determining the polarity of transformer windings using an oscilloscope

The polarity of each winding of a power transformer can be determined by applying an ac voltage to one winding (generally the primary winding) and using an oscilloscope to observe the phase of the voltage induced across each of the other windings of the transformer relative to the phase of the ac source voltage. When the phase of the voltage induced across a winding is the same as that of the voltage applied to the primary winding, this indicates that the windings are connected to the oscilloscope with the same polarity, as shown in Figure 11a. On the other hand, when the phase of the voltage induced across a winding is opposite (phase shifted by 180°) to that of the voltage applied to the primary winding, this indicates that the windings are connected to the oscilloscope with opposite polarities, as shown in Figure 11b.

(a)

(b)
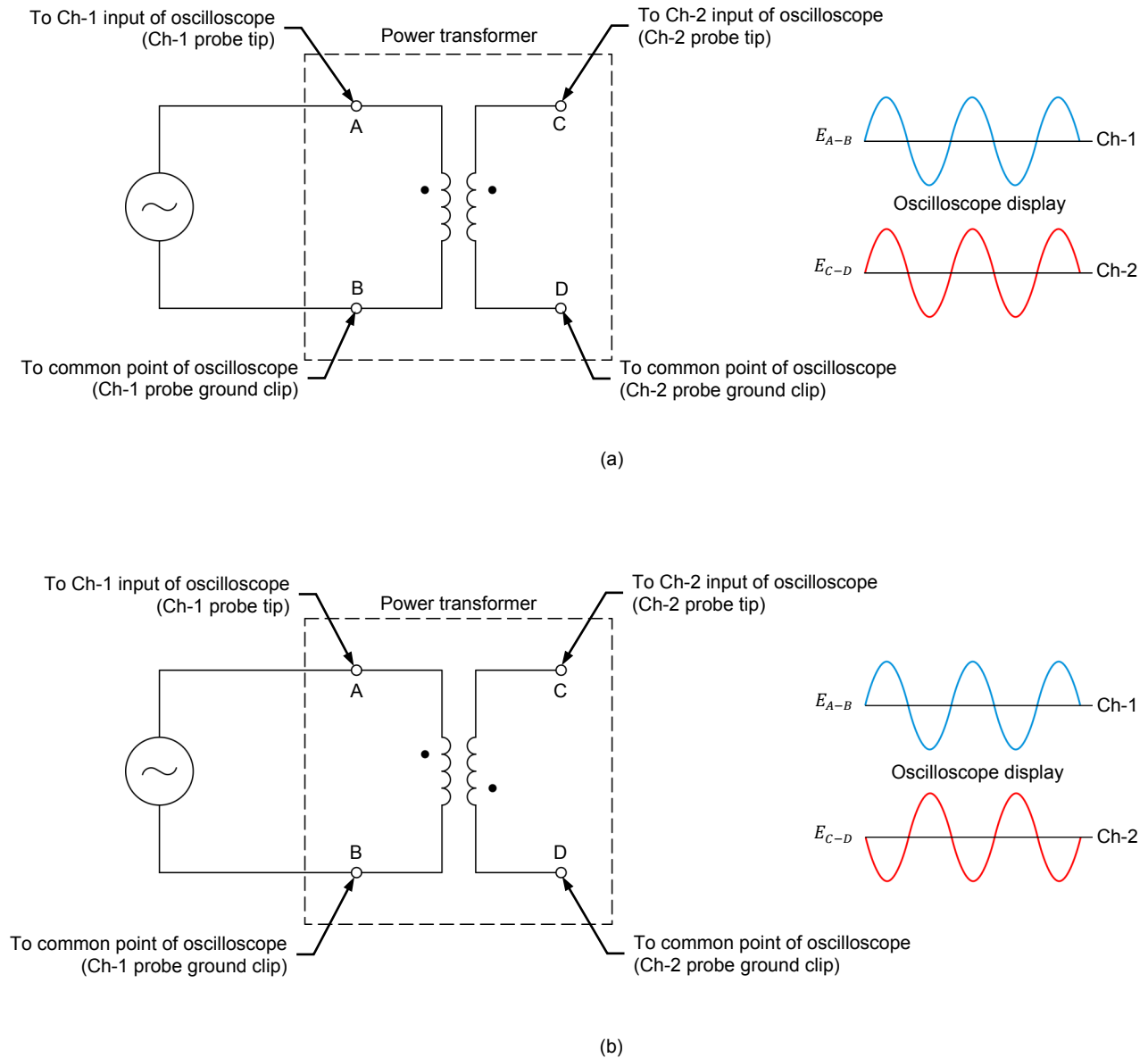
Figure 11. Determining the polarity of power transformer windings using an oscilloscope.

Series connection of transformer windings

Two or more power transformer windings can be connected in series so that the total voltage across the windings is either the sum (series-aiding connection) or difference (series-opposing connection) of the voltages across the individual windings. As mentioned earlier, it is important to know the polarity of each of the windings connected in series, as this determines whether the windings are connected in series-aiding or in series-opposing.

