

Electricity and New Energy

Single-Phase Power Transformers

Student Manual

86377-00

Order no.: 86377-00
First Edition
Revision level: 01/2015

By the staff of Festo Didactic

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Internet: www.festo-didactic.com
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Printed in Canada
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ISBN 978-2-89640-502-2 (Printed version)
ISBN 978-2-89747-240-5 (CD-ROM)
Legal Deposit – Bibliothèque et Archives nationales du Québec, 2011
Legal Deposit – Library and Archives Canada, 2011

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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 indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	WARNING indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	CAUTION indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	CAUTION used without the <i>Caution, risk of danger</i> 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
	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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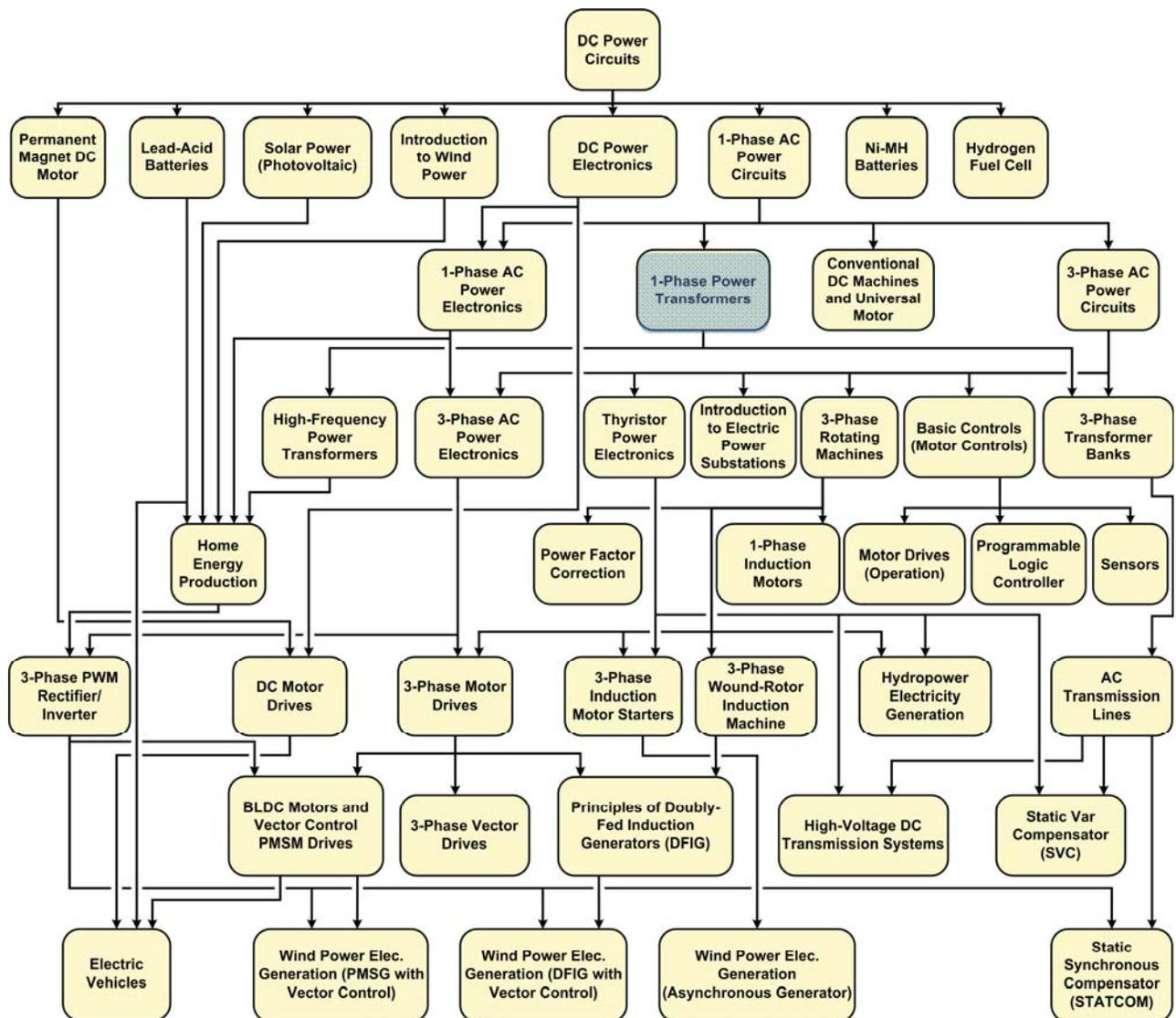
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Preface

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

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



The Electric Power Technology Training Program.

Preface

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

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

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 doing so, they 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 power supplied to the transformer is virtually equal to the power that the power transformer supplies to the load. Power transformers also have the ability to 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. They learn about different transformer connections, such as series-aiding, series-opposing, parallel, and autotransformer connections. Finally, students will verify the theory presented in each exercise by performing circuit measurements and calculations.



Typical single-phase power transformer.

About This Manual

Safety considerations

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

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

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

Prerequisite

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

Systems of units

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

Single-Phase Power Transformers

MANUAL OBJECTIVE

When you have completed this manual, you will be familiar with the operation of single-phase power transformers. You will be able to discuss what the turns, current, and voltage ratios of a power transformer are, and how to calculate them. You will be able to determine the polarity of the windings of a power transformer, and know how to connect transformer windings in series-aiding, in series-opposing, and in parallel. You will be familiar with the different power losses occurring in a power transformer, as well as with the transformer efficiency and voltage regulation. You will be able to determine the power rating of a power transformer, and know the effects of the operating frequency on the power rating. Finally, you will also know what an autotransformer is, and what its operating characteristics are.

DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Introduction to single-phase power transformers

DISCUSSION OF FUNDAMENTALS

Introduction to single-phase power transformers

Power transformers are magnetically operated devices that are used to change voltage, current, and impedance values in ac circuits. In its simplest form, a power transformer consists of two coils of wire wound around a common core of ferromagnetic material, such as iron. One coil is called the **primary winding** while the other is called the **secondary winding**. The primary winding is the power input winding of the transformer and corresponds to the side that is connected to the ac power source. The secondary winding corresponds to the side that is connected to the load and is physically and electrically isolated from the primary winding. Since power transformers are bidirectional devices, both windings can either be the primary winding or the secondary winding, depending on the direction of the power transfer in the transformer.

When ac current supplied by an ac power source flows through the primary winding of a power transformer, a varying magnetic flux is created in the iron core. This varying magnetic flux produces a varying magnetic field through the secondary winding of the power transformer. This varying magnetic field then induces a voltage across the secondary winding of the transformer, which causes current to flow from the secondary winding to the load connected to the transformer. Power has thus been transferred from the primary winding of the transformer to the secondary winding through electromagnetic induction only, which means that there is no electric contact between the primary and the secondary windings. Therefore, power transformers not only perform ac power conversion but also electrically isolate the ac power source from the load. Electrical isolation is a very important feature of power transformers that makes them very difficult to replace in certain applications.

In certain power transformers, the primary winding actually consists of two or more individual windings. These windings can be connected in series or in parallel to form a single primary winding that is connected to an ac power source. Similarly, the secondary winding of certain transformers actually consists of several individual windings. These windings can be connected in series or in parallel to form a single secondary winding that is connected to a load. These windings can also be connected individually to supply ac power to different loads.



Figure 1. Power transformers are often used in power distribution lines.

Voltage and Current Ratios

EXERCISE OBJECTIVE

When you have completed this exercise, you will know the relationships between the turns, voltage, and current ratios of a power transformer. You will be familiar with the different characteristics of step-up and step-down power transformers. You will also know how to determine in practice the voltage and current ratios of a power transformer.

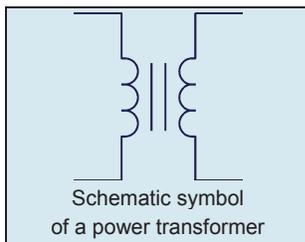
DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Transformer voltage and current ratios
- Step-up and step-down transformers
- Determining the voltage and current ratios of a transformer

DISCUSSION

Transformer voltage and current ratios



As mentioned in the introduction, power transformers have a primary winding and a secondary winding. The ratio between the number of turns of wire in the primary winding ($N_{Pri.}$) and the number of turns of wire in the secondary winding ($N_{Sec.}$) is called the **turns ratio**. This ratio sets the relationship between the input and output values of the transformer and thus, determines the basic characteristics of the transformer. Figure 2a shows a single-phase power transformer having a turns ratio $N_{Pri.}/N_{Sec.}$ of 1:1 connected to a single-phase ac power source and a resistive load. Figure 2b represents the circuit diagram of the setup shown in Figure 2a.

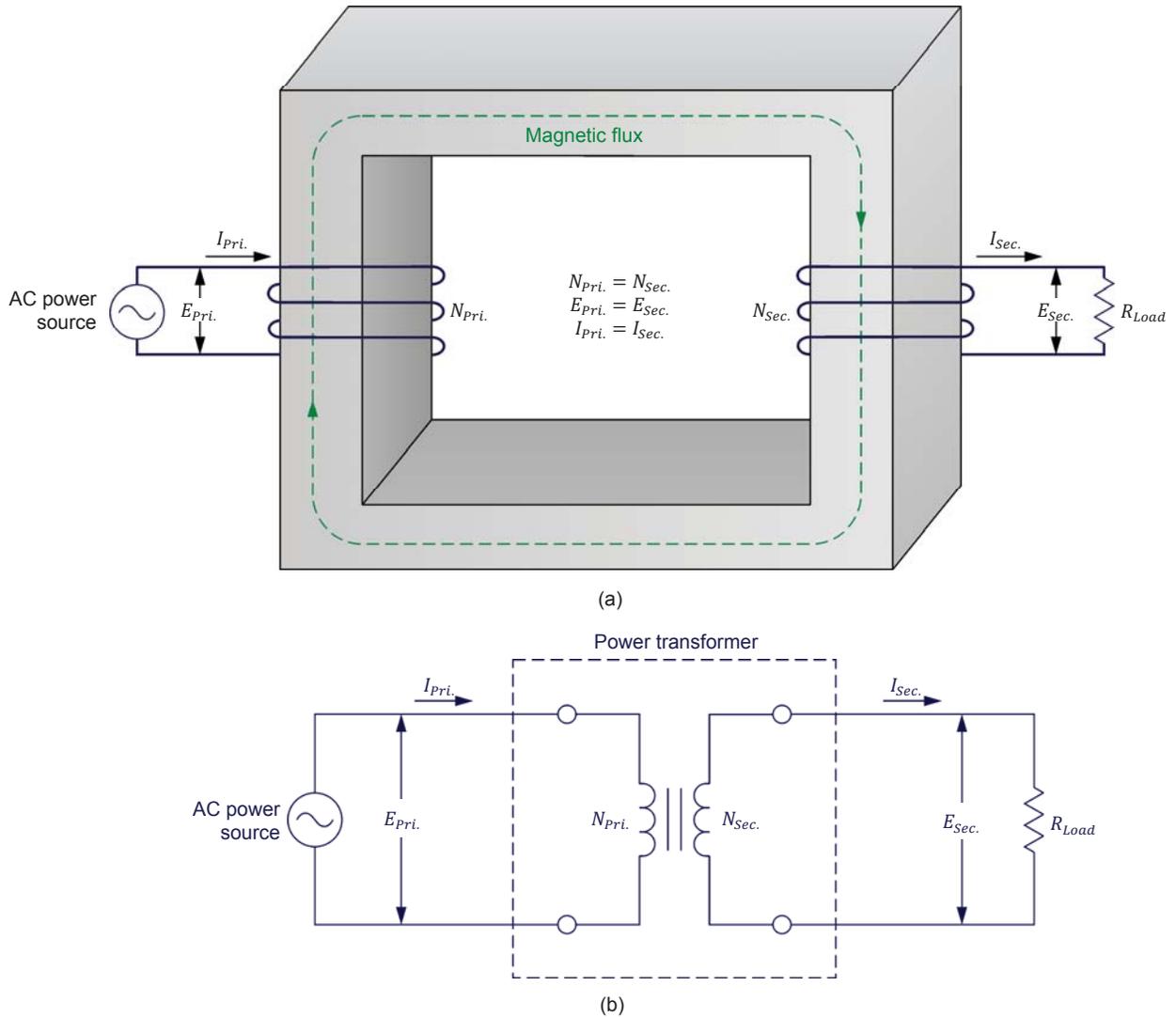


Figure 2. Power transformer with a turns ratio of 1:1.

The ratio between the voltage across the primary winding and the voltage across the secondary winding of a power transformer is directly proportional to the transformer turns ratio $N_{Pri.}/N_{Sec.}$ as indicated in the following equation:

$$\frac{E_{Pri.}}{E_{Sec.}} = \frac{N_{Pri.}}{N_{Sec.}} \quad (1)$$

where $E_{Pri.}$ is the voltage across the primary winding of the transformer, expressed in volts (V).
 $E_{Sec.}$ is the voltage across the secondary winding of the transformer, expressed in volts (V).
 $N_{Pri.}$ is the number of turns in the primary winding of the transformer.
 $N_{Sec.}$ is the number of turns in the secondary winding of the transformer.

The voltage across the secondary winding of a transformer can thus be calculated using the following equation:

$$E_{Sec.} = \frac{E_{Pri.} \times N_{Sec.}}{N_{Pri.}} \quad (2)$$

Conversely, the ratio between the current flowing in the primary winding and the current flowing in the secondary winding of a power transformer is inversely proportional to the transformer turns ratio $N_{Pri.}/N_{Sec.}$, as indicated in the following equation:

$$\frac{I_{Pri.}}{I_{Sec.}} = \frac{N_{Sec.}}{N_{Pri.}} \quad (3)$$

where $I_{Pri.}$ is the current flowing in the primary winding of the transformer, expressed in amperes (A).
 $I_{Sec.}$ is the current flowing in the secondary winding of the transformer, expressed in amperes (A).

The current flowing in the secondary winding of a transformer can thus be calculated using the following equation:

$$I_{Sec.} = \frac{I_{Pri.} \times N_{Pri.}}{N_{Sec.}} \quad (4)$$

As you can see, the ratio between the voltage across the primary winding of a transformer and the voltage across the secondary winding is equal to $N_{Pri.}/N_{Sec.}$. Conversely, the ratio between the current flowing in the primary winding of a transformer and the current flowing in the secondary winding is equal to the inverse of the turns ratio, i.e., $N_{Sec.}/N_{Pri.}$.

Power transformers are highly efficient devices. Because of this, the voltage and current measured at the secondary winding of a transformer are virtually equal to the values that can be predicted using the voltage and current measured at the primary windings and the transformer **voltage ratio** and **current ratio**. Similarly, the apparent power at the secondary winding of a transformer is virtually equal to apparent power supplied to the primary winding of the transformer. This is true regardless of whether the primary and secondary windings are made of a single winding or of several windings. In other words, the total apparent power at the windings forming the secondary winding of a transformer is virtually equal to the total apparent power at the windings forming the primary winding.

Step-up and step-down transformers

Depending on its turns ratio, a power transformer can either be a **step-up transformer** or a **step-down transformer**. In step-up transformers, the number of turns in the transformer primary winding is lower than the number of turns in the secondary winding, as is illustrated in Figure 3. Consequently, step-up transformers increase the voltage from the primary winding to the secondary winding, hence the name. Conversely, step-up transformers decrease the current from the primary winding to the secondary winding.

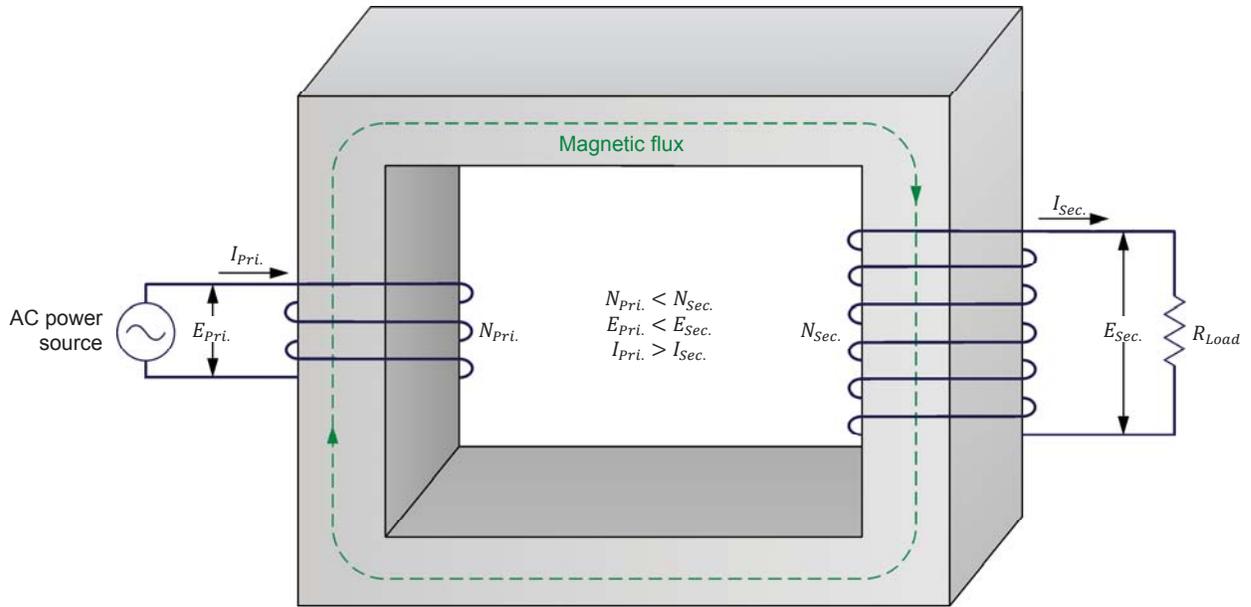


Figure 3. Step-up power transformer.