When two windings of a power transformer are connected in series so that the marked end of one winding is connected to the non-marked end of the other winding, the windings are connected in series-aiding, i.e., the voltage across both windings is equal to the sum of the voltages across each individual winding. For example, consider the transformer in Figure 12a. The primary winding of the transformer has a nominal voltage of 25 V, while the secondary windings have nominal voltages of 100 V and 50 V. Since the secondary windings of the transformer are connected in series-aiding, the total voltage across the secondary windings is equal to 150 V (i.e., 100 V + 50 V) when the primary winding is connected to a 25 V ac power source. The transformer thus acts as a step-up transformer with a voltage ratio of 1:6.
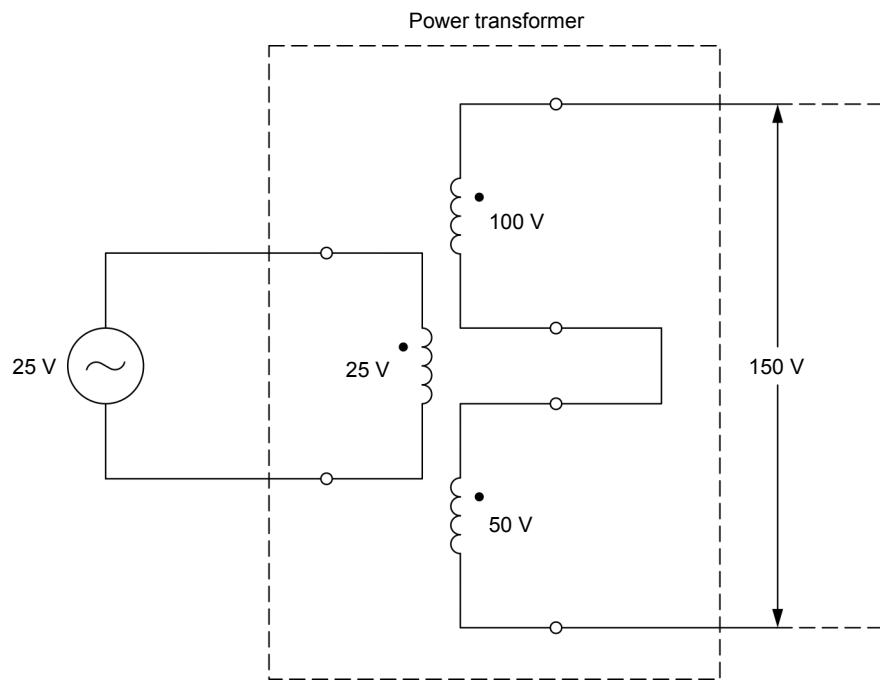
(a) Series-aiding connection
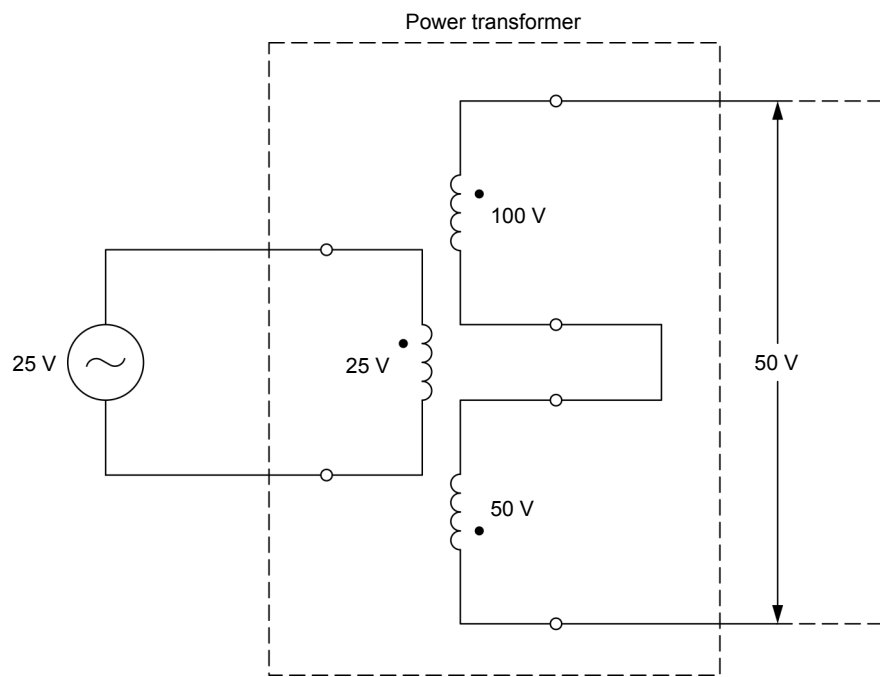
(b) Series-opposing connection

Figure 12. Power transformer whose secondary windings are connected in series.

When two windings of a power transformer are connected so that the marked end of one winding is connected to the marked end of the other winding, or the non-marked end of one winding is connected to the non-marked end of the other winding, the windings are connected in series-opposing, i.e., the voltage across both windings is equal to the difference between the voltages across each individual winding. For example, consider the transformer in Figure 12b. The primary winding of the transformer has a nominal voltage of 25 V, while the secondary windings have nominal voltages of 100 V and 50 V (this is in fact the same transformer as in Figure 12a. Since the secondary windings of the transformer are connected in series-opposing, the total voltage across the secondary windings is equal to 50 V (i.e., 100 V - 50 V) when the primary winding is connected to a 25 V ac power source. The transformer thus acts as a step-up transformer with a voltage ratio of 1:2.

Series-opposing connections are seldom used as the windings oppose each other. Consequently, the number of wire turns required to achieve a given ac power conversion (i.e., to obtain a certain voltage) is much higher than when a winding with the exact number of wire turns is used (i.e., a winding with a number of wire turns equal to the difference between the number of wire turns in the series-connected windings that act in one direction and the number of wire turns in the series-connected windings that act in the opposite direction). In the example given in Figure 12b, the two secondary windings of the transformer total 150 V but, when connected in series-opposing, only apply a voltage of 50 V. Thus, if a single winding with the exact number of turns is used, the transformer secondary winding requires only one third of the number of turns in two windings connected in series-opposing.

Determining the polarity of transformer windings using a voltmeter

When an oscilloscope is not available, the polarity of power transformer windings can be determined by connecting the primary and secondary windings in series, then applying an ac voltage to one of the two windings (generally the primary winding), and measuring the total voltage across the windings. When the total voltage is equal to the sum of the voltages across the individual windings, the ends of the windings that are connected together have opposite polarities. This is illustrated in Figure 13a. In this figure, the primary and secondary windings of a power transformer, which have nominal voltages of 200 V and 100 V, respectively, are series connected. A 200 V ac power source is connected to the primary winding. An ac voltmeter reads 300 V across the series-connected windings, indicating that the transformer terminals connected together are of opposite polarity, as the windings are connected in series-aiding (i.e., the winding voltages add up one another). Conversely, when the total voltage is equal to the difference between the voltages across the individual windings, the ends of the windings that are connected together have the same polarity. This is illustrated in Figure 13b. In this figure, the ac voltmeter reads 100 V across the series-connected windings, indicating that the transformer terminals connected together have the same polarity (i.e., the winding voltages subtract from each other).

(a)

(b)
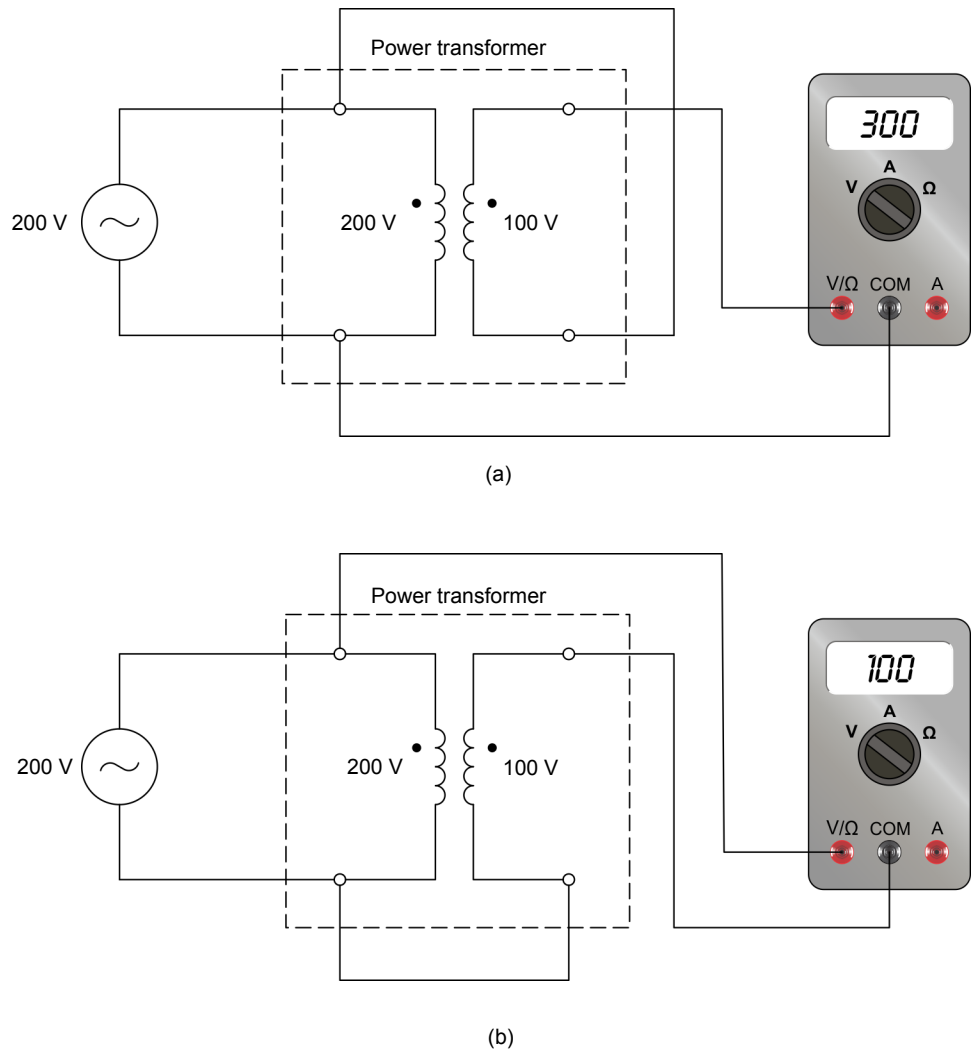
Figure 13. Determining the polarity of transformer windings using a voltmeter.

When a power transformer has additional windings, the test is repeated with each of the other windings to determine their respective polarity.

Parallel connection of transformer windings

Two windings of a power transformer having the same nominal voltage (i.e., the same number of turns) can be connected in parallel to increase the current capability, and thus, the power that can be delivered to a load. The polarity of each winding must be respected when connecting transformer windings in parallel. Otherwise, a current greatly exceeding the nominal winding current will flow in the windings, which can permanently damage the transformer. For example, consider the power transformer in Figure 14. This power transformer is connected to a 200 V ac power source. The transformer has a primary winding with nominal ratings of 200 V and 1 A, as well as two secondary windings with nominal ratings of 100 V and 1 A each that are connected in parallel. Notice that the marked ends of the two secondary windings are connected together and that the non-marked ends of the two secondary windings are connected together. When the ac power source is turned on, a voltage of 100 V can be measured across the secondary windings, and a current of 2 A flows in the 50 Ω resistive load connected to the secondary windings.
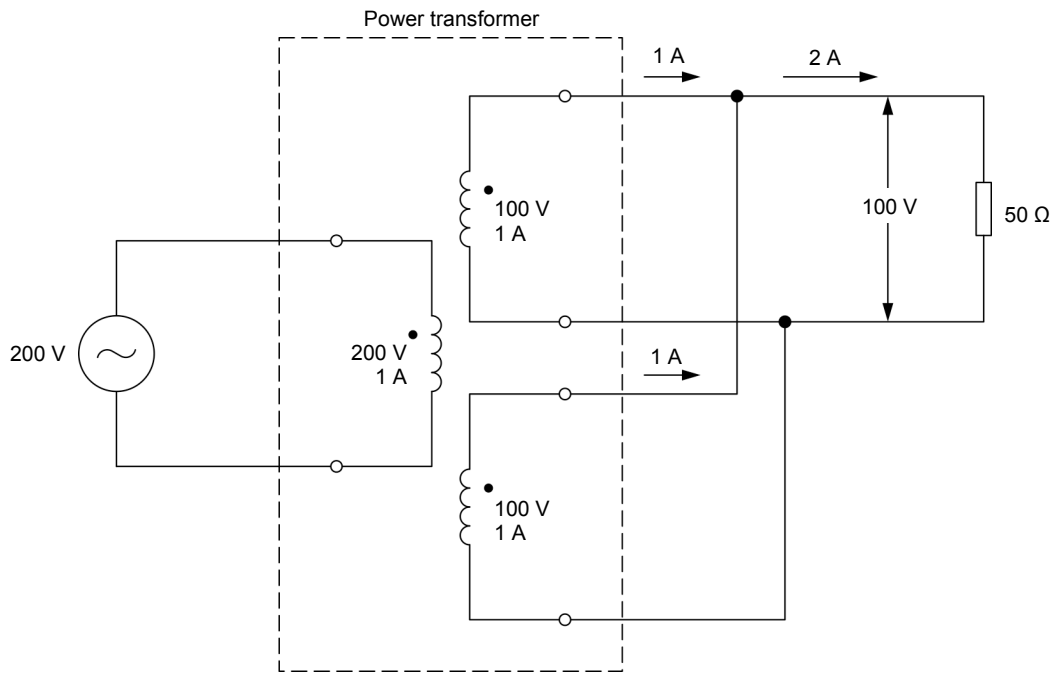
Figure 14. Power transformer whose secondary windings are connected in parallel.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Determining transformer winding polarity using an oscilloscope
- Series connection of transformer windings
- Determining transformer winding polarity using a voltmeter
- Parallel connection of transformer windings

PROCEDURE

⚠ **WARNING**

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

Set up and connections

In this section, you will set up the equipment to study the operation of a power transformer. You will observe the polarity markings on the front panel of the Transformer module and note which terminals have the same polarity as terminal 1.

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

   Install the required equipment in the Workstation.

2. Make sure that the main power switch on the Four-Quadrant Dynamometer/Power Supply is set to the *O* (off) position, then connect its *Power Input* to an ac power wall outlet.

3. Connect the *Power Input* of the Data Acquisition and Control Interface to the *Power Output* of the 24 V AC Power Supply module. Turn the 24 V AC Power Supply module on.

4. Turn the Four-Quadrant Dynamometer/Power Supply on, then set the *Operating Mode* switch to *Power Supply*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a power supply.

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

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

6. 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 and the Four-Quadrant Dynamometer/Power Supply are 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.

7. Observe the polarity markings on the front panel of the Transformer module. Determine which ends (terminals) of windings 3-4, 5-6, and 7-8 have the same polarity as terminal *1* of winding 1-2.

Terminals with the same polarity as terminal *1*: _____

Terminals with the same polarity as terminal *1*: *3*, *5*, and *7*.

Determining transformer winding polarity using an oscilloscope

In this section, you will connect a circuit containing a power transformer and set up the equipment to determine the transformer winding polarity, using the Oscilloscope. You will start the ac power source. You will observe the waveforms of the voltage across each transformer winding, and determine the polarity of each transformer terminal. You will then observe in the Phasor Analyzer the phasors of the voltages across each transformer winding, and confirm the results obtained using the Oscilloscope. You will reverse the connections at a voltage input of the Data Acquisition and Control Interface, and observe what happens to the corresponding voltage waveform on the Oscilloscope. You will determine if this inversion has any effect on the winding polarity found.