In step-down transformers, the number of turns in the transformer primary winding is higher than the number of turns in the secondary winding, as is illustrated in Figure 4. Consequently, step-down transformers decrease the voltage from the primary winding to the secondary winding, hence the name. Conversely, step-down transformers increase the current from the primary winding to the secondary winding.

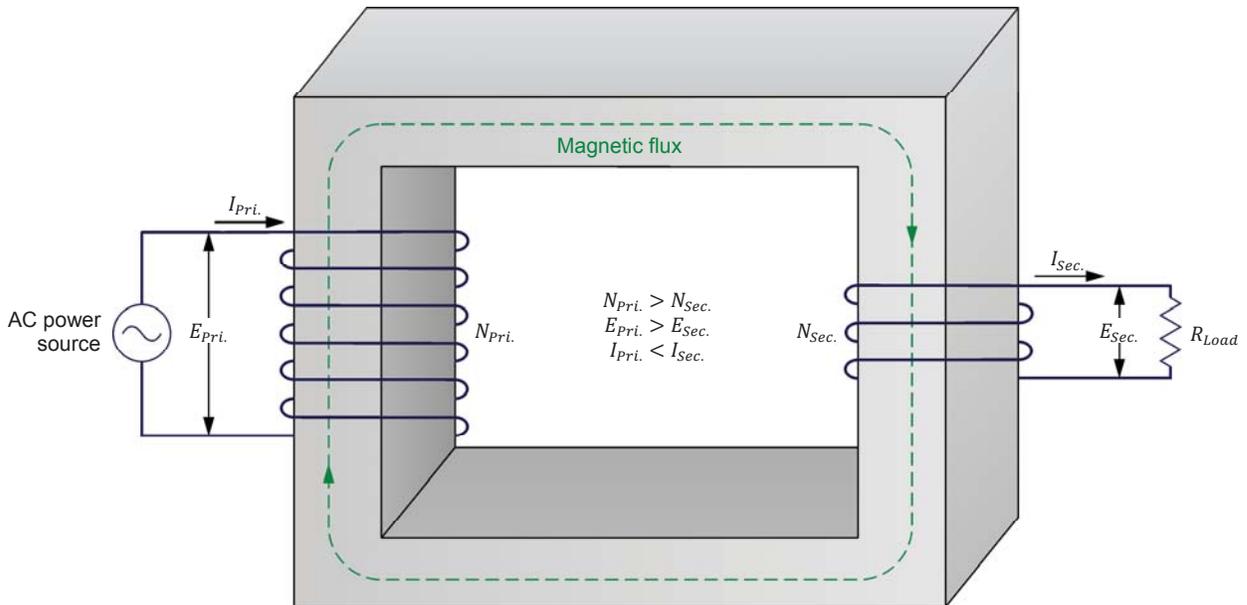


Figure 4. Step-down power transformer.

Power transformers are bidirectional devices. This means that power in a transformer can flow from the primary winding to the secondary winding or from the secondary winding to the primary winding. When power flows from the secondary winding to the primary winding of a step-up transformer, this

transformer in fact behaves as a step-down transformer as the voltage supplied to the load (i.e., the primary voltage) is lower than the ac source voltage (i.e., the secondary voltage). Conversely, when power flows from the secondary winding to the primary winding of a step-down transformer, this transformer in fact behaves as a step-up transformer as the voltage supplied to the load (i.e., the primary voltage) is higher than the ac source voltage (i.e., the secondary voltage). For example, if the ac power source connected to the primary winding of the step-up transformer in Figure 3 is connected to the secondary winding instead, the transformer operates as a step-down transformer. The resulting circuit diagram is shown in Figure 5. The inverse is true for the step-down transformer in Figure 4, i.e., if the ac power source is connected to the secondary winding instead of the primary winding, the transformer operates as a step-up transformer.

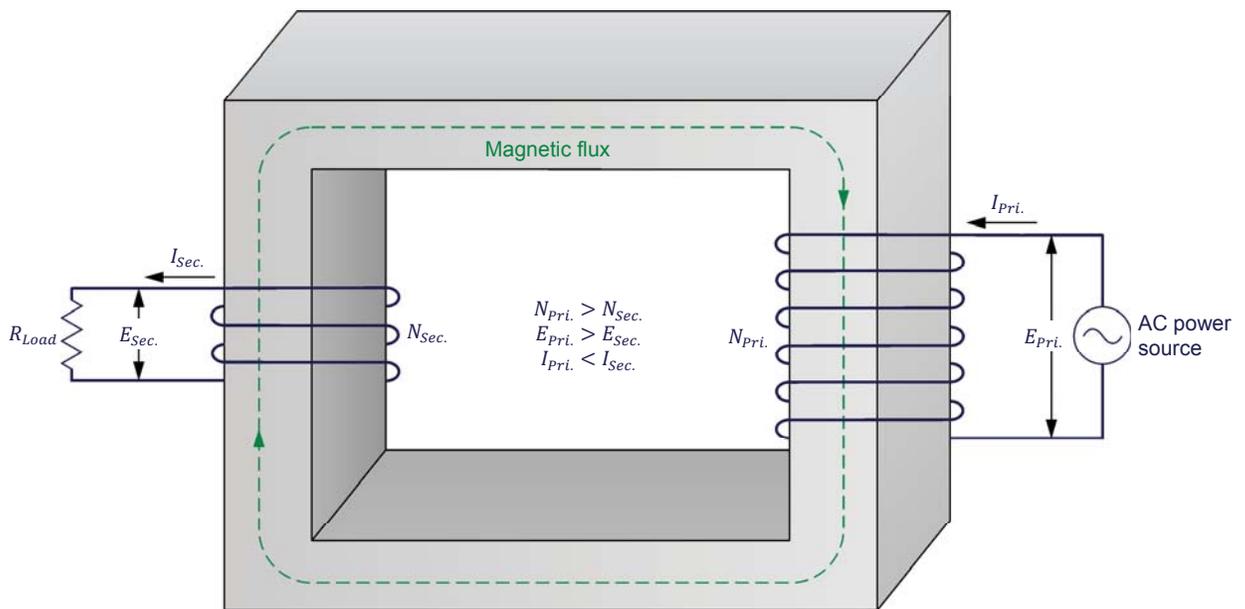


Figure 5. Step-up transformer of Figure 3 converted into a step-down transformer by connecting the ac power source to what is usually the secondary winding.

Determining the voltage and current ratios of a transformer

Determining the voltage ratio of a power transformer is simple. When no load is connected to the secondary winding of the transformer, only the small exciting current necessary to create the magnetic flux inside the transformer flows in the primary winding of the transformer (the transformer exciting current is discussed later in this manual). The transformer losses are thus at a minimum and the ratio of the primary voltage to the secondary voltage is equal to the transformer turns ratio. The transformer voltage (turns) ratio can be found by measuring with a voltmeter the voltage across the secondary winding (without load) of the transformer when nominal voltage is applied to the primary winding.

Determining the current ratio of a transformer can be achieved through a number of methods. The safest method in order to avoid damaging the transformer is to connect the transformer to a resistive load, and to connect two ammeters to the circuit in order to measure the current flowing in the primary winding and in the

secondary winding. Nominal voltage is then applied across the primary winding and the load resistance is adjusted so that the current flowing in the secondary winding is close to the nominal value. The transformer current ratio is equal to the ratio of the current flowing in the primary winding to the current flowing in the secondary winding.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Primary and secondary windings of the Transformer module
- Electrical isolation between the primary and secondary windings
- Voltage induction across the windings of a transformer
- Step-up transformer
- Step-down transformer (OPTIONAL)

PROCEDURE



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 section, you will set up the equipment to study the operation of a power transformer.

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.

Connect the *Power Input* of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

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

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

In the **Module Selector** 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 selected. Also, 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 **Module Selector** window.

Primary and secondary windings of the Transformer module

In this section, you will observe the transformer module and notice the ratings of the transformer windings.

6. Observe the front panel of the **Transformer** module (Model 8353). Notice that the power transformer in the module can be used as a step-up transformer. In this case, the two 24 V – 5 A windings form the primary winding and are connected to the ac power source. The two 120 V - 1 A windings form the secondary winding and can be connected to a single load or to two separate loads.

Conversely, the power transformer in the **Transformer** module can also be used as a step-down transformer. In this case, the two 120 V - 1 A windings form the primary winding and are connected to the ac power source. The two 24 V – 5 A windings form the secondary winding and can be connected to a single load or to two separate loads.

Electrical isolation between the primary and secondary windings

In this section, you will use an ohmmeter to verify that a power transformer provides isolation between its primary and secondary windings.

7. Using an ohmmeter, verify that terminals 1, 2, 3, and 4 of the primary winding of the power transformer in the **Transformer** module are all isolated from terminals 5, 6, 7, and 8 of the secondary winding.

Does this confirm that a power transformer provides electrical isolation between its primary and secondary windings?

Yes No

Voltage induction across the windings of a transformer

In this section, you will calculate the voltages induced across the various windings of the Transformer module when a voltage of 24 V is applied to winding 1-2. You will set up the equipment to measure the voltage across each winding of the Transformer module. You will apply a voltage of 24 V to winding 1-2, and measure the voltages induced across each other windings. You will compare the measured voltages with the calculated voltages. You will then calculate the voltages induced across the various windings of the Transformer module when a voltage of 100 V is applied to winding 5-6. You will apply a voltage of 100 V to winding 5-6, and measure the voltages induced across each other windings. Finally, you will compare the measured voltages with the calculated voltages.

From now on, the Transformer module will be referred to simply as the power transformer or transformer.

8. The number of turns in each of the two 24 V – 5 A windings of the power transformer in the Transformer module is 57 turns. The number of turns in each of the two 120 V – 1 A windings of the transformer is 285 turns. The number of turns in each winding of the transformer is important in order to calculate the transformer turns ratio, which in turn determines the transformer voltage and current ratios.
9. Using the number of turns in each winding of the power transformer provided in the previous step, determine the voltage induced across windings 3-4, 5-6, and 7-8 of the transformer when a voltage of 24 V is applied to winding 1-2.

Voltage E_{3-4} across winding 3-4 = _____ V

Voltage E_{5-6} across winding 5-6 = _____ V

Voltage E_{7-8} across winding 7-8 = _____ V

10. Connect the equipment as shown in Figure 6.

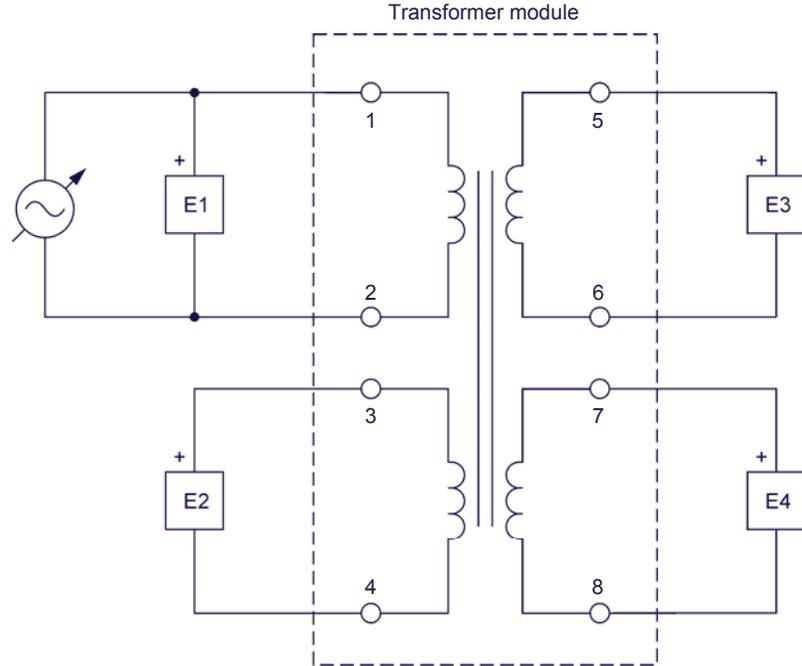


Figure 6. Circuit for measuring the voltage induced across each winding of the transformer when the ac power source is connected to winding 1-2.

11. 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* parameter to 24 V.
- Set the *Frequency* parameter to the frequency of your local ac power network.
- Start the *AC Power Source*.

12. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms values (ac) of voltage E_{1-2} across winding 1-2, voltage E_{3-4} across winding 3-4, voltage E_{5-6} across winding 5-6, and voltage E_{7-8} across winding 7-8 (inputs $E1$, $E2$, $E3$, and $E4$, respectively).

13. In the Four-Quadrant Dynamometer/Power Supply window, readjust the *Voltage* parameter so that the voltage E_{1-2} across winding 1-2 indicated in the Metering window is as close as possible to 24 V.

In the **Metering** window, measure the voltage across each winding of the transformer (except the one to which the ac power source is connected). Record the values below.

Voltage E_{3-4} across winding 3-4 = _____ V

Voltage E_{5-6} across winding 5-6 = _____ V

Voltage E_{7-8} across winding 7-8 = _____ V

Compare the voltages measured across the windings of the transformer to the voltages you calculated in step 9. Are the values virtually equal?

Yes No

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

15. Using the number of turns in each winding of the transformer, determine the voltage induced across windings 1-2, 3-4, and 7-8 of the power transformer when a voltage of 100 V is applied to winding 5-6.

Voltage E_{1-2} across winding 1-2 = _____ V

Voltage E_{3-4} across winding 3-4 = _____ V

Voltage E_{7-8} across winding 7-8 = _____ V

16. Connect the equipment as shown in Figure 7.

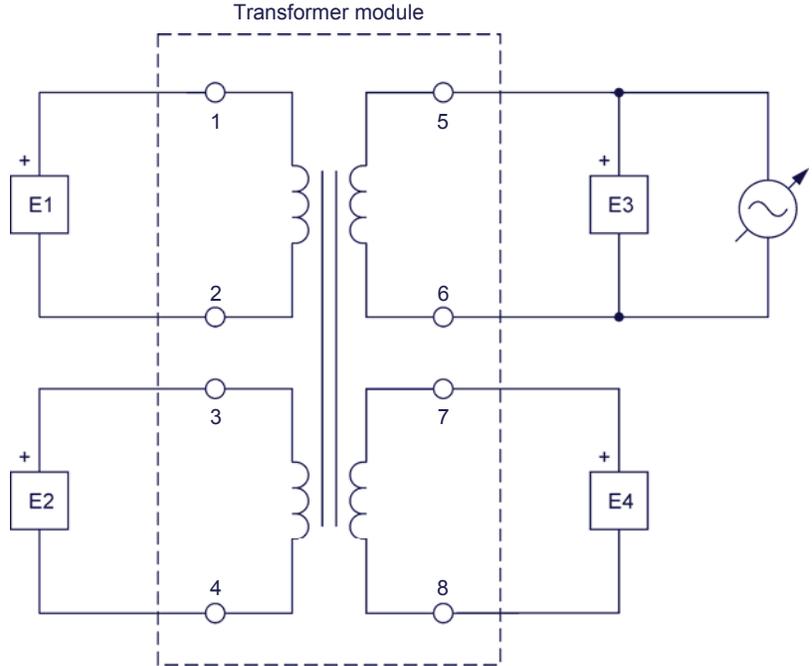


Figure 7. Circuit for measuring the voltage induced across each winding of the transformer when the ac power source is connected to winding 5-6.

17. In the *Four-Quadrant Dynamometer/Power Supply* window, set the *Voltage* parameter to 100 V, then start the *AC Power Source*. Readjust the *Voltage* parameter so that the voltage E_{5-6} across winding 5-6 indicated in the *Metering* window is as close as possible to 100 V.

In the *Metering* window, measure the voltage across each winding of the transformer (except the one to which the ac power source is connected). Record the values below.

Voltage E_{1-2} across winding 1-2 = _____ V

Voltage E_{3-4} across winding 3-4 = _____ V

Voltage E_{7-8} across winding 7-8 = _____ V

Compare the voltage measured across the windings of the transformer to the voltages you calculated in step 15. Are the values virtually equal?

Yes No

Do the above manipulations confirm the relationship between the turns ratio and the voltage ratio?

Yes No

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

Step-up transformer

In this section, you will set up a circuit containing a step-up transformer connected to a resistive load, and calculate the step-up transformer turns ratio. You will start the ac power source. You will measure the transformer primary and secondary voltages (with the load resistance set to infinite), and calculate the transformer voltage ratio. You will compare the transformer voltage ratio with the calculated turns ratio, and confirm that the transformer currently operates as a step-up transformer. You will then set the resistance of the resistive load to $120\ \Omega$. You will measure the transformer primary and secondary currents, and calculate the transformer current ratio. Finally, you will measure the step-up transformer apparent power at the primary and secondary, and confirm that both values are virtually equal.