8. Connect the equipment as shown in Figure 15.
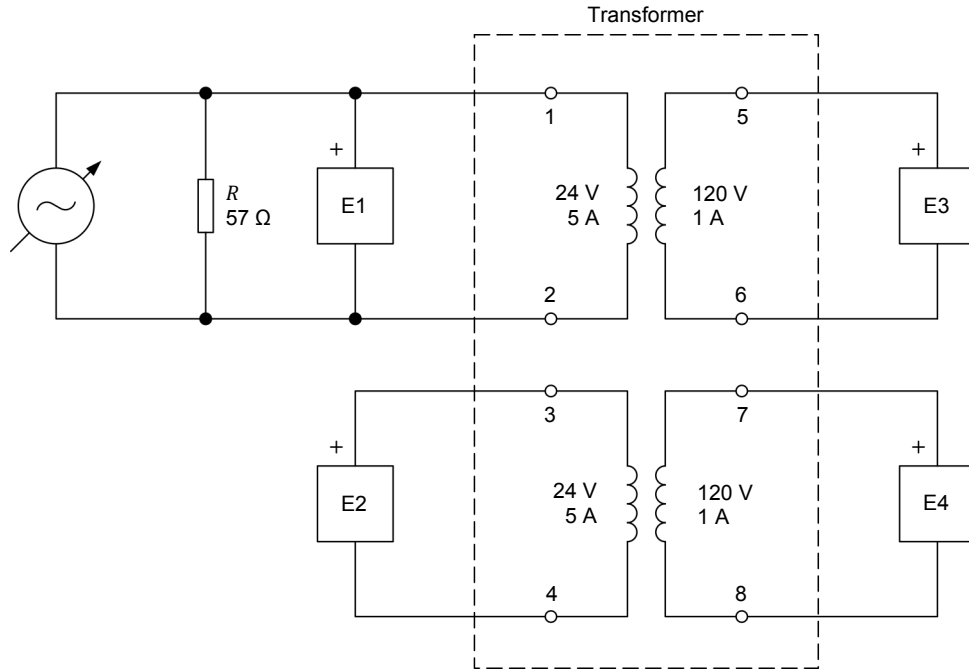
Figure 15. Circuit for determining transformer winding polarity using an oscilloscope.

> *The resistive load in the circuit of Figure 15 is used to improve the appearance of the voltage waveforms. As the resistive load is connected in parallel with the ac power source, it has no effect on the measured voltages.*

9. Make the necessary switch settings on the Resistive Load to obtain the resistance value required.

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

  – Set the *Function* parameter to *AC Power Source*.

  – Set the *Voltage (V at no load)* parameter to 24 V.

  – Set the *Frequency* parameter to the frequency of your local ac power network.

  – Start the *AC Power Source*.

11. In LVDAC-EMS, open the Oscilloscope and display the waveforms of the voltages measured across each winding of the transformer.

In the Four-Quadrant Dynamometer/Power Supply window, readjust the *Voltage (V at no load)* parameter so that the rms (ac) value of the voltage E_{1-2} across transformer winding 1-2 indicated in the Oscilloscope is as close as possible to 24 V.

Using the waveforms displayed on the Oscilloscope, determine the polarity of each transformer winding, i.e., which ends of the windings have the same polarity.

The resulting waveforms are shown in the following pictures.

For 50 Hz ac power networks:

Oscilloscope Settings
Channel-1 Scale .... 50 V/div
Channel-2 Scale .... 50 V/div
Channel-3 Scale .... 200 V/div
Channel-4 Scale .... 200 V/div
Time Base .... 5 ms/div
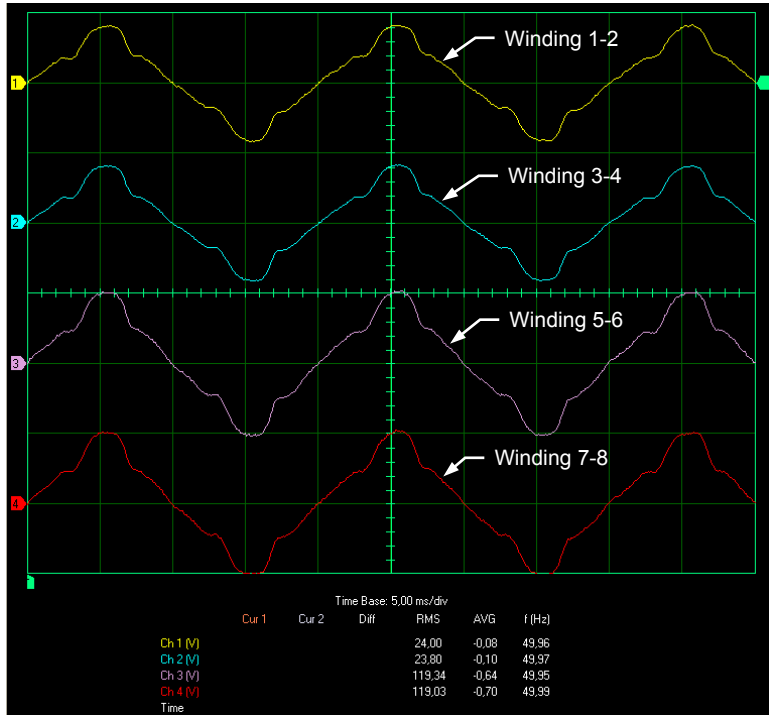
Voltage waveforms used for determining winding polarity.

For 60 Hz ac power networks:

Oscilloscope Settings
Channel-1 Scale .... 50 V/div
Channel-2 Scale .... 50 V/div
Channel-3 Scale .... 200 V/div
Channel-4 Scale .... 200 V/div
Time Base .... 5 ms/div
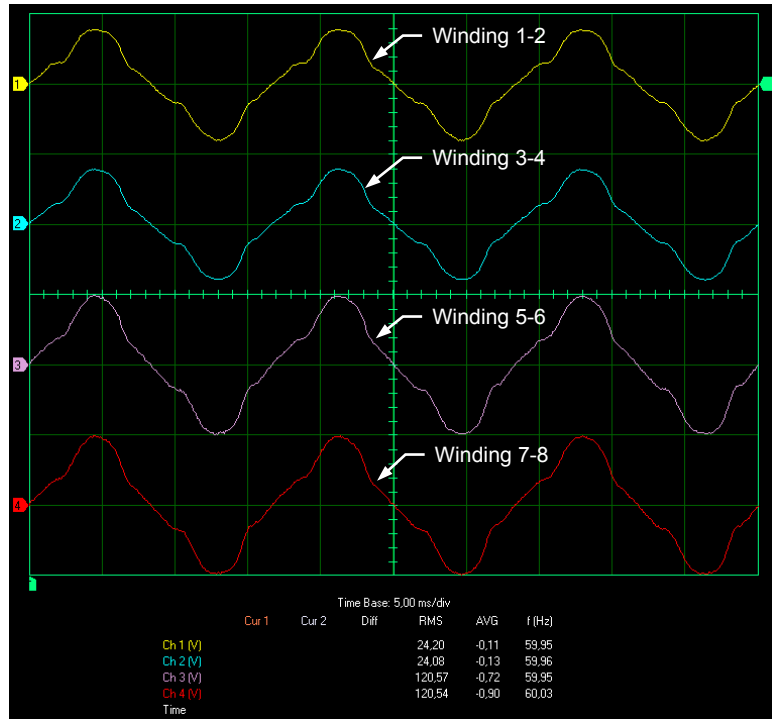
Voltage waveforms used for determining winding polarity.

Terminals *1*, *3*, *5*, and *7* have the same polarity.

Consequently, terminals *2*, *4*, *6*, and *8* also have the same polarity.

Are the results obtained consistent with the polarity markings indicated on the front panel of the Transformer module?

❑ Yes ❑ No

Yes

12. In LVDAC-EMS, open the Phasor Analyzer and display the phasors of the voltages measured across each winding of the transformer. Do the voltage phasors displayed in the Phasor Analyzer confirm what you observed using the Oscilloscope?

❑ Yes ❑ No

Yes

13. In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source*.

Reverse the connections at voltage input *E3* of the Data Acquisition and Control Interface.

In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source*.

14. On the Oscilloscope, observe the voltage waveforms. What happened to the waveform of the voltage measured across winding 5-6 (input *E3*)?