19. Set up the 120 VA step-up transformer shown in Figure 8.

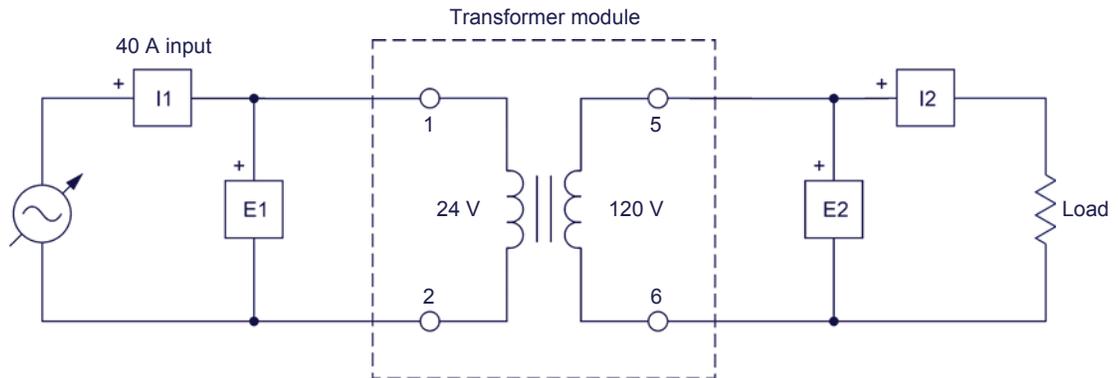


Figure 8. 120 VA step-up transformer connected to a resistive load.

In LVDAC-EMS, set the *Range* setting of current input *I1* to high.

20. Make the necessary switch settings on the Resistive Load so that the resistance value of the resistive load is infinite.
21. Calculate the turns ratio of the step-up transformer you set up in the previous step.

Step-up transformer turns ratio = _____

22. In the Metering window, make the required settings in order to measure the rms values (ac) of the power transformer primary voltage $E_{Pri.}$ and current $I_{Pri.}$ (inputs *E1* and *I1*, respectively), as well as the transformer secondary voltage $E_{Sec.}$ and current $I_{Sec.}$ (inputs *E2* and *I2*, respectively). Set two other meters to measure the transformer apparent power $S_{Pri.}$ at the primary and apparent power $S_{Sec.}$ at the secondary (from inputs *E1* and *I1*, and inputs *E2* and *I2*, respectively).

- 23.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Voltage** parameter to 24 V, then start the **AC Power Source**. Readjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 24 V.

In the **Metering** window, temporarily set the meter measuring the transformer primary current so that it displays dc current values. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **DC Offset Correction** parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it displays ac current values.



*Adjusting the **DC Offset Correction** parameter of the ac power source ensures that virtually no dc current is supplied to the power transformer. This adjustment is required because dc current negatively affects the operation of power transformers.*

- 24.** In the **Metering** window, measure the step-up transformer primary and secondary voltages. Record the values below.

Step-up transformer primary voltage $E_{Pri.} = \underline{\hspace{2cm}}$ V

Step-up transformer secondary voltage $E_{Sec.} = \underline{\hspace{2cm}}$ V

Using the step-up transformer primary and secondary voltages you just recorded, calculate the transformer voltage ratio.

Step-up transformer voltage ratio = $\underline{\hspace{2cm}}$

- 25.** Is the step-up transformer voltage ratio you recorded in the previous step coherent with the transformer turns ratio you calculated in step 21?

Yes No

Considering the transformer primary and secondary voltages you recorded in the previous step, can you conclude that the transformer currently operates as a step-up transformer? Explain briefly.

- 26.** On the **Resistive Load**, make the necessary switch settings in order to obtain a resistive load value R_{Load} of 120 Ω .

- 27.** In the **Four-Quadrant Dynamometer/Power Supply** window, readjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 24 V. The current flowing in the secondary winding should now be close to the nominal current (1 A).

- 28.** In the **Metering** window, measure the step-up transformer primary and secondary currents. Record the values below.

Step-up transformer primary current $I_{pri.} = \underline{\hspace{2cm}}$ A

Step-up transformer secondary current $I_{sec.} = \underline{\hspace{2cm}}$ A

Using the step-up transformer primary and secondary currents you just recorded, calculate the transformer current ratio.

Step-up transformer current ratio = $\underline{\hspace{2cm}}$

- 29.** Is the step-up transformer current ratio you recorded in the previous step the inverse of the transformer turns ratio you calculated in step 21 and the transformer voltage ratio you recorded in step 24?

Yes No

- 30.** In the **Metering** window, measure the step-up transformer apparent power $S_{pri.}$ at the primary and apparent power $S_{sec.}$ at the secondary. Record the values below.

Apparent power $S_{pri.}$ at the primary = $\underline{\hspace{2cm}}$ VA

Apparent power $S_{sec.}$ at the secondary = $\underline{\hspace{2cm}}$ VA

Is the apparent power $S_{sec.}$ at the secondary of the step-up transformer close to the apparent power $S_{pri.}$ at the primary?

Yes No

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

Step-down transformer (OPTIONAL)



This section is optional as it requires the use of the load resistors available in the *Wind Turbine Generator/Controller* module. These low-resistance load resistors are necessary to ensure that the current flowing in the primary winding of the step-down transformer is significant (in relation to the transformer nominal current).

In this section, you will set up a circuit containing a step-down transformer connected to a resistive load, and calculate the step-down transformer turns ratio. You will start the ac power source. You will measure the transformer primary and secondary voltages (with the load resistance set to infinite), and calculate the transformer voltage ratio. You will compare the transformer voltage ratio with the calculated turns ratio, and confirm that the transformer currently operates as a step-down transformer. You will then set the resistance of the resistive load to $5\ \Omega$. You will measure the transformer primary and secondary currents, and calculate the transformer current ratio. Finally, you will measure the step-down transformer apparent power values at the primary and secondary, and confirm that both values are virtually equal.

- 32.** Set-up the 120 VA step-down transformer shown in Figure 9. Do not connect the resistive load, i.e., the load resistors of the *Wind Turbine Generator/Controller* module, to the circuit for the moment. The load resistance at the transformer secondary is thus infinite.

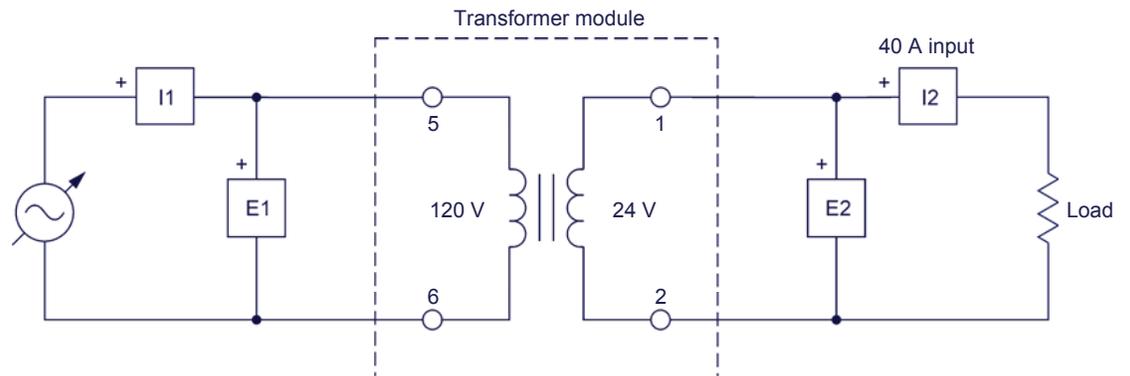


Figure 9. 120 VA step-down transformer connected to the low-resistance load available in the *Wind Turbine Generator/Controller* module.

In LVDAC-EMS, set the *Range* setting of current input *I1* to low, and the *Range* setting of current input *I2* to high.

- 33.** Calculate the turns ratio of the step-down transformer you set up in the previous step.

Step-down transformer turns ratio = _____

34. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Voltage** parameter to 100 V, then start the **AC Power Source**. Readjust the **Voltage** parameter so that the transformer primary voltage E_{pri} , indicated in the **Metering** window is as close as possible to 100 V.



*It is possible that you may not be able to set the transformer primary voltage E_{pri} , indicated in the **Metering** window to 100 V because you have reached the voltage limit of the **Four-Quadrant Dynamometer/Power Supply**. If so, simply set the **Voltage** parameter to the highest possible value before proceeding to the next step.*

35. In the **Metering** window, measure the step-down transformer primary and secondary voltages. Record the values below.

Step-down transformer primary voltage E_{pri} = _____ V

Step-down transformer secondary voltage E_{sec} = _____ V

Using the step-down transformer primary and secondary voltages you just recorded, calculate the transformer voltage ratio.

Step-down transformer voltage ratio = _____

36. Is the step-down transformer voltage ratio you recorded in the previous step coherent with the transformer turns ratio you calculated in step 33?

Yes No

Considering the transformer primary and secondary voltages you recorded in the previous step, can you conclude that the transformer currently operates as a step-down transformer? Explain briefly.

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

On the **Wind Turbine Generator/Controller** module, connect all three 15 Ω load resistors in parallel. Then, connect the resulting 5 Ω resistive load to the circuit, as shown in Figure 9.

In the **Four-Quadrant Dynamometer/Power Supply** window, start the **AC Power Source**. Adjust the **Voltage** parameter so that the transformer primary voltage E_{pri} , indicated in the **Metering** window is as close as possible to 100 V.



It is possible that you may not be able to set the transformer primary voltage $E_{pri.}$ indicated in the Metering window to 100 V because you have reached the voltage limit of the Four-Quadrant Dynamometer/Power Supply. If so, simply set the Voltage parameter to the highest possible value before proceeding to the next step.

- 38.** In the Metering window, measure the step-down transformer primary and secondary currents. Record the values below.

Step-down transformer primary current $I_{pri.} = \underline{\hspace{2cm}}$ A

Step-down transformer secondary current $I_{sec.} = \underline{\hspace{2cm}}$ A

Using the step-down transformer primary and secondary currents you just recorded, calculate the transformer current ratio.

Step-down transformer current ratio = $\underline{\hspace{2cm}}$

- 39.** Is the step-down transformer current ratio you recorded in the previous step the inverse of the transformer voltage ratio you calculated in step 33 and the transformer voltage ratio you recorded in step 35?

Yes No

- 40.** In the Metering window, measure the step-down transformer apparent power $S_{pri.}$ at the primary and apparent power $S_{sec.}$ at the secondary. Record the apparent power values below.

Apparent power $S_{pri.}$ at the primary = $\underline{\hspace{2cm}}$ VA

Apparent power $S_{sec.}$ at the secondary = $\underline{\hspace{2cm}}$ VA

Is the apparent power $S_{sec.}$ at the secondary of the step-down transformer close to the apparent power $S_{pri.}$ at the primary?

Yes No

- 41.** From the observations you have made so far, can you conclude that power transformers are bidirectional devices? Explain briefly.

Can a single power transformer operate either as a step-up or a step-down transformer? Explain briefly.

- 42. In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **AC Power Source**.
- 43. 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 relationships between the turns, voltage, and current ratios of a power transformer are. You familiarized yourself with the different characteristics of step-up and step-down transformers. You also learned how to determine in practice the voltage and current ratios of a power transformer.

REVIEW QUESTIONS

- 1. A power transformer has 125 turns of wire in one of its windings, and 375 turns of wire in the other. What is the transformer turns ratio when it is used as a step-up transformer? What is the transformer turns ratio when it is used as a step-down transformer?

- 2. A step-up transformer connected to a resistive load has 300 turns of wire in the primary winding and 1000 turns of wire in the secondary winding. Determine the amount of current $I_{Sec.}$ flowing in the secondary winding of the transformer when a current $I_{Pri.}$ of 3 A flows in the primary winding.

3. Is it possible for a single power transformer to operate at one time as a step-up transformer and at another time as a step-down transformer? Explain why.

4. A step-down transformer has 480 turns of wire in the primary winding and 120 turns of wire in the secondary winding. Determine the voltage across the primary winding of the transformer when a voltage of 60 V is measured across the secondary winding of the transformer.

5. A voltage of 60 V is measured across the primary winding of a step-up transformer while a voltage of 300 V is measured across the secondary winding. Knowing that a current of 2.5 A flows in the primary winding of the transformer, calculate the current flowing in the secondary winding.

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 one end of two windings of a transformer are of the same polarity, it means that the polarity of the voltage at this end, with respect to the voltage at the other end of the winding, is the same for both windings, and thus, that the ac voltages across these windings are in phase. Conversely, when one end of two windings of a transformer are of opposite polarity, it means that the polarity of the voltage at this end for one winding is opposite 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 in schematic diagrams is to put a dot beside the ends of the transformer windings that have the same polarity. Figure 10 shows an example where dots have been used to mark the ends of the transformer windings that have the same polarity.

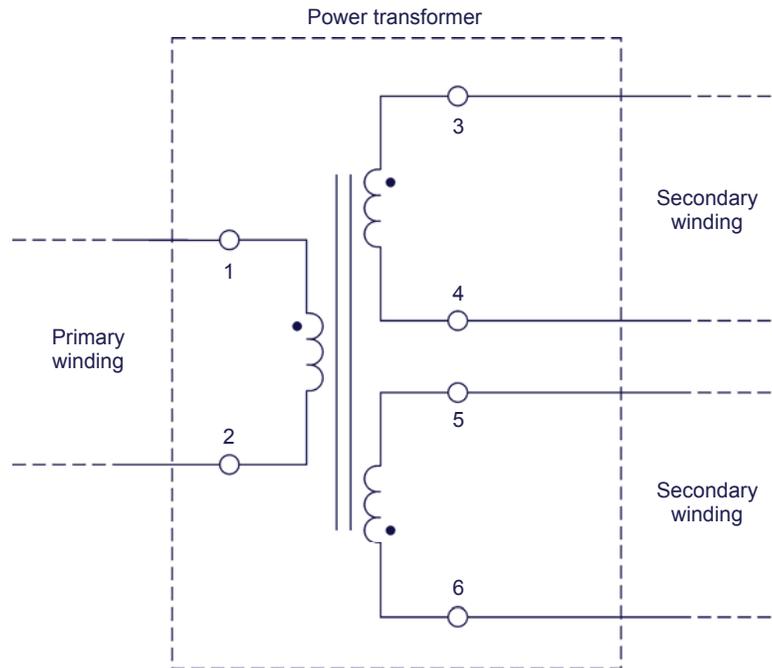


Figure 10. Example of the schematic diagram of a power transformer where dots mark the windings that have the same polarity.

In Figure 10, when the voltage at terminal 1 is positive with respect to (i.e., higher than) the voltage at terminal 2, then 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, then 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 is shown in Figure 11b.

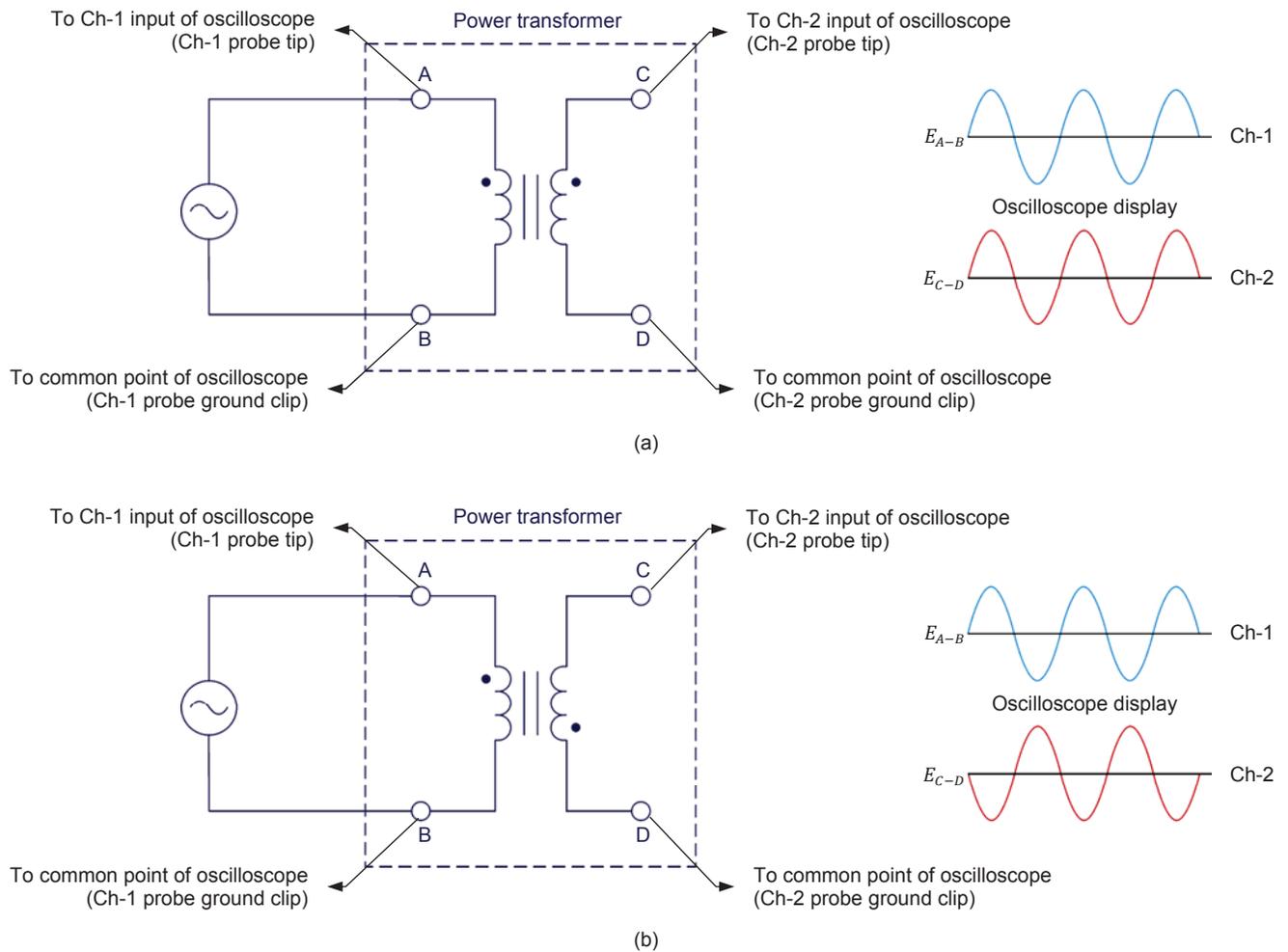


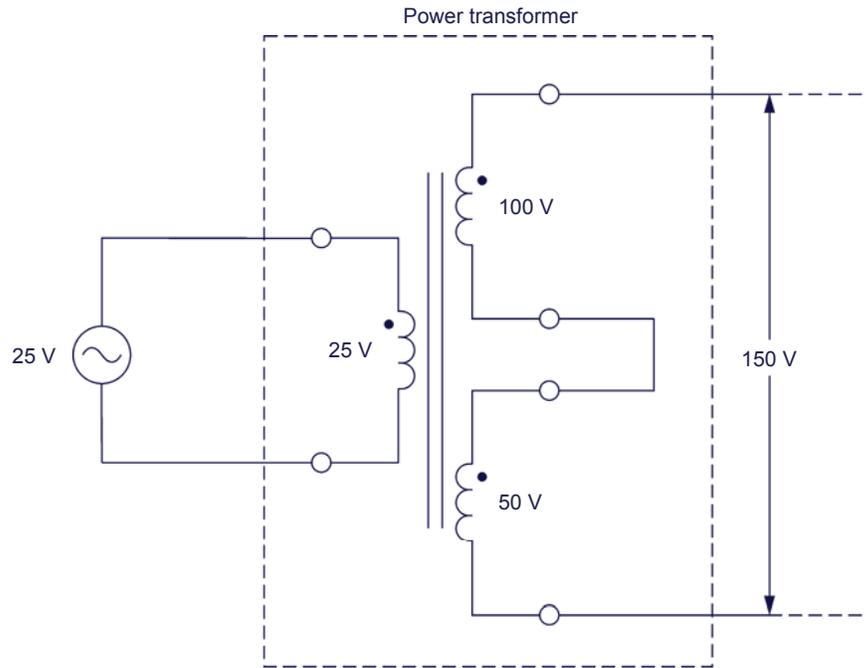
Figure 11. Determining the polarity of power transformer windings using an oscilloscope.

Series connection of transformer windings

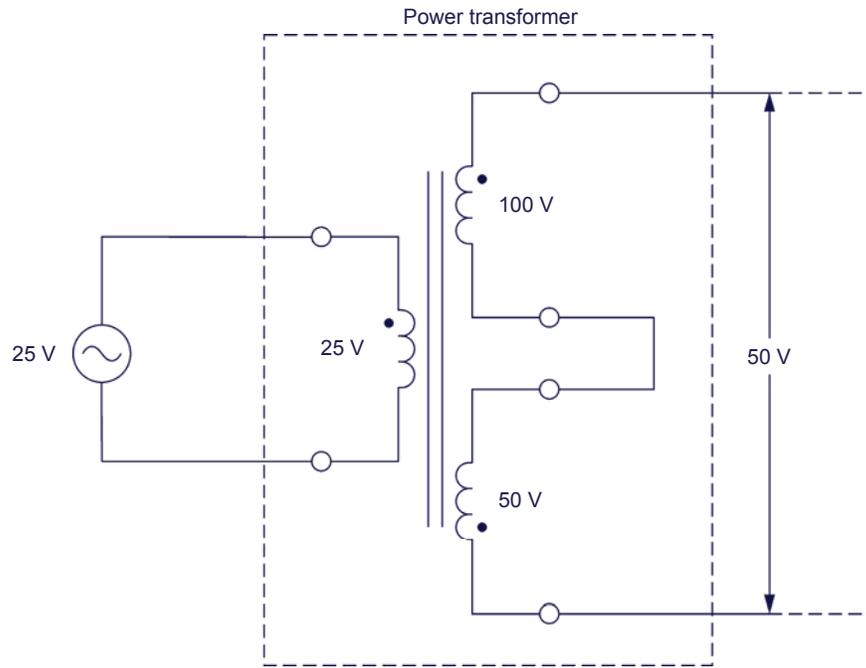
Two or more power transformer windings can be connected in series so that the total voltage across the windings is either the sum (series-aiding connection) or difference (series-opposing connection) of the voltages across the individual windings. As mentioned earlier, it is important to know the polarity 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. The secondary windings of the transformer being connected in series-aiding, the total voltage across the secondary windings is equal to 150 V (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). The secondary windings of the transformer being connected in series-opposing, the total voltage across the secondary windings is equal to 50 V ($100\text{ V} - 50\text{ V}$) 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 supply 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 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, 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 equals 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 the 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 measures 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 equals 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 the figure, the ac voltmeter measures 100 V across the series-connected windings, indicating that the transformer terminals connected together have the same polarity (i.e., the winding voltages subtract one from the other).

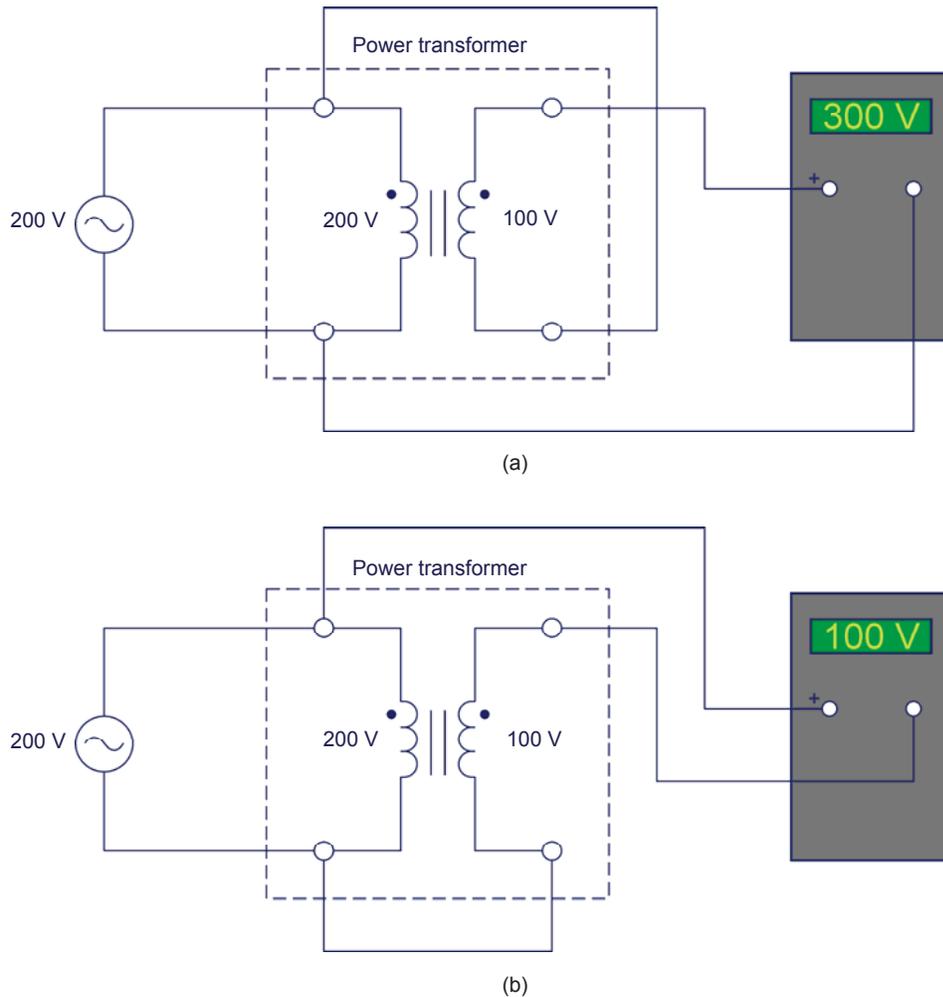


Figure 13. Determining the polarity of transformer windings using a voltmeter.

When a power transformer has other 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 and could 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.

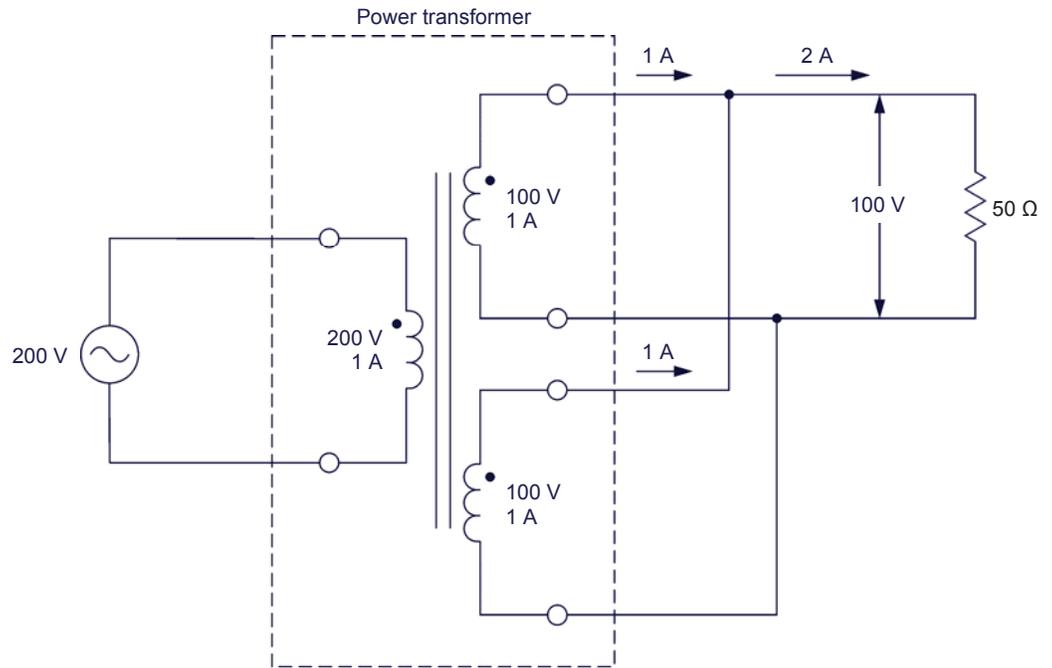


Figure 14. Power transformer whose secondary windings are connected in parallel.

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



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 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.

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

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

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

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

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

In the Module Selector 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 selected. Also, 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 Module Selector window.

6. 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: _____

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 measured across each transformer winding, and determine the polarity of each transformer terminal. You will then observe in the Phasor Analyzer the phasors of the voltage measured across each transformer winding, and confirm the results you 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 that is found.

7. Connect the equipment as shown in Figure 15.

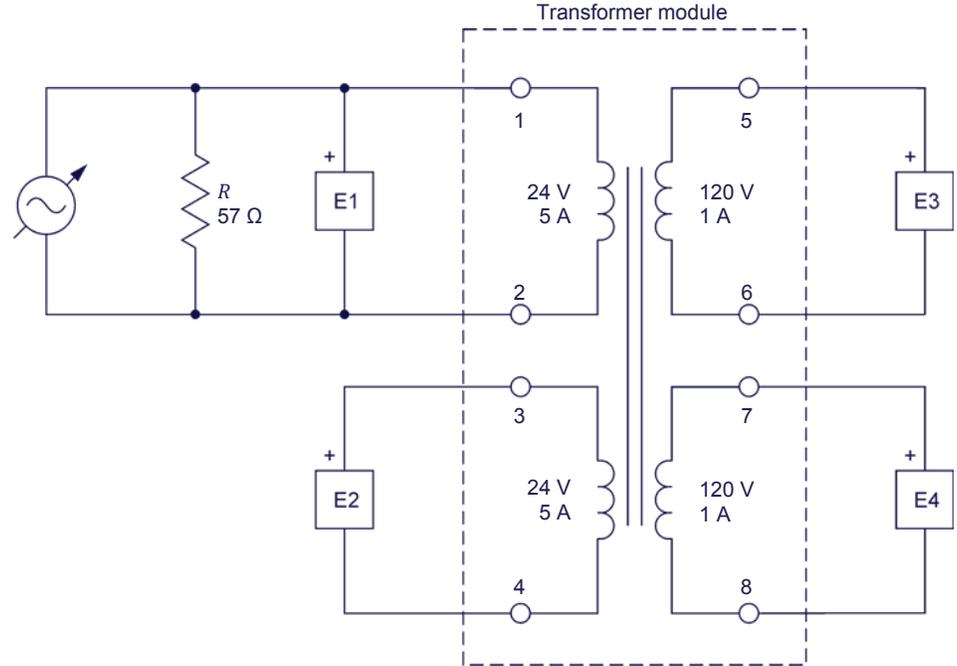


Figure 15. Circuit for determining transformer winding polarity using an oscilloscope.



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 to the ac power source, it has no effect on the measured voltages.

8. Make the necessary switch settings on the **Resistive Load** in order to obtain the resistance value required.
9. 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* parameter to 24 V.
 - Set the *Frequency* parameter to the frequency of your local ac power network.
 - Start the *AC Power Source*.
10. 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* parameter so that the rms value of the transformer voltage E_{1-2}

across 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., determine which ends of the windings have the same polarity.

Are the results you obtained consistent with the polarity markings indicated on the front panel of the [Transformer](#) module?

Yes No

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

- 11.** 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](#).

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

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

13. 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 measured voltages across the series windings with the calculated voltages.

14. Consider the three transformer connections shown in Figure 16.

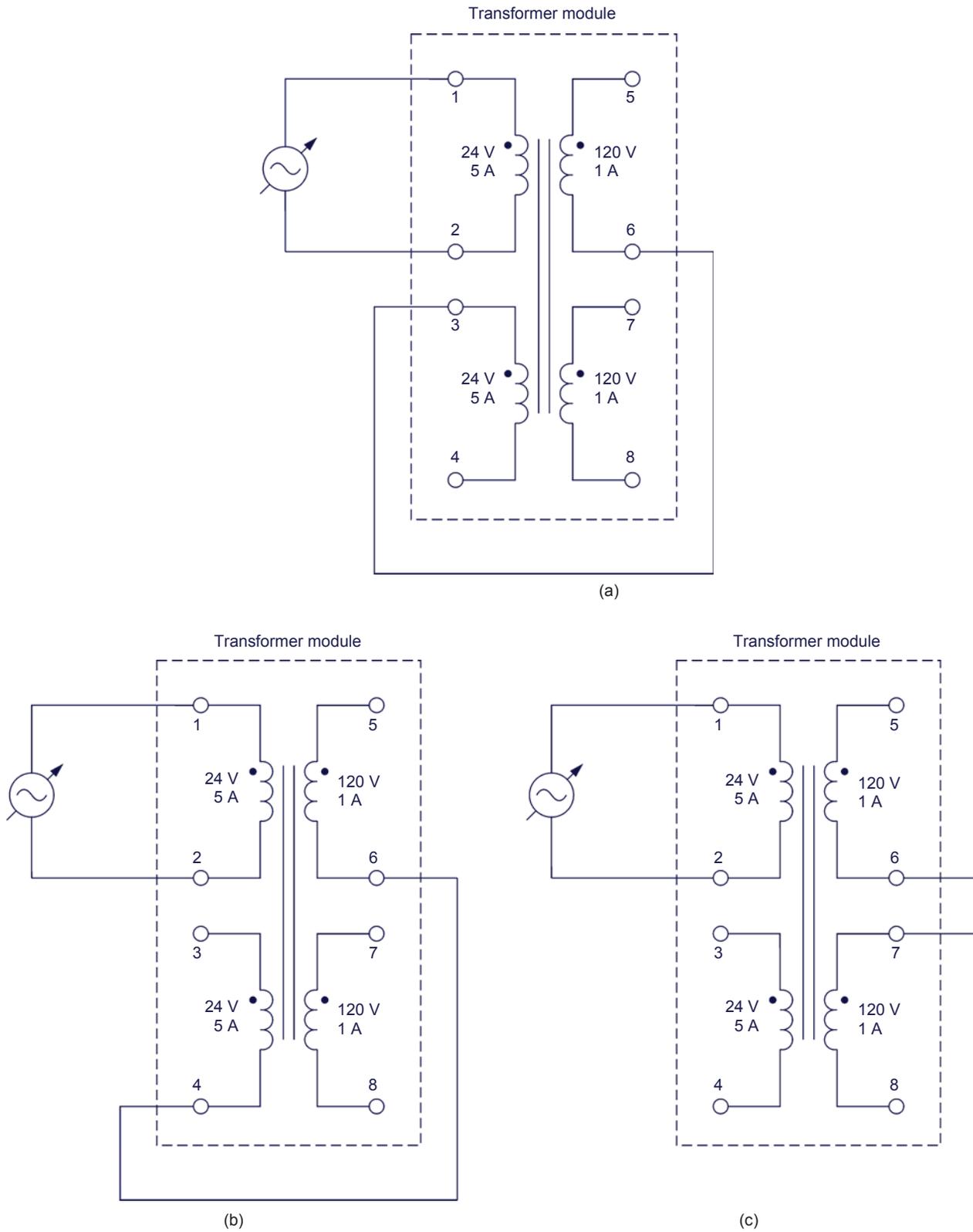


Figure 16. Different series connections of transformer windings.