The voltage across winding 5-6 is now phase shifted 180° with respect to the voltage across the winding connected to the ac power source.

Does this observation change your conclusion about the polarity of winding 5-6? Explain briefly.

No. Since the waveform of the voltage across winding 5-6 is now phase shifted 180° with respect to the voltage across the winding connected to the ac power source, it means that winding 5-6 is connected to the oscilloscope in a way such that the winding polarity is inverted with respect to the polarity of the oscilloscope input terminals. (i.e., the polarity of voltage input *E3* of the Data Acquisition and Control Interface). Therefore, the polarity of winding 5-6 has not changed.

15. In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source*.

Series connection of transformer windings

In this section, you will calculate the voltages induced across the series-connected windings of three different transformer setups. You will then set up each series connection of windings successively, and measure the voltage across each one. You will compare the voltages measured across the series windings with the calculated voltages.

16. Consider the three transformer winding connections shown in Figure 16. In this figure, winding 1-2 is considered the primary winding of the transformer and is connected to a 24 V ac power source. Determine the voltage that should be induced across each series-connected winding combinations.

> *In all the transformer connections of Figure 16, the capacity of the transformer is limited to 120 VA, because all power is transferred through primary winding 1-2, which is rated 24 V and 5 A.*

Voltage across windings 3-4 and 5-6 in Figure 16a = _____ V

Voltage across windings 3-4 and 5-6 in Figure 16b = _____ V

Voltage across windings 5-6 and 7-8 in Figure 16c = _____ V

Voltage across windings 3-4 and 5-6 in Figure 16a = 120 V + 24 V = 144 V

Voltage across windings 3-4 and 5-6 in Figure 16b = 120 V – 24 V = 96 V

Voltage across windings 5-6 and 7-8 in Figure 16c = 120 V + 120 V = 240 V

17. Set up the series connection of windings shown in Figure 16a. Use input *E1* of the Data Acquisition and Control Interface to measure the voltage across winding 1-2 and input *E2* to measure the voltage across the series-connected windings.

In LVDAC-EMS, open the Metering window. Make the required settings to measure the rms (ac) values of the voltage E_{1-2} across transformer winding 1-2 and the voltage across the series-connected transformer windings.

In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source*. Adjust the *Voltage (V at no load)* parameter so that the voltage across transformer winding 1-2 indicated in the Metering window is as close as possible to 24 V.

In the Metering window, measure the transformer voltage across the series-connected windings. Record the value below.

Voltage measured across windings 3-4 and 5-6 in Figure 16a = _____ V

In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source.*

Voltage measured across windings 3-4 and 5-6 in Figure 16a = 145 V

(a)

(b)

(c)
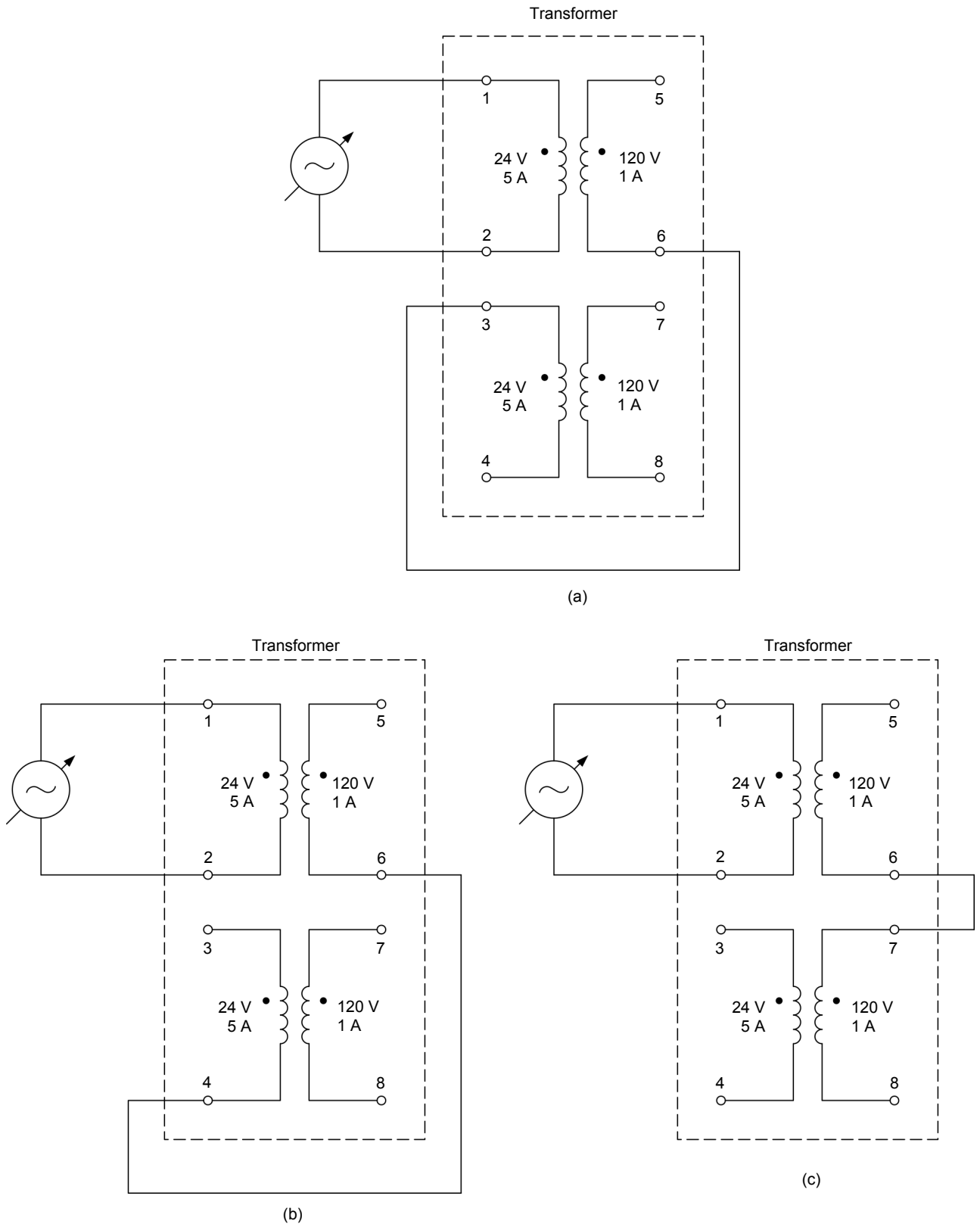
Figure 16. Different series connections of transformer windings.

18. Repeat step 17 for the series connections of windings shown in Figure 16b and Figure 16c. Record the measured voltages below.

Voltage measured across windings 3-4 and 5-6 in Figure 16b = _____ V

Voltage measured across windings 5-6 and 7-8 in Figure 16c = _____ V

Voltage measured across windings 3-4 and 5-6 in Figure 16b = 96.2 V

Voltage measured across windings 5-6 and 7-8 in Figure 15c = 239 V

Compare the voltages across the series windings measured in this step and in the previous step to the voltages calculated in step 16. Are the measured voltages virtually equal to the calculated voltages?