In the 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

- 15.** Set up the series connection of windings shown in Figure 16a. Use input *E1* of the *DACI* 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 in order to measure the rms values (ac) of the transformer voltage E_{1-2} across winding 1-2 and of the voltage across the series-connected windings.

In the *Four-Quadrant Dynamometer/Power Supply* window, start the *AC Power Source*. Adjust the *Voltage* parameter so that the transformer voltage across 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*.

- 16.** Repeat step 15 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

Compare the voltages across the series windings you measured in this step and in the previous step to the voltages you calculated in step 14. Are the measured voltage values virtually equal to the calculated voltage values?

Yes No

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 start the ac power source and measure the voltages across the series-connected windings. Using the measured voltage, you will determine the polarity of the transformer windings. You will compare the winding polarities you obtained using this method with the winding polarities you determined previously 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.

17. 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).

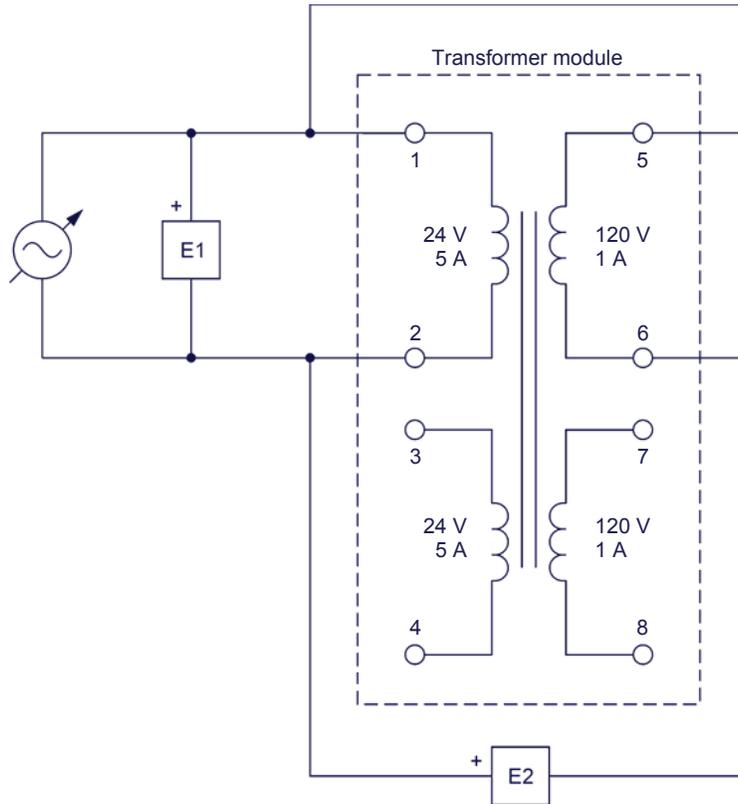


Figure 17. Circuit for determining transformer winding polarity using a voltmeter.

18. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **AC Power Source**. Adjust the **Voltage** parameter so that the transformer voltage across 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 windings 1-2 and 5-6 = _____ V

19. In the Four-Quadrant Dynamometer/Power Supply window, stop the AC Power Source.
20. Using the voltage across the series windings you measured in step 18, determine the polarity of winding 5-6 of the power transformer relative to that of winding 1-2 [i.e., determine which terminal (5 or 6) of winding 5-6 has the same polarity as terminal 1 of winding 1-2]. Explain briefly.

Are the results consistent with the polarity of the power transformer windings you determined in steps 6 and 10?

- Yes No

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

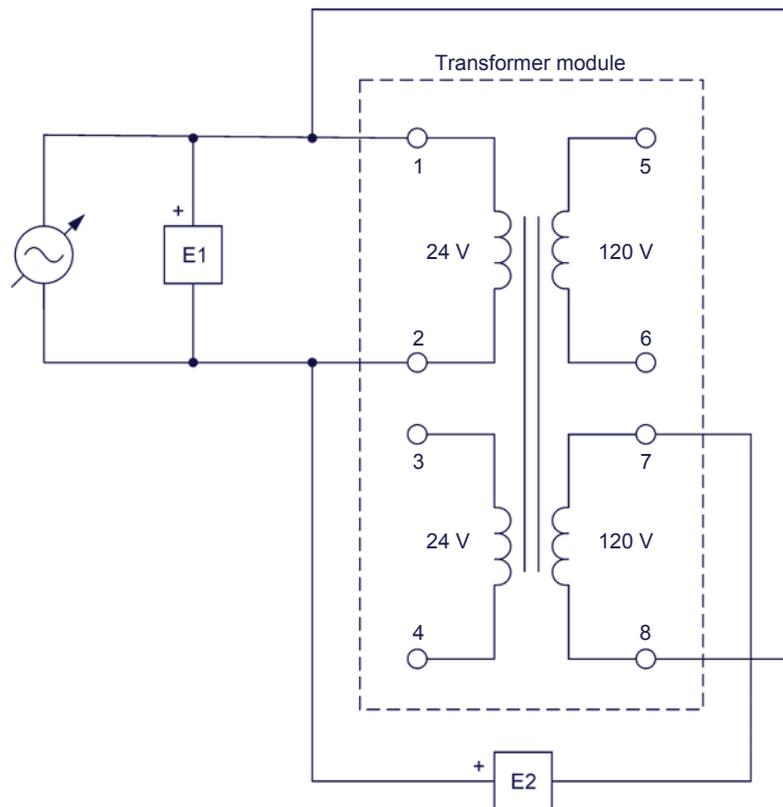


Figure 18. Circuit for determining transformer winding polarity using a voltmeter.

22. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **AC Power Source**. Adjust the **Voltage** parameter so that the transformer voltage across winding 1-2 indicated in the **Metering** window is as close as possible to 24 V.

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

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

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

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

Are the results consistent with the polarity of the power transformer windings determined in steps 6 and 10?

Yes No

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.

25. Connect the equipment as shown in Figure 19.

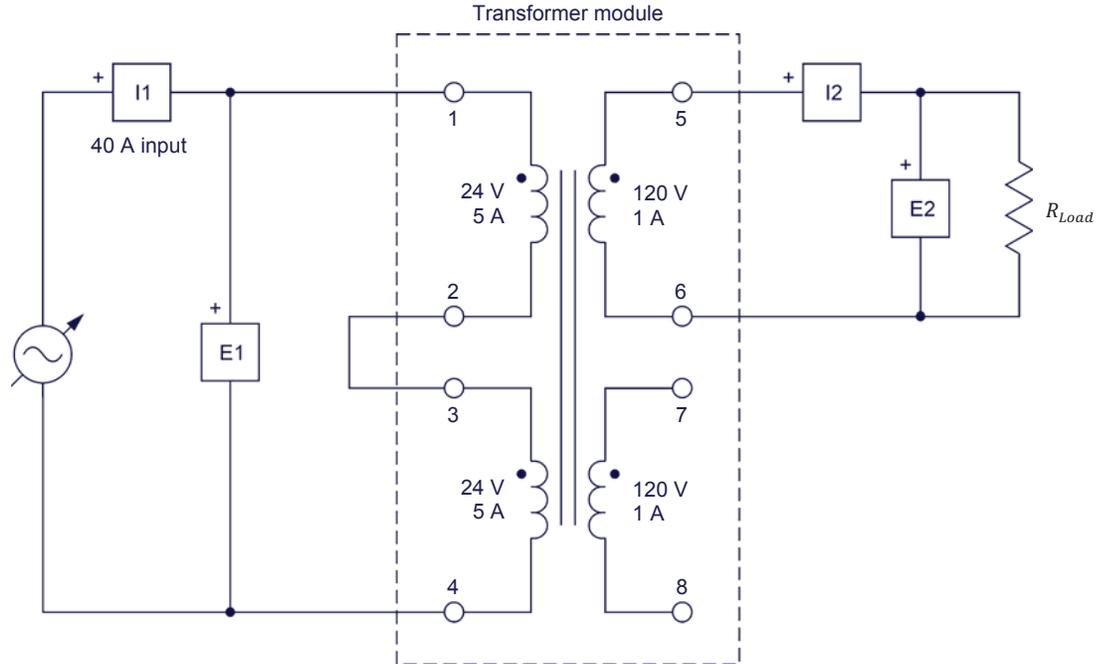


Figure 19. Step-up transformer connected to a resistive load.

In LVDAC-EMS, set the *Range* setting of current input *I1* to high.

26. Make the necessary switch settings on the *Resistive Load* so that the resistance value of the resistive load is infinite.

27. In the *Metering* window, make the required settings in order to measure the rms values (ac) 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 other 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.

28. In the *Four-Quadrant Dynamometer/Power Supply* window, set the *Voltage* parameter to 48 V, then start the *AC Power Source*. Readjust the *Voltage* 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, temporarily set the meter measuring the transformer primary current so that it displays dc current values. Then, in the *Four-Quadrant Dynamometer/Power Supply* window, adjust the *DC Offset Correction* parameter so that the dc current flowing in the transformer

primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it displays ac current values.

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

- 29.** On the **Resistive Load**, make the necessary switch settings in order to obtain a resistive load value R_{Load} of 120 Ω .

In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Voltage** 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.

$$E_{Pri.} = \underline{\hspace{2cm}} \text{ V}$$

$$E_{Sec.} = \underline{\hspace{2cm}} \text{ V}$$

$$I_{Pri.} = \underline{\hspace{2cm}} \text{ A}$$

$$I_{Sec.} = \underline{\hspace{2cm}} \text{ A}$$

$$S_{Pri.} = \underline{\hspace{2cm}} \text{ VA}$$

$$S_{Sec.} = \underline{\hspace{2cm}} \text{ VA}$$

- 30.** In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **AC Power Source**.
- 31.** Modify the connections in the circuit to obtain the circuit shown in Figure 20. Do not change the resistance 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.

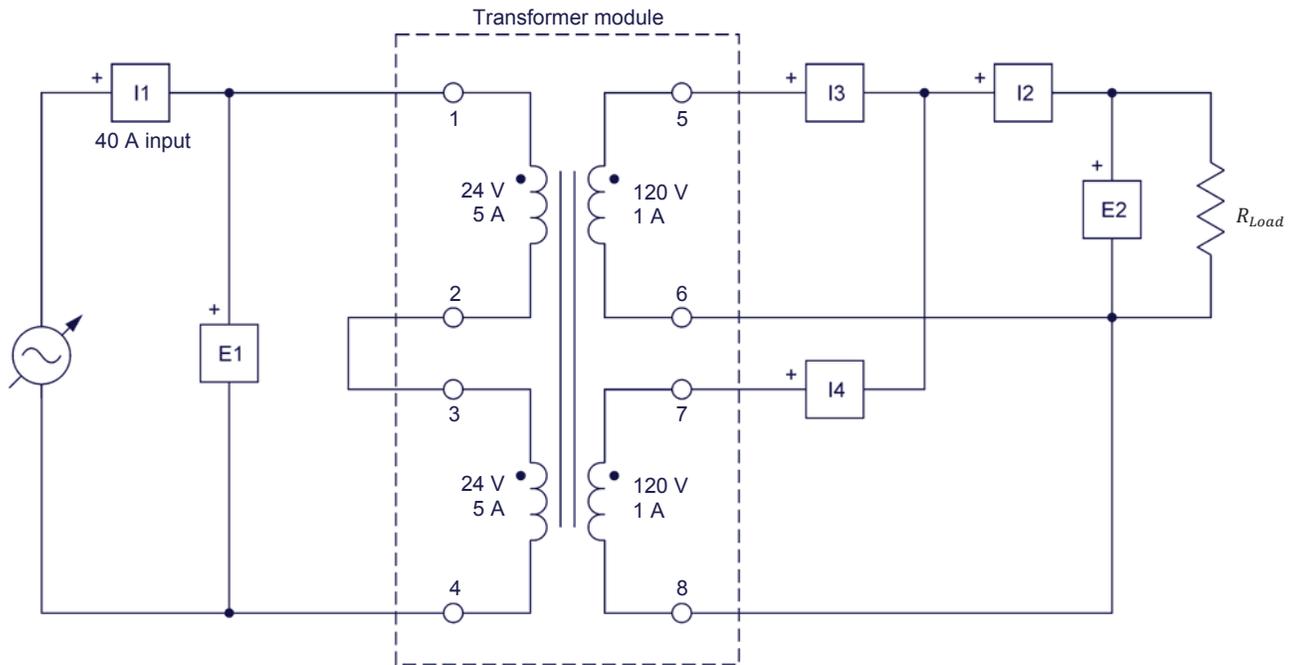


Figure 20. Step-up transformer with windings connected in parallel.

32. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **AC Power Source**. Adjust the **Voltage** 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 the values changed from the values you measured when the circuit windings were not connected in parallel?

Yes 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

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

In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Voltage** 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 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.

$$E_{Pri.} = \text{_____ V}$$

$$E_{Sec.} = \text{_____ V}$$

$$I_{Pri.} = \text{_____ A}$$

$$I_{Sec.} = \text{_____ A}$$

$$S_{Pri.} = \text{_____ VA}$$

$$S_{Sec.} = \text{_____ VA}$$

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

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

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

36. 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?

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. Knowing 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.

3. How is it possible to determine the polarity of each winding of a power transformer using an oscilloscope?

4. How is it possible to determine the polarity of two transformer windings using a voltmeter?

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

Transformer Losses, Efficiency, and Regulation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the equivalent circuit diagram of a power transformer. You will know what the copper and iron losses that occur in a power transformer are, as well as their causes. You will also know how efficient power transformers are, as well as how to calculate their efficiency. You will be introduced to the concept of voltage regulation in power transformers. You will know how to determine the voltage regulation of a power transformer.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Transformer losses
- Transformer efficiency
- Transformer voltage regulation

DISCUSSION

Transformer losses

In an ideal power transformer, there are no losses of energy. Consequently, the power transferred to a load by an ideal transformer is equal to the power that the ac power source delivers to the transformer. In other words, the power at the secondary winding of the transformer is equal to the power at the primary winding of the transformer.

Like all other electric devices, however, actual power transformers are not perfect, i.e., some energy is lost in the transformer during the voltage and current conversion process. In the case of actual power transformers, power is even lost when no load is connected to the transformer. The origin of the various losses in an actual power transformer can be explained by using the equivalent circuit of an actual transformer. The equivalent circuit of an actual power transformer is shown in Figure 21.

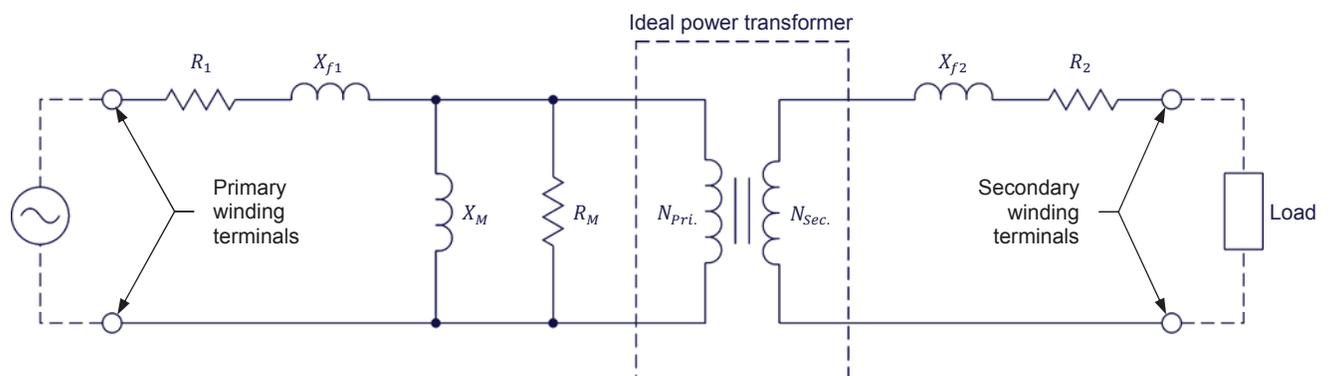


Figure 21. Equivalent circuit of an actual power transformer.

The equivalent circuit of an actual power transformer consists of an ideal transformer with a turns ratio $N_{pri.}/N_{sec.}$ plus several resistors and inductors connected in series and parallel with the primary and secondary windings of the ideal transformer. All these additional resistors and inductors represent the various imperfections of an actual transformer with respect to an ideal transformer. Resistors R_1 and R_M , inductors X_{f1} and X_M , and winding $N_{pri.}$ of the ideal transformer represent the equivalent circuit of the primary winding of an actual power transformer. Similarly, resistor R_2 , inductor X_{f2} , and winding $N_{sec.}$ of the ideal transformer represent the equivalent circuit of the secondary winding of an actual power transformer.

Resistor R_M represents the energy losses in the iron core of an actual power transformer. These losses, which are of two different natures, are referred to as the hysteresis losses and eddy-current losses. Since both the hysteresis losses and eddy-current losses occur in the iron core of an actual power transformer, they are referred to as the **iron losses**.