❏ Yes   ❏ No

Yes

Determining transformer winding polarity using a voltmeter

In this section, you will connect a circuit containing a transformer with series-connected windings (windings 1-2 and 5-6). You will measure the voltage across the series-connected windings. Using the measured voltage, you will determine the polarity of the transformer windings. You will compare the winding polarities obtained using this method with the winding polarities previously determined in this exercise. You will then connect another circuit containing a transformer with series-connected windings (windings 1-2 and 7-8) and repeat the above manipulations.

19. Connect the equipment as shown in Figure 17. In this circuit, one of the secondary windings (winding 5-6) of the power transformer is connected in series with the primary winding (winding 1-2).
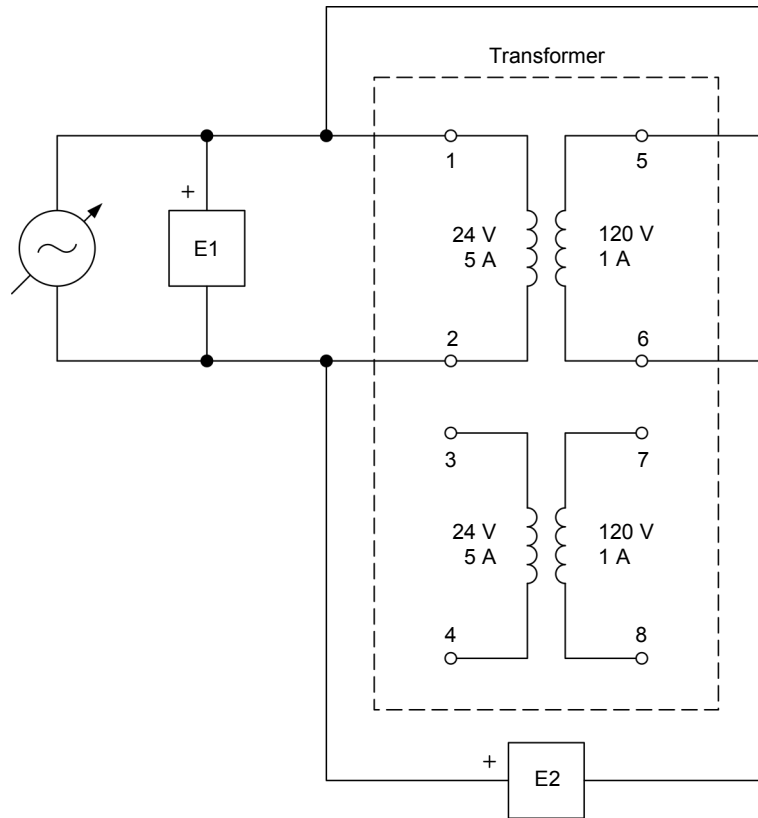
Figure 17. Circuit for determining transformer winding polarity using a voltmeter.

20. In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source*. Adjust the *Voltage (V at no load)* parameter so that the voltage across transformer winding 1-2 indicated in the Metering window is as close as possible to 24 V.

In the Metering window, measure the transformer voltage across the series-connected windings (windings 1-2 and 5-6). Record the value below.

Voltage across transformer windings 1-2 and 5-6 = _____ V

Voltage across transformer windings 1-2 and 5-6 = 95.7 V

21. In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source.*

22. Using the voltage across the series windings measured in step 20, determine the polarity of winding 5-6 of the transformer relative to that of winding 1-2 [i.e., which terminal (5 or 6) of winding 5-6 has the same polarity as terminal 1 of winding 1-2]. Explain briefly.

The voltage across the series-connected transformer windings is equal to the difference between the voltages across each winding, indicating that the windings are connected in series-opposing. Because of this, it can be deduced that terminal 5 of the transformer has the same polarity as terminal 1.

Are the results consistent with the polarity of the transformer windings determined in steps 7 and 11?

❑ Yes   ❑ No

Yes

23. Connect the equipment as shown in Figure 18. In this circuit, the other secondary winding (winding 7-8) of the transformer is connected in series with the primary winding (winding 1-2).
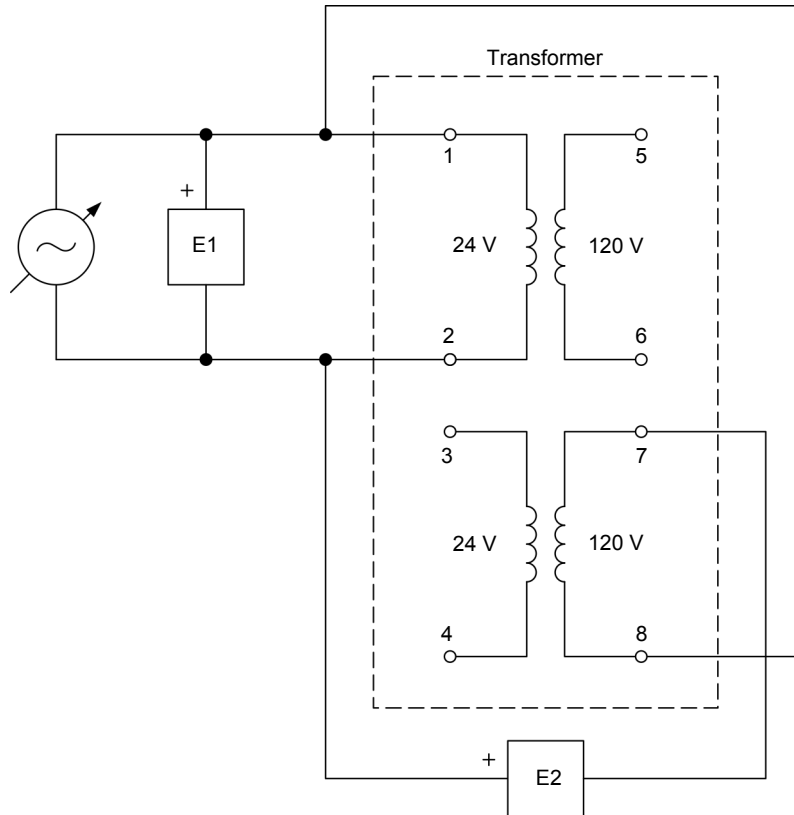

Figure 18. Circuit for determining transformer winding polarity using a voltmeter.

24. In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source*. Adjust the *Voltage (V at no load)* parameter so that the voltage across transformer winding 1-2 indicated in the Metering window is as close as possible to 24 V.

In the Metering window, measure the voltage across the series-connected windings. Record the value below.

Voltage measured across windings 1-2 and 7-8 = _____ V

Voltage measured across windings 1-2 and 7-8 = 144 V

25. In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source*.

26. Using the voltage across the series windings measured in the previous step, determine the polarity of winding 7-8 of the transformer relative to that of winding 1-2 [i.e., which terminal (7 or 8) of winding 7-8 has the same polarity as terminal 1 of winding 1-2]. Explain briefly.

The voltage across the series-connected transformer windings is equal to the sum of both winding voltages, indicating that the windings are connected in series-aiding. Because of this, it can be deduced that the polarity of terminal 8 is opposite to the polarity of terminal 1, and thus, that terminal 7 has the same polarity as terminal 1.

27. Are the results consistent with the polarity of the transformer windings determined in step 7 and 11?

❑ Yes   ❑ No

Yes

Parallel connection of transformer windings

In this section, you will set up a step-up transformer connected to a resistive load. You will start the ac power source and confirm that the transformer secondary voltage is equal to 120 V. You will set the resistance of the resistive load to 120 Ω. The secondary current should thus be virtually equal to the nominal current (1 A). You will measure the transformer primary voltage, current, and apparent power, as well as the secondary voltage, current, and apparent power. You will then modify the circuit so that the secondary windings of the transformer are connected in parallel. You will confirm that the secondary voltage, current, and apparent power have not changed, and that the two windings of the secondary are now sharing the secondary current equally. You will set the resistance of the resistive load to 57 Ω. The current flowing in each winding of the secondary should thus be virtually equal to the nominal current (1 A). You will measure the transformer primary voltage, current and apparent power, as well as the secondary voltage, current, and apparent power, and analyze the results.

28. Connect the equipment as shown in Figure 19.

In LVDAC-EMS, set the *Range* setting of current input *I1* to high.
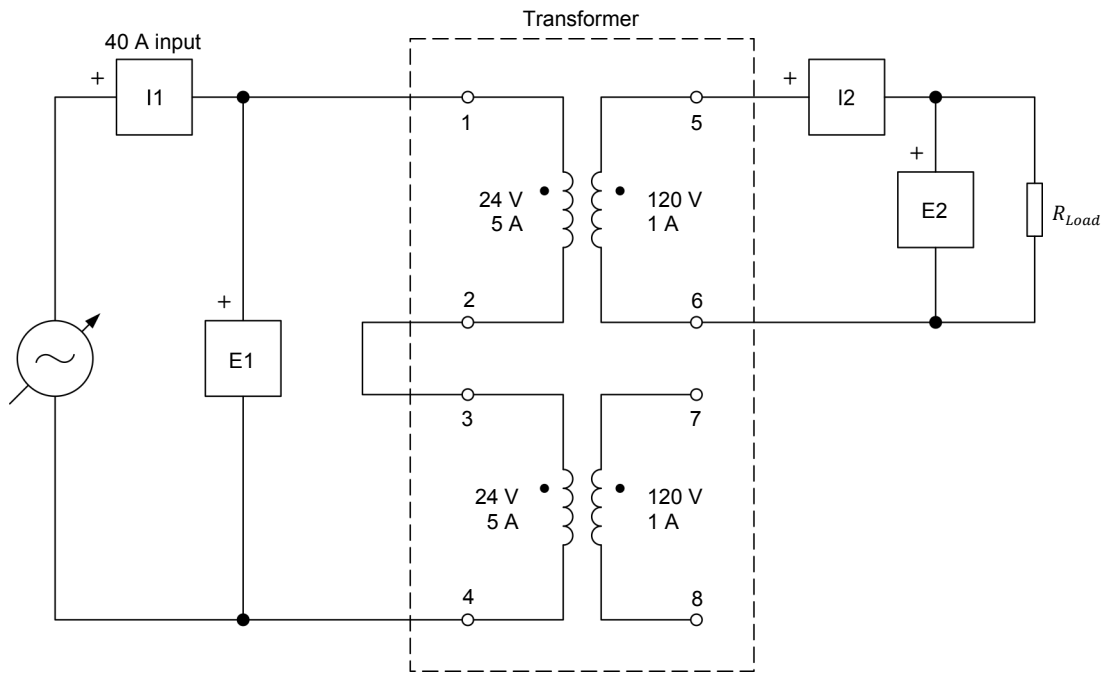
Figure 19. Step-up transformer connected to a resistive load.

29. Do the necessary switch settings on the Resistive Load so that the resistance value of the resistive load is infinite.

30. In the Metering window, make the required settings to measure the rms (ac) values of the transformer primary voltage $E_{Pri.}$ and secondary voltage $E_{Sec.}$ (inputs *E1* and *E2*, respectively). Set four meters to measure the transformer primary current $I_{Pri.}$, secondary current $I_{Sec.}$, winding current I_{5-6}, and winding current I_{7-8} (inputs *I1*, *I2*, *I3*, and *I4*, respectively). Finally, set two meters to measure the apparent power $S_{Pri.}$ at the primary from inputs *E1* and *I1*, and the apparent power $S_{Sec.}$ at the secondary from inputs *E2* and *I2*.

Inputs *I3* and *I4* will be connected to windings 5-6 and 7-8, respectively, later in this section.

31. In the Four-Quadrant Dynamometer/Power Supply window, set the *Voltage* parameter to 48 V, then start the *AC Power Source*. Readjust the *Voltage (V at no load)* parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the Metering window is as close as possible to 48 V.

Is the transformer secondary voltage $E_{Sec.}$ virtually equal to 120 V, thereby indicating that the transformer is a step-up transformer with a voltage ratio of 48 V:120 V?

❑ Yes   ❑ No

Yes

32. On the Resistive Load, make the necessary switch settings to obtain a resistive load value R_{Load} of 120 Ω.

33. In the Four-Quadrant Dynamometer/Power Supply window, adjust the *Voltage (V at no load)* parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the Metering window is as close as possible to 48 V. The secondary current $I_{Sec.}$ should now be virtually equal to the nominal current (1 A).

In the Metering window, measure the primary voltage $E_{Pri.}$, current $I_{Pri.}$, and apparent power $S_{Pri.}$, as well as the secondary voltage $E_{Sec.}$, current $I_{Sec.}$, and apparent power $S_{Sec.}$. Record the values below.

$E_{Pri.}$ = _____ V $E_{Sec.}$ = _____ V

$I_{Pri.}$ _____ A $I_{Sec.}$ = _____ A

$S_{Pri.}$ = _____ A $S_{Sec.}$ = _____ VA

$E_{Pri.}$ = 48.2 V $E_{Sec.}$ = 115 V

$I_{Pri.}$ = 2.58 A $I_{Sec.}$ = 0.97 A

$S_{Pri.}$ = 122 VA $S_{Sec.}$ = 113 VA

34. In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source*.

35. Modify the circuit connections to obtain the circuit shown in Figure 20. Do not change the resistance value of the resistive load. In this circuit, the two secondary windings (windings 5-6 and 7-8) are connected in parallel with the resistive load.
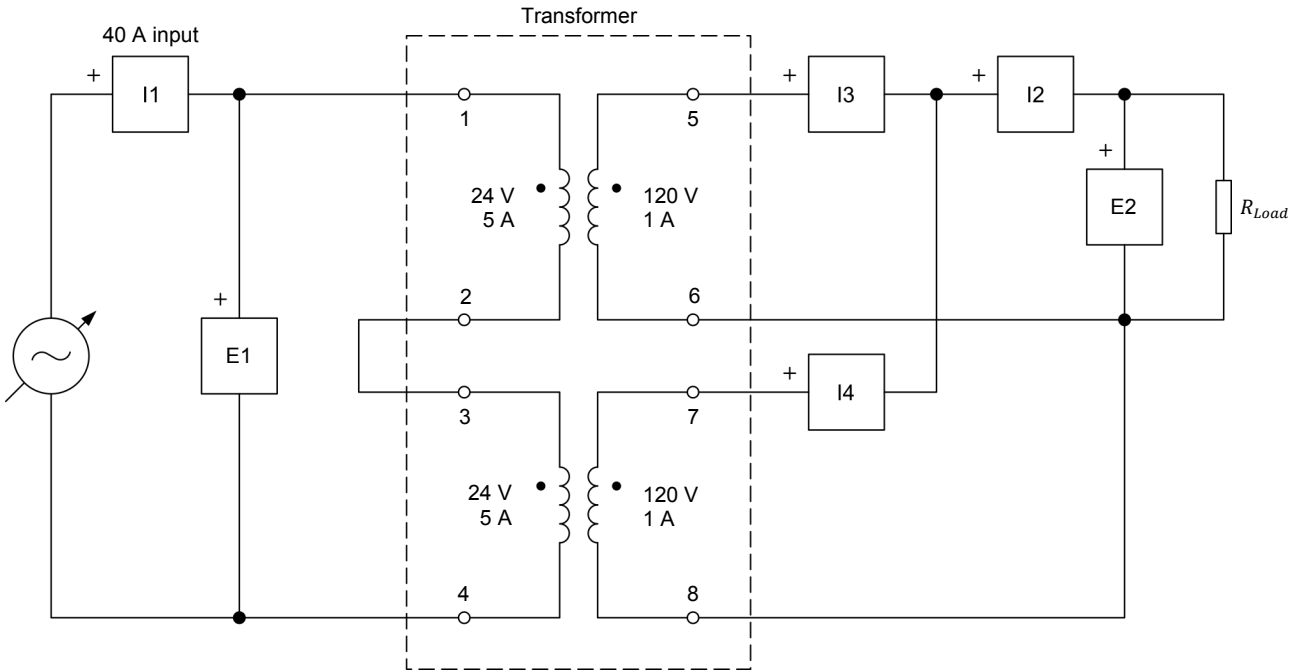
Figure 20. Step-up transformer with windings connected in parallel.