Resistor R_1 represents the resistance of the copper wire forming the primary winding of an actual power transformer. Similarly, resistor R_2 represents the resistance of the copper wire forming the secondary winding of an actual power transformer.

Inductors X_M and X_{f1} represent the inductive reactance at the primary winding of an actual power transformer. Similarly, inductor X_{f2} represents the inductive reactance at the secondary winding of an actual power transformer. Since these three inductors are considered ideal, they dissipate no power, and thus, cause no power losses in an actual power transformer.

Observing the equivalent circuit in Figure 21 reveals that current flows through the primary winding as soon as ac voltage is applied to the primary winding terminals of an actual power transformer, even with no load connected to the secondary winding. This current produces the magnetic field required for the operation of the transformer, and is commonly referred to as the **magnetizing current** or the **exciting current**. It is represented by the symbol I_o . The magnetizing current I_o flows through resistor R_1 while a fraction of this current flows through resistor R_M . Consequently, some power is dissipated as heat in these resistors. In other words, some power is lost as heat in an actual power transformer even with no load connected to the secondary winding. The power dissipated in resistor R_1 is included in the **copper losses** since this resistor represents the resistance of the copper wire making the primary winding. On the other hand, the power dissipated in resistor R_M is referred to as the iron losses since this resistor represents all the energy lost in the iron core of the transformer.

When a load is connected to the secondary winding of a power transformer, current flows in this winding. This current also flows through resistor R_2 in the equivalent circuit of an actual power transformer. Consequently, some power is dissipated as heat in this resistor. Furthermore, the current flowing through the secondary winding causes an increase in the current flowing through the primary winding. This increases the current flowing through resistor R_1 in the equivalent circuit of an actual power transformer and, thus, the power which this resistor dissipates. The power losses in resistors R_1 and R_2 are generally referred to as copper losses because these resistors represent the resistance of the copper wire that makes the transformer windings. The higher the load, the higher the

primary and secondary currents, and thus, the higher the copper losses in the transformer.

A certain amount of power is lost (a mix of iron losses and copper losses) in an actual power transformer even with no load connected to the secondary winding. The power losses in an actual power transformer increase when a load is connected to the secondary winding because the copper losses increase. Figure 22 shows the typical curve of the power losses in a low power transformer as a function of the load (secondary) current.

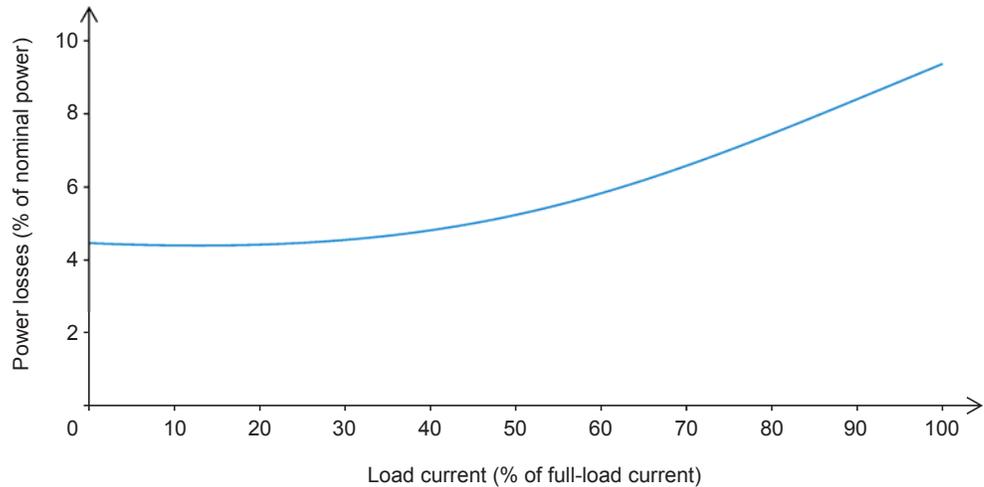


Figure 22. Typical curve of the power losses in a low-power transformer as a function of the load current.

Transformer efficiency

As mentioned in the previous section of this discussion, some power is lost in actual power transformers, the value of the power losses increasing as the load current increases. The **efficiency** of a power transformer is a measure of the ability of the transformer to transfer power from the ac power source to the load with minimal power losses. Transformer efficiency thus represents the amount (generally expressed as a percentage) of power from the ac power source that is actually delivered to the load.

The efficiency of power transformers is generally determined by measuring the power P_S that the ac power source delivers to the transformer and the power P_{Load} supplied by the transformer to a load when the load current is equal to the secondary winding nominal current (full-load current). The efficiency η of the power transformer can then be calculated using Equation (5). Note that load power P_{Load} and source power P_S are sometimes referred to as output power P_{Out} and input power P_{In} .

$$\eta = \frac{P_{Load}}{P_S} \times 100\% \quad (5)$$

where η is the efficiency of the transformer, expressed in percentage (%).
 P_{Load} is the amount of active power delivered to the load by the transformer, expressed in watts (W).
 P_S is the amount of active power supplied to the transformer by the ac power source, expressed in watts (W).

The difference in percentage between the transformer efficiency and 100% represents the different power losses occurring in the transformer. For instance, when the efficiency η of a power transformer is 96%, the power losses in the transformer correspond to 4% of the power the ac source delivers to the transformer.

Since the power losses in a power transformer vary with the load current, the efficiency of the transformer also varies with the load current. Transformer efficiency is generally determined using power measurements made when the nominal current (full-load current) flows in the secondary winding, as mentioned previously in this discussion. However, it is common practice to determine the efficiency of a power transformer at various percentage values of the nominal current (full-load current) to provide information about the variation of the transformer efficiency with the load. Figure 23 shows the typical curve of the efficiency of a low-power transformer as a function of the load current.

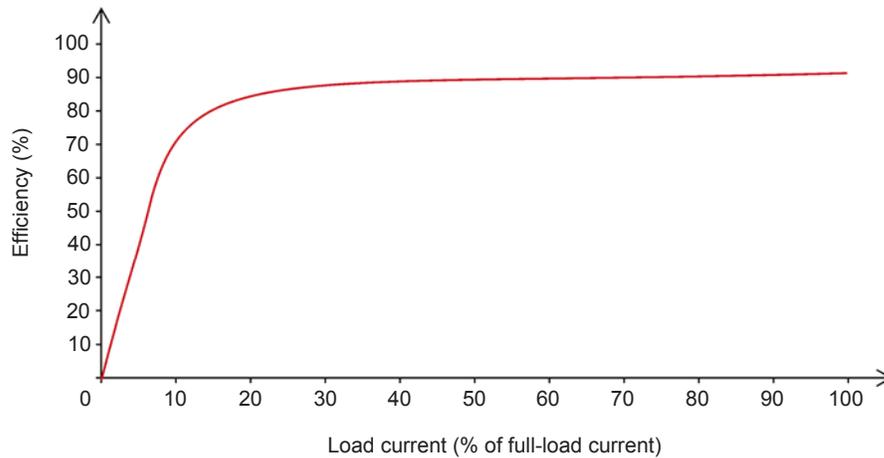


Figure 23. Typical curve of the efficiency of a low-power transformer as a function of the load current.

The efficiency of power transformers operating at full load is generally at least 90% for small units, above 98% for medium-sized units (e.g., transformers used for energy distribution), and close to 100% for large units (transformers with power ratings expressed in MVA).

Transformer voltage regulation

In an actual power transformer (such as the one whose equivalent circuit is shown in Figure 21), the higher the load, the more the load (secondary) current increases and the higher the voltage drops that occur across resistors R_1 and R_2 . Consequently, the higher the load, the more the load (secondary) voltage decreases. This is illustrated in Figure 24, which shows the graph of the voltage across a resistive load as the load current increases. The curve in this graph is commonly referred to as the transformer **voltage regulation** curve.

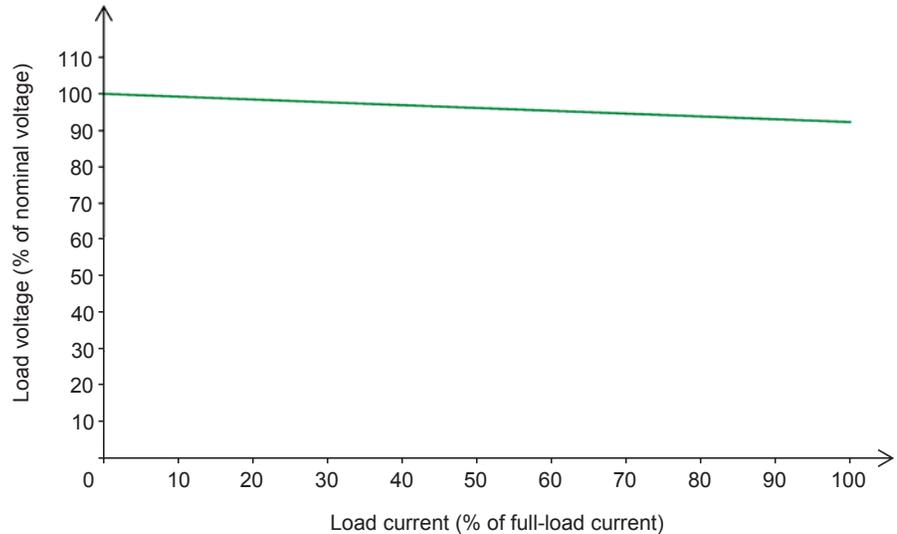


Figure 24. Typical voltage regulation curve of a low-power transformer.

There are two ways to define the voltage regulation of a power transformer: regulation down and regulation up. Regulation down indicates the extent of the variation in the load (secondary) voltage of the power transformer as the load current increases. Regulation up, on the other hand, indicates the extent of the variation in the load (secondary) voltage of the power transformer when the load is lost. In the case of power transformers, regulation down is more commonly used as it expresses the ability of a power transformer to maintain the load (secondary) voltage constant as the load current increases. The better the voltage regulation down of a transformer, the less the load (secondary) voltage decreases as the load current increases.

The voltage regulation down of a power transformer can be calculated using Equation (6). As the equation shows, the lower the value of the voltage regulation down of a power transformer, the better the regulation, i.e., the lower the decrease in load (secondary) voltage as the load current increases.

$$\text{Voltage regulation down (\%)} = \frac{E_{NL} - E_{FL}}{E_{NL}} \times 100\% \quad (6)$$

where E_{NL} is the no-load voltage across the secondary winding of the transformer, expressed in volts (V).

E_{FL} is the full-load voltage across the secondary winding of the transformer, expressed in volts (V).

As the load on power transformers used for electrical energy transmission and distribution generally varies greatly depending on the time of the day, it is necessary that these transformers have good voltage regulation down (i.e., a value as low as possible) in order to minimize the voltage fluctuations occurring during the day. This is important since many electrical devices (e.g., motors, incandescent lamps, etc.) are quite sensitive to voltage variation.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Transformer no-load operation
- Transformer power losses, efficiency, and voltage regulation

PROCEDURE



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 section, you will set up a circuit containing a power transformer connected to a resistive load. You will then set the measuring equipment required to study the transformer power losses, efficiency, and voltage regulation.

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

Record below the serial number of the **Transformer** module, Model 8353, that you are using.

Serial number: _____

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.

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

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

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

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

In the **Module Selector** 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 selected. Also, 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 **Module Selector** window.

6. Connect the equipment as shown in Figure 25.

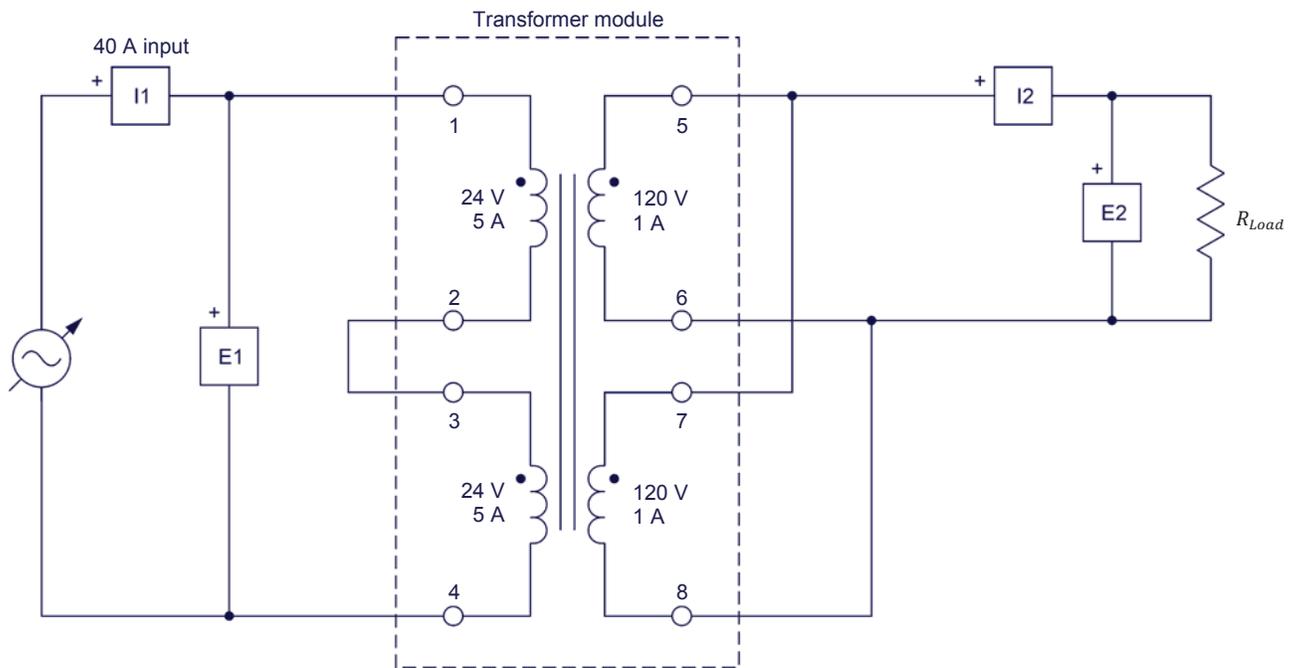


Figure 25. Transformer circuit used for studying transformer losses, efficiency, and voltage regulation.

In **LVDAC-EMS**, set the **Range** setting of current input **I1** to high.

7. Make the necessary switch settings on the **Resistive Load** so that the resistance value of the resistive load is infinite.

8. 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* parameter to 48 V.
 - Set the *Frequency* parameter to 50 Hz.



Most power transformers are generally designed to operate at frequencies of 50 Hz and 60 Hz. Because transformer design requirements are more stringent at 50 Hz, most transformer designs are based on operation at 50 Hz, hence the setting of the ac power source frequency to 50 Hz.

9. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms values (ac) of the transformer primary voltage E_{pri} and current I_{pri} (inputs *E1* and *I1*, respectively), as well as the secondary voltage E_{sec} and current I_{sec} (inputs *E2* and *I2*, respectively). Set two other meters to measure the primary active power P_{pri} from inputs *E1* and *I1*, as well as the secondary active power P_{sec} from inputs *E2* and *I2*.

Transformer no-load operation

In this section, you will start the ac power source. You will measure the current and active power at the transformer primary during no-load operation, and explain why they are not equal to zero.

10. In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source*. Adjust the *Voltage* 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, temporarily set the meter measuring the transformer primary current so that it displays dc current values. Then, in the Four-Quadrant Dynamometer/Power Supply window, adjust the *DC Offset Correction* parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. When this is done, set the meter measuring the transformer primary current so that it displays ac current values.

11. In the Metering window, measure the power transformer primary (source) current I_{pri} . Record the value below.

Primary current I_{pri} = _____ A

Explain why the primary current I_{pri} is not zero during no-load operation.

12. In the **Metering** window, measure the active power $P_{Pri.}$ supplied to the primary winding of the power transformer. Record the value below.

Primary active power $P_{Pri.} =$ _____ W

Explain why the active power $P_{Pri.}$ at the primary is not zero despite the fact that no power is supplied to the load.

Transformer power losses, efficiency, and voltage regulation

In this section, you will decrease the resistance of the load connected to the secondary so that the secondary current increases to 2.0 A (nominal full-load current) by steps of about 0.2 A. For each step, you will record in the Data Table the transformer primary voltage, current, and active power, as well as the secondary voltage, current, and active power. You will export the data to a spreadsheet, and calculate the transformer power losses and efficiency using the recorded transformer parameters. You will plot a graph of the transformer power losses as a function of the secondary current, and analyze the results. You will also plot a graph of the transformer efficiency as a function of the secondary current, and analyze the results. Finally, you will plot the transformer voltage regulation curve (i.e., a graph of the transformer secondary voltage as a function of the secondary current), and analyze the results.

13. In LVDAC-EMS, open the **Data Table** window.

Set the **Data Table** to record the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$, and active power $P_{Pri.}$, as well as the secondary voltage $E_{Sec.}$, current $I_{Sec.}$, and active power $P_{Sec.}$ indicated in the **Metering** window.

14. In the **Data Table**, click on the **Record Data** button to record the current values (i.e., the no-load values) of the power transformer parameters.

15. On the **Resistive Load**, decrease the load resistance R_{Load} so that the secondary (load) current $I_{Sec.}$ increases to 2.0 A (nominal secondary current or full-load current of the transformer) by steps of about 0.2 A. For each step, adjust the **Voltage** parameter in the **Four-Quadrant Dynamometer/Power Supply** window so that the primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 48 V, then record the transformer parameters in the **Data Table**.