36. In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source.* Adjust the *Voltage (V at no load)* parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the Metering window is as close as possible to 48 V.

In the Metering window, measure the secondary voltage $E_{Sec.}$, current $I_{Sec.}$, and apparent power $S_{Sec.}$. Have these values changed with respect to the values measured when the circuit windings were not connected in parallel?

❏ Yes   ❏ No

No

Measure the current flowing in each secondary winding (using inputs *I3* and *I4*). Is the current flowing in each winding virtually equal to 0.5 A, thereby indicating that each winding is sharing the load current equally?

❏ Yes   ❏ No

Yes

37. On the Resistive Load, make the necessary switch settings to obtain a resistive load value R_{Load} of 57 Ω.

38. In the Four-Quadrant Dynamometer/Power Supply window, adjust the *Voltage (V at no load)* parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the Metering window is as close as possible to 48 V. The current flowing through each transformer secondary winding (winding currents I_{5-6} and I_{7-8}) should now be virtually equal to the nominal current (1 A).

In the Metering window, measure the primary voltage $E_{Pri.}$, current $I_{Pri.}$, and apparent power $S_{Pri.}$, as well as the secondary voltage $E_{Sec.}$, current $I_{Sec.}$, and apparent power $S_{Sec.}$. Record the values below.

$E_{Pri.}$ = _____ V $E_{Sec.}$ = _____ V

$I_{Pri.}$ = _____ A $I_{Sec.}$ = _____ A

$S_{Pri.}$ = _____ VA $S_{Sec.}$ = _____ VA

$E_{Pri.}$ = 48.3 V $E_{Sec.}$ = 115 V

$I_{Pri.}$ = 5.09 A $I_{Sec.}$ = 1.97 A

$S_{Pri.}$ = 242 VA $S_{Sec.}$ = 223 VA

39. In the Four-Quadrant Dynamometer/Power Supply window, stop the *AC Power Source*.

40. What happens to the apparent power $S_{Sec.}$ at the transformer secondary when you connect the secondary windings in parallel and adjust the load resistance so that the current in each secondary winding is virtually equal to the nominal value? Explain briefly.

The apparent power $S_{Sec.}$ at the transformer secondary doubles when the secondary windings are connected in parallel and the load resistance is adjusted so that the current in each secondary winding is virtually equal to the nominal value. This is because the total secondary current $I_{Sec.}$ flowing in the secondary windings doubles, the secondary voltage $E_{Sec.}$ remaining unchanged.

What happens to the primary voltage $E_{Pri.}$, current $I_{Pri.}$, and apparent power $S_{Pri.}$ when you connect the secondary windings in parallel and adjust the load resistance so that the current in each secondary winding is virtually equal to the nominal value? Explain briefly.

The primary current $I_{Pri.}$ and apparent power $S_{Pri.}$ double when the secondary windings are connected in parallel and the load resistance is adjusted so that the current in each secondary winding is virtually equal to the nominal value. On the other hand, the transformer primary voltage $E_{Pri.}$ remains constant since it is determined by the ac power source. This is because doubling the secondary current $I_{Sec.}$ and apparent power $S_{Sec.}$ doubles the primary current $I_{Pri.}$ and apparent power $S_{Pri.}$, the primary voltage $E_{Pri.}$ and secondary voltage $E_{Sec.}$ remaining virtually unchanged.

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

CONCLUSION

In this exercise, you learned what the polarity of a power transformer winding is, and how to represent it in a schematic diagram. You saw how to determine the polarity of power transformer windings using either an oscilloscope or a voltmeter. You also learned how to connect transformer windings in series and in parallel, as well as the effects of each type of connection on the transformer voltage, current, and power.

REVIEW QUESTIONS

1. Why is it important to know the polarity of each winding of a power transformer before connecting the transformer windings in series?

It is important to know the polarity of each winding of a power transformer before connecting the transformer windings in series because polarity determines whether the windings are connected in series-aiding (their voltages add together) or in series-opposing (their voltages subtract from each other).

2. Consider a power transformer having a single primary winding with a nominal voltage of 50 V connected to a 25 V ac power source, as well as two secondary windings with nominal voltages of 125 V and 225 V connected in series. Assuming that the ends of the windings that are connected in series are of the same polarity, calculate the total voltage induced across the secondary windings when the ac power source is turned on.

Since the ends of the windings that are connected in series are of the same polarity (series-opposing connection), their voltages subtract one from the other. The total voltage rating of the series-connected secondary windings is thus equal to 100 V, which means that the transformer is a step-up transformer with a voltage ratio of 50 V:100 V. Consequently, when an ac voltage of 25 V is applied to the primary winding, the voltage induced across the secondary windings is equal to 50 V.

3. How can the polarity of each winding of a power transformer be determined using an oscilloscope?

The polarity of each winding of a power transformer can be determined by applying an ac voltage to one winding and using the oscilloscope to observe the phase of the voltage waveforms induced across the other windings in relation to the phase of the ac power source voltage. When the voltage waveforms have the same phase, the corresponding windings are connected to the oscilloscope with the same polarity. When the voltage waveforms are 180° out of phase, the corresponding windings are connected to the oscilloscope with opposite polarities.

4. How can the polarity of two transformer windings be determined using a voltmeter?

The polarity of two transformer windings can be determined by connecting them in series and applying an ac voltage to one of the two windings. The voltage across the two windings is then measured. If the total voltage equals the sum of the voltages across each winding, the ends of the windings that are connected together have opposite polarities (series-aiding connection). Conversely, if the total voltage equals the difference between the voltages across each winding, the ends of the windings that are connected together have the same polarity (series-opposing connection).

5. What is the effect of connecting the secondary windings of a power transformer in parallel?

When the secondary windings of a power transformer are connected in parallel, the current flowing through each winding add up one another. The total current and power that can be supplied to a load are thus higher than if either winding is used alone.

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