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

17. In the **Data Table** window, save the recorded data, then export it to a spreadsheet application.

In the spreadsheet application, add a new parameter to the results: the transformer power losses P_{Losses} . To calculate the transformer power losses P_{Losses} , subtract the secondary active power $P_{Sec.}$ (i.e., the active power delivered to the load by the transformer) from the primary active power $P_{Pri.}$ (i.e., the active power supplied to the transformer by the ac power source).

Also add another parameter to the results: the transformer efficiency η . To calculate the transformer efficiency η , divide the transformer secondary active power $P_{Sec.}$ by the primary active power $P_{Pri.}$, then multiply the result by 100 to express the efficiency η as a percentage.

- 18.** Plot a graph of the transformer power losses P_{Losses} as a function of the secondary (load) current $I_{Sec.}$.

Observe the graph. Describe the relationship between the transformer power losses P_{Losses} and the transformer secondary (load) current $I_{Sec.}$. Explain briefly why.

- 19.** Plot a graph of the transformer efficiency η as a function of the secondary (load) current $I_{Sec.}$.

Observe the graph. What happens to the transformer efficiency η at low values of secondary (load) current $I_{Sec.}$? Explain briefly why.

Are power transformers high-efficiency devices? Explain briefly.

- 20.** Plot the transformer voltage regulation curve, i.e., plot a graph of the transformer secondary (load) voltage $E_{Sec.}$ as a function of the secondary (load) current $I_{Sec.}$.

Observe the graph. Describe the relationship between the transformer secondary (load) voltage $E_{Sec.}$ and the secondary (load) current $I_{Sec.}$. Explain briefly why.

- 21.** Calculate the voltage regulation down of the power transformer using the values you recorded in this section.

Voltage regulation down = _____ %

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

CONCLUSION

In this exercise, you familiarized yourself with the equivalent circuit diagram of a power transformer. You learned what the copper and iron losses occurring in a power transformer are, as well as their causes. You also learned how efficient power transformers are, and how to calculate their efficiency. You were introduced to the concept of voltage regulation in power transformers. You learned how to determine the voltage regulation of a power transformer.

REVIEW QUESTIONS

1. What is the magnetizing current of a power transformer? Explain briefly.

2. What is the difference between copper losses and iron losses in a power transformer?

3. What is the relationship between the power losses and the load current of a power transformer? Explain briefly.

4. Are power transformers ideal devices, i.e., is their efficiency equal to 100%? Explain briefly.

5. Explain what the voltage regulation down of a power transformer is.

Transformer Rating

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the voltage, current, and power ratings of a power transformer, and know how they can be determined. You will also know the effects of saturation on the magnetizing current and no-load power losses of a power transformer.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

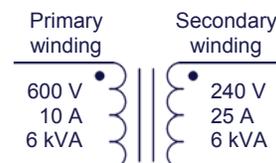
- Transformer rating
- Determining the current rating of a transformer winding
- Transformer saturation
- Determining the voltage rating of a transformer winding

DISCUSSION

Transformer rating

Each winding of a power transformer has a voltage rating and a current rating. The product of the voltage rating and current rating of a winding, which is sometimes referred to as the volt-ampere (VA) product, determines the power rating of the winding.

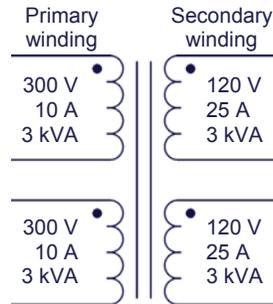
Since power transformers are high efficiency devices, the power rating of the secondary winding is generally considered equal to that of the primary winding. The power rating of a power transformer is thus the same as the power rating of the primary winding and secondary winding. This is shown in Figure 26.



Transformer power rating = 6 kVA

Figure 26. Power rating of a power transformer with a single primary winding and a single secondary winding.

When a power transformer has multiple primary windings and multiple secondary windings, the power rating of the transformer is equal to the sum of the power ratings of the primary windings (this sum is equal to the sum of the power ratings of the secondary windings). Figure 27 shows an example of a transformer having two primary windings and two secondary windings.



Transformer power rating = 6 kVA

Figure 27. Power rating of a power transformer with more than one primary winding and more than one secondary winding.

Determining the current rating of a transformer winding

The current rating of any winding in a power transformer mainly depends on the size (gauge) of the copper wire used to make the winding. The relationship between the current rating of a transformer winding and the size of the wires in the winding is direct: the larger the wire, the higher the current rating of the winding. This is due to the fact that the larger the wire size used to make a winding, the lower the wire resistance and, thus, the lower the copper losses, i.e., the lower the power dissipated as heat due to the current flowing in the winding.

The current rating of any transformer winding is set to a value that results in copper losses producing an acceptable warming of the transformer core and windings, and thus, an operating temperature that ensures maximum service life of the wire insulation (and, thus, of the power transformer).

The wire insulation used in transformer windings consists of a thin coat of varnish. This varnish dries when it is subjected to heating over a long period of time, and this may cause cracks to appear in the coat of varnish. This may ultimately lead to a short-circuit in a winding and prevent normal operation of the power transformer. Since the deterioration of the wire insulation varnish is faster at high operating temperatures, the current rating of any winding of a power transformer must be carefully determined to prevent excessive operating temperatures.

Transformer saturation

The magnetic properties of the material used to build the core of a power transformer are best described by the saturation curve of the material. The saturation curve of any magnetic material is a plot of the flux density B as a function of the magnetic field intensity H . Figure 28 shows the typical saturation curve of an iron-core power transformer (most power transformers have an iron core).

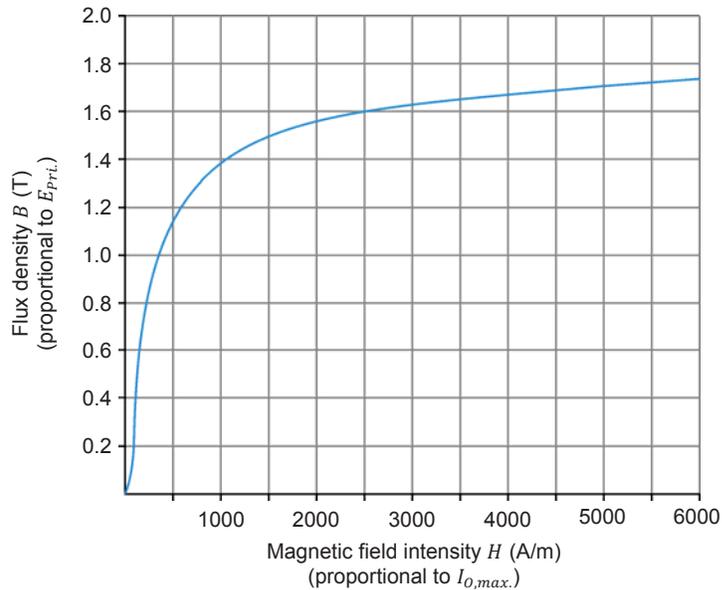


Figure 28. Typical saturation curve of an iron-core power transformer.

As you can see from the figure, the flux density B in the iron core increases rapidly when the intensity H of the magnetic field in the transformer increases. However, when the flux density B reaches about 1.2 T (the letter T is the symbol for teslas, the unit of measurement of flux density), it starts to increase less and less as the magnetic field intensity H continues to increase. This phenomenon is called saturation, hence the name of the curve shown above.

At a given frequency of the ac power source, the maximum value of the flux density $B_{Max.}$ in the iron core of the power transformer is directly proportional to the rms value of the voltage $E_{pri.}$ applied to the winding (usually the primary winding). Also, the maximum value of the magnetizing current $I_{O,max.}$ is directly proportional to the magnetic field intensity H . When voltage is applied to a transformer winding, a magnetizing current I_O flows in the winding, and a magnetic field appears in the transformer core. The values of the resulting flux density B and magnetic field intensity H , and thus the peak value of the winding current (peak value of the magnetizing current $I_{O,max.}$), all depend on the rms value of the voltage applied to the winding.

As long as the voltage applied to the transformer winding results in a maximum flux density $B_{Max.}$ of about 1.2 T or less (see saturation curve above), there is virtually no saturation and the magnetic field intensity H remains relatively low. Consequently, the peak value of the magnetizing current $I_{O,max.}$ is also fairly low. However, when the voltage applied to the transformer winding increases in such a way as to cause the maximum flux density to significantly exceed 1.2 T (this corresponds to values of $B_{Max.}$ higher than about 1.5 T), significant saturation starts to occur in the transformer. Consequently, both the magnetic field intensity H and the peak value of the magnetizing current $I_{O,max.}$ increase sharply.

Figure 29a shows the waveforms of the primary voltage $E_{pri.}$ and of the magnetizing current I_O of a power transformer when the transformer core is not saturated. Figure 29b shows the same waveforms when the transformer core is

saturated. Both figures also show the maximum operating point on the transformer saturation curve.

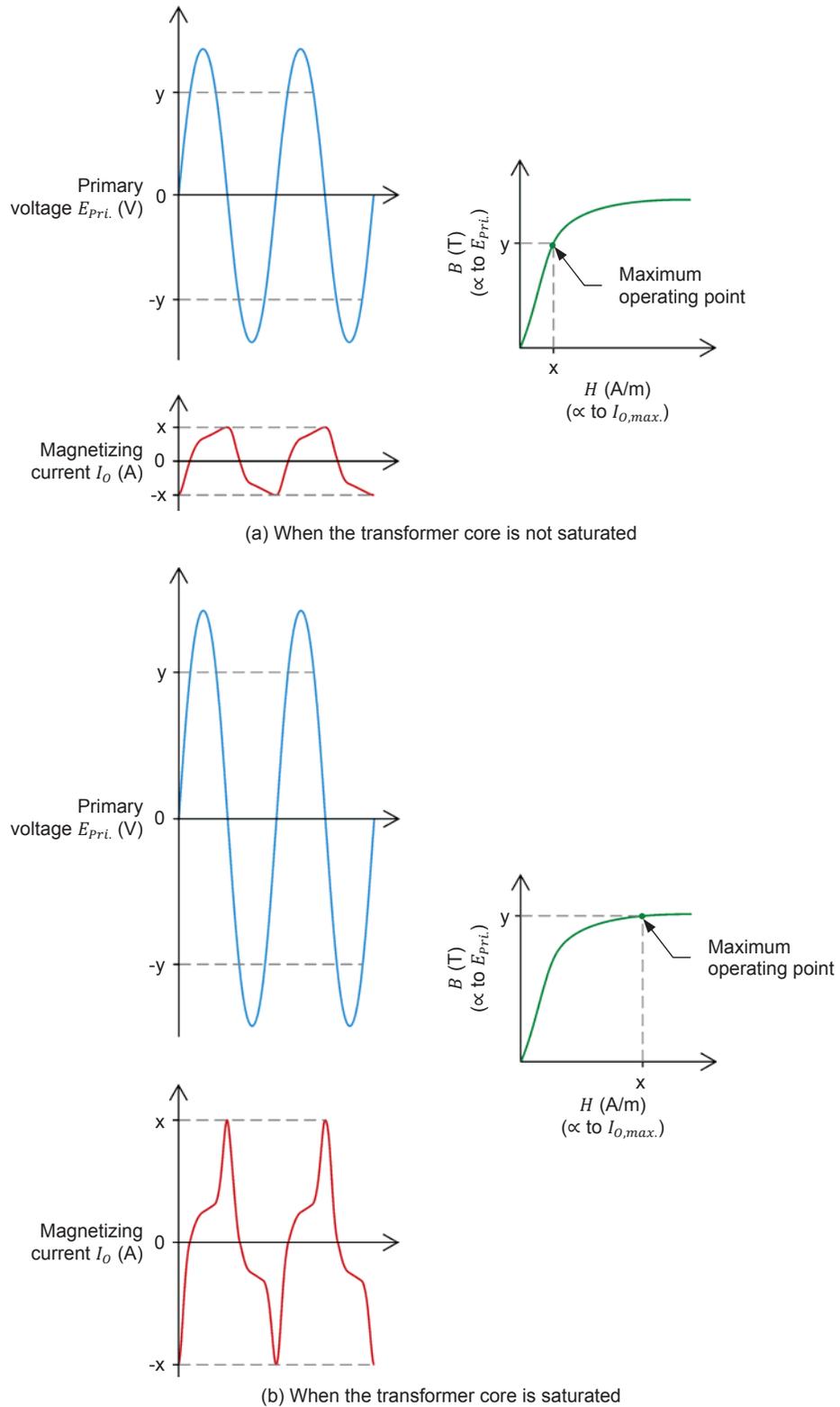


Figure 29. Waveforms of a power transformer primary voltage $E_{Pri.}$ and magnetizing current I_o , as well as the transformer maximum operating point on the saturation curve.

As you can see in Figure 29, the waveform of the magnetizing current I_o is distorted whether the transformer is saturated or not. Therefore, the magnetizing current I_o always contains some **harmonics**. However, as shown in Figure 29b, saturation causes large spikes to appear in the waveform of the magnetizing current. In other words, saturation significantly increases the harmonic content in the magnetizing current of a power transformer. The large spikes appearing in the magnetizing current waveform when saturation occurs also increase the rms value of the magnetizing current and, thus, increase the no-load power losses in the power transformer.

Since the magnetizing current I_o is provided by the ac power source, harmonics are produced in the ac power network when saturation occurs in a power transformer. Harmonics are highly undesirable in any ac power network because they can affect the operation of other equipment connected to the network. Also, harmonics decrease the power factor of the network, and thus, its efficiency. For more information about harmonics, refer to Appendix D at the end of this manual.

To summarize, saturation of the transformer core results in an increase in the rms value of the magnetizing current I_o , which leads to the following two undesirable effects:

1. An increase in the no-load power losses in the transformer that reduces the transformer efficiency.
2. An increase in the harmonic content of the primary current (i.e., the sum of the magnetizing current and the current due to the load connected to the transformer secondary).

Determining the voltage rating of a transformer winding

Due to its undesirable effects on transformer operation, saturation of the iron core in a power transformer is the main factor that determines the nominal voltage (or voltage rating) of transformer windings. The amount of saturation accepted in a power transformer is the result of a design trade-off that depends on the application requirements. For instance, when high efficiency is crucial, the nominal voltage is generally set to a rather conservative value so that the maximum flux density B_{Max} is 1.2 T or less. This results in little or no saturation (see saturation curve in Figure 28). This minimizes the rms value of the magnetizing current I_o and the resulting no-load power losses and thus, provides maximal transformer efficiency. Furthermore, this minimizes the harmonic content in the primary current. However, this choice also limits the power rating of the transformer since a conservative winding voltage rating is used. Therefore, for a given power rating, this results in a larger and heavier transformer.

On the other hand, if transformer size and weight must be minimized, then a maximal power rating is desirable. Consequently, the nominal voltage is set to the maximum value producing acceptable transformer saturation. This generally corresponds to a voltage resulting in a maximum flux density B_{Max} of about 1.6 T (see saturation curve in Figure 28). This, however, significantly increases the rms value of the magnetizing current I_o . Consequently, the no-load power losses increase, thereby resulting in a lower transformer efficiency (especially at low load currents). Also, the harmonic content in the primary current is increased because the transformer core is severely saturated.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Transformer saturation
- Saturation curve of a power transformer
- Voltage rating of transformer windings and transformer power rating
- Effect of transformer nominal voltage on the power losses and efficiency
- Transformer operating temperature

PROCEDURE



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 section, you will observe the current ratings of the transformer windings indicated on the front panel of the Transformer module, Model 8353, and record their value. You will observe the power transformer in the Transformer module and identify which terminals correspond to the transformer primary windings and which terminals correspond to the transformer secondary windings. You will set up a circuit containing a step-up power transformer without load. You will then set the measuring equipment required to study the transformer voltage, current, and power ratings, as well as the transformer saturation curve.

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](#).



Make sure you use the same Transformer module, Model 8353, as in Exercise 3 of this manual by confirming that the module's serial number is the same as the serial number you recorded in the first step of Exercise 3.

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.

Connect the *Power Input* of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

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

In the **Module Selector** 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 selected. Also, 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 **Module Selector** window.

6. Observe the current ratings indicated on the front panel of the **Transformer** module. Record below the current ratings of the transformer primary and secondary windings.

Current rating of each of the two primary windings = _____ A

Current rating of each of the two secondary windings = _____ A

7. Observe the power transformer in the **Transformer** module. Determine which terminals of the power transformer are used for the primary windings and which terminals are used for the secondary windings. Explain your reasoning by using the transformer current ratings you recorded in the previous step.



The two terminals of the power transformer with the thinnest wires are used for the thermistor in the transformer. Do not take these terminals into account while answering this question.

8. Connect the equipment as shown in Figure 30. In this circuit, the two 24 V primary windings of the Transformer module are connected in series to form a primary winding rated 48 V and 5 A. Also, the two 120 V secondary windings are connected in parallel to form a secondary winding rated 120 V and 2 A.

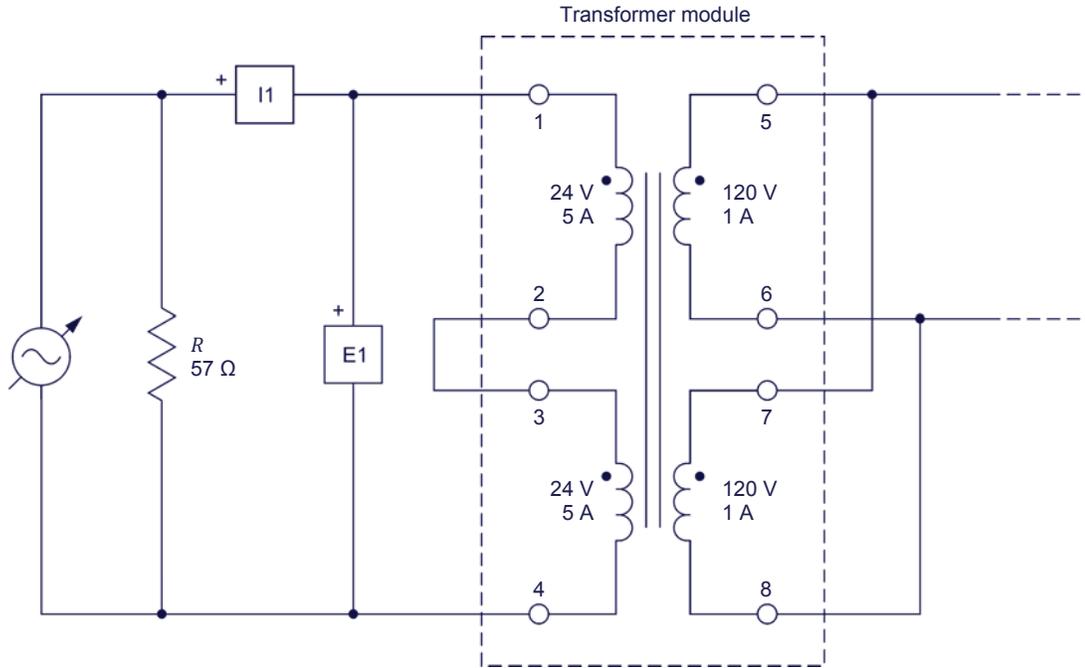


Figure 30. Step-up transformer operating without load.



The resistive load in the circuit of Figure 30 is used to improve the appearance of the voltage waveforms. As the resistive load is connected in parallel to the ac power source, it has no effect on the measured voltages.

9. 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* parameter to 28 V.
 - Set the *Frequency* parameter to 50 Hz.



Most power transformers are generally designed to operate at frequencies of 50 Hz and 60 Hz. Because transformer design requirements are more stringent at 50 Hz, most transformer designs are based on operation at 50 Hz, hence the setting of the ac power source frequency to 50 Hz.

10. In LVDAC-EMS, open the Metering window. Make the required settings in order to measure the rms values (ac) of the transformer primary voltage E_{Pri} and current I_{Pri} (inputs *E1* and *I1*, respectively). Set another meter to measure the primary active power P_{Pri} from inputs *E1* and *I1*.

Transformer saturation

In this section, you will measure the transformer primary voltage, current, and active power when the transformer is not saturated, and analyze the results. You will use the Oscilloscope to observe the waveform of the transformer magnetizing current. You will measure the total harmonic distortion (THD) of the magnetizing current using the Harmonic Analyzer. You will then increase the transformer primary voltage to 56 V and observe what happens to the waveform of the magnetizing current displayed on the Oscilloscope. You will measure the transformer primary voltage, current, and active power when the transformer is saturated, and compare the results with those obtained when the transformer is not saturated. You will measure the THD of the magnetizing current using the Harmonic Analyzer, and compare the result with the THD value you measured when the transformer is not saturated.

11. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **AC Power Source**. Adjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 28 V.

In the **Metering** window, temporarily set the meter measuring the transformer primary current so that it indicates dc current values. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **DC Offset Correction** parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it indicates ac current values.

12. In the **Metering** window, measure the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$, and active power $P_{Pri.}$. Record the values below.

Primary voltage $E_{Pri.} = \underline{\hspace{2cm}}$ V

Primary current $I_{Pri.} = \underline{\hspace{2cm}}$ A

Primary active power $P_{Pri.} = \underline{\hspace{2cm}}$ W

13. What conclusion can you draw regarding the transformer primary voltage $E_{Pri.}$ you recorded in the previous step in relation to the voltage rating of the transformer primary winding? Explain briefly.

What does the primary current $I_{Pri.}$ you recorded in the previous step correspond to? Explain briefly why.

What does the primary active power $P_{Pri.}$ you recorded in the previous step correspond to?

14. In LVDAC-EMS, open the **Oscilloscope**, and display the waveforms of the transformer primary voltage $E_{Pri.}$ and magnetizing current I_O (i.e., the primary current $I_{Pri.}$).

Is the waveform of the transformer magnetizing current I_O distorted, even though the transformer is not saturated (i.e., even though the primary voltage $E_{Pri.}$ is well below the nominal voltage of the transformer primary winding)?

Yes No

15. In LVDAC-EMS, open the **Harmonic Analyzer**. Set the fundamental frequency to 50 Hz and the number of harmonics to 15, then display the harmonic content of the transformer magnetizing current I_O . Record the value of the total harmonic distortion (THD) of the transformer magnetizing current I_O .

THD of magnetizing current $I_O = \underline{\hspace{2cm}}\%$



The total harmonic distortion (THD) of a waveform indicates the amount of harmonic distortion present in that waveform. The higher the percentage, the more the waveform is distorted due to the presence of harmonics.

Does the value you just recorded confirm that the waveform of the transformer magnetizing current I_O is distorted even when the transformer is not saturated?

Yes No

16. In the **Four-Quadrant Dynamometer/Power Supply** window, gradually increase the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is close to 56 V. While doing so, observe the waveform of the transformer magnetizing current I_O on the **Oscilloscope**.



The transformer primary voltage $E_{Pri.}$ is now equal to 56 V, which is nearly 20% above the nominal voltage of the transformer primary windings. The transformer is thus saturated.

Describe what happens to the waveform of the transformer magnetizing current I_O as you increase the primary voltage $E_{Pri.}$. Explain briefly why it is so.

- 17.** In the **Metering** window, measure the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$, and active power $P_{Pri.}$ when the transformer is saturated. Record the values below.

Primary voltage $E_{Pri.} = \underline{\hspace{2cm}}$ V

Primary current $I_{Pri.} = \underline{\hspace{2cm}}$ A

Primary active power $P_{Pri.} = \underline{\hspace{2cm}}$ W

- 18.** Compare the transformer parameters you recorded in the previous step to the parameters you recorded in step 12. Describe the effects which transformer saturation has on the rms value of the magnetizing current I_O (i.e., the primary current $I_{Pri.}$), as well as on the no-load power losses (i.e., the primary active power $P_{Pri.}$).

- 19.** In the **Harmonic Analyzer**, record the value of the total harmonic distortion (THD) of the transformer magnetizing current I_O when the transformer is saturated.

THD of magnetizing current $I_O = \underline{\hspace{2cm}}$ %

Compare the THD value you just recorded with the THD value you recorded in step 15. Has transformer saturation increased the amount of harmonic distortion in the transformer magnetizing current I_O significantly?

Yes No

Saturation curve of a power transformer

In this section, you will reduce the power transformer primary voltage to 12 V then you will increase the transformer primary voltage to 56 V by steps. For each voltage step, you will record in the Data Table the transformer primary voltage, current (magnetizing current), and active power (no-load power losses), as well as the peak magnetizing current. You will use the measured values to plot the saturation curve of the power transformer.

- 20.** In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 12 V.

On the **Oscilloscope**, set a horizontal cursor to measure the peak value of the transformer magnetizing current ($I_{O,max.}$), which corresponds to the peak value of the primary current $I_{Pri.}$.

- 21.** In **LVDAC-EMS**, open the **Data Table** window.

Set the **Data Table** to record the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$ (magnetizing current I_O), and active power $P_{Pri.}$ (transformer no-load power losses) indicated in the **Metering** window.

Also, set the **Data Table** to record the peak value of the transformer magnetizing current $I_{O,max.}$ measured using one of the horizontal cursors of the **Oscilloscope**.

In the **Data Table** window, click on the **Record Data** button to record the values of the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$ (magnetizing current I_O), and active power $P_{Pri.}$ (transformer no-load power losses), as well as the peak magnetizing current $I_{O,max.}$.

- 22.** In the **Four-Quadrant Dynamometer/Power Supply** window, increase the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window increases by steps of 4 V up to 28 V. For each voltage step, adjust the horizontal cursor on the **Oscilloscope** to measure the peak value of the magnetizing current ($I_{O,max.}$) then record the transformer parameters in the **Data Table**.

- 23.** In the **Four-Quadrant Dynamometer/Power Supply** window, continue to increase the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window increases by steps of 2 V up to 56 V. For each voltage step, adjust the horizontal cursor on the **Oscilloscope** to measure the peak value of the magnetizing current ($I_{O,max.}$) then record the transformer parameters in the **Data Table**.

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

In the **Data Table** window, save the recorded data, then export it to a spreadsheet application.

- 25.** Using the recorded values, plot the saturation curve of the power transformer (i.e., plot a graph of the transformer primary voltage E_{pri} as a function of the peak magnetizing current $I_{o,max}$).

Voltage rating of transformer windings and transformer power rating

In this section, you will determine at which point on the saturation curve the power transformer operates when the nominal voltage of 48 V is applied to the primary, and analyze the result. You will record the transformer magnetizing current, no-load power losses, and power rating when the nominal voltage of 48 V is applied to the primary. Using the saturation curve, you will determine at which primary voltage value the transformer should operate for maximal efficiency, and determine the corresponding transformer magnetizing current, no-load power losses, and power rating. You will compare these results to the transformer parameters measured at the nominal voltage of 48 V.

- 26.** On the transformer saturation curve you plotted in step 25, indicate at which point the power transformer operates when the nominal voltage (48 V) is applied to the primary winding.

Considering your results, can you conclude that the transformer is designed for maximal efficiency or maximal power output? Explain why.

- 27.** Using the measured values, note below the transformer magnetizing current I_o and no-load power losses when the transformer operates at the nominal voltage (48 V). Also, calculate the power rating of the transformer when operating at the nominal voltage and current values.

Magnetizing current $I_o =$ _____ A

No-load power losses = _____ W

Power rating = _____ VA

- 28.** Using the transformer saturation curve you plotted in step 25, evaluate what would the nominal primary voltage E_{pri} be if the transformer were designed for maximal efficiency (i.e., to operate with little or no saturation).

For maximal efficiency, the nominal primary voltage E_{pri} of the transformer should be close to _____ V.

- 29.** Using the measured values, determine the transformer magnetizing current I_o and no-load power losses at the nominal primary voltage you

recorded in the previous step. Calculate also the power rating of the transformer when operating at this nominal voltage value.

Magnetizing current $I_o =$ _____ A

No-load power losses = _____ W

Power rating = _____ VA

- 30.** Compare the transformer parameters you recorded in the previous step to the parameters you recorded in step 27. What happens to the transformer magnetizing current I_o , no-load power losses, and power rating when the transformer is designed for maximal efficiency instead of maximal power?

Effect of transformer nominal voltage on the power losses and efficiency

In this section, you will connect a resistive load to the step-up transformer. You will start the ac power source and set the transformer primary voltage to the value you determined in the previous section of the exercise (for maximizing transformer efficiency). By varying the resistance of the resistive load, you will increase the transformer secondary (load) current by steps of 0.1 A up to 1.2 A (60% of the nominal load current). For each load current, you will record the transformer primary voltage, current, and active power, as well as the secondary voltage, current, and active power in the Data Table. You will export the results to a spreadsheet application and, for each load current, you will calculate the corresponding transformer power losses and efficiency. On the same graph, you will plot the transformer power losses as a function of the load current, at the nominal voltage (using the values recorded in the previous exercise) and at a voltage maximizing efficiency, and analyze the results. You will do the same for the transformer efficiency as a function of the load current, and analyze the results. Finally, you will compare the transformer load voltage at the nominal voltage and at the voltage you determined for maximizing transformer efficiency, and analyze the results.

31. Connect the equipment as shown in Figure 31.

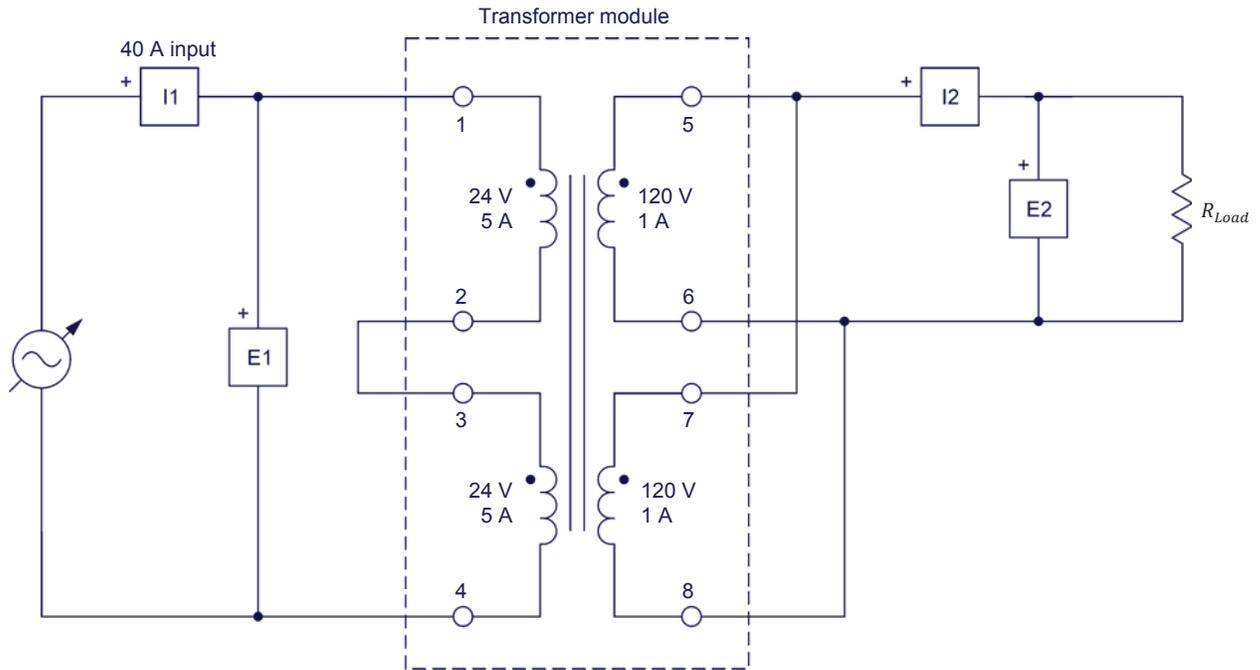


Figure 31. Step-up transformer connected to a resistive load.

In LVDAC-EMS, set the *Range* setting of current input *I1* to high.

32. Make the necessary switch settings on the *Resistive Load* so that the resistance of the resistive load is infinite.
33. In the *Metering* window, make the required settings on additional meters in order to measure the rms values (ac) of the transformer secondary voltage $E_{Sec.}$ and current $I_{Sec.}$ (inputs *E2* and *I2*, respectively). Set another meter to measure the secondary active power $P_{Sec.}$ from inputs *E2* and *I2*.
34. In the *Four-Quadrant Dynamometer/Power Supply* window, start the *AC Power Source*. Adjust the *Voltage* parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the *Metering* window is as close as possible to the value for maximizing transformer efficiency you recorded in step 28.

In the *Metering* window, temporarily set the meter measuring the transformer primary current so that it indicates dc current values. Then, in the *Four-Quadrant Dynamometer/Power Supply* window, adjust the *DC Offset Correction* parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it indicates ac current values.

- 35.** Set the **Data Table** to record, in addition to the parameters already selected (i.e., the primary voltage, current, and active power), the transformer secondary voltage $E_{Sec.}$, current $I_{Sec.}$, and active power $P_{Sec.}$ indicated in the **Metering** window.

In the **Data Table** window, click on the **Record Data** button to record the values of the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$ (magnetizing current I_O), and active power $P_{Pri.}$, as well as the secondary voltage $E_{Sec.}$, current $I_{Sec.}$, and active power $P_{Sec.}$.

- 36.** On the **Resistive Load**, decrease the resistance R_{Load} so that the secondary (load) current $I_{Sec.}$ increases to about 1.2 A (60% of nominal secondary current or full-load current of the transformer) by steps of about 0.1 A. For each step, adjust the **Voltage** parameter in the **Four-Quadrant Dynamometer/ Power Supply** window so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window remains constant, then record the transformer parameters in the **Data Table**.

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

- 38.** In the **Data Table** window, save the recorded data, then export it to a spreadsheet application.

In the spreadsheet application, add a new parameter to the results: the transformer power losses P_{Losses} . To calculate the transformer power losses P_{Losses} , subtract the secondary active power $P_{Sec.}$ (i.e., the active power delivered to the load by the transformer) from the primary active power $P_{Pri.}$ (i.e., the active power supplied to the transformer by the ac power source).

Also add another parameter to the results: the transformer efficiency η . To calculate the transformer efficiency η , divide the transformer secondary active power $P_{Sec.}$ by the primary active power $P_{Pri.}$, then multiply the result by 100 to express the efficiency η as a percentage.

- 39.** On the same graph, plot curves of the transformer power losses P_{Losses} as a function of the secondary (load) current $I_{Sec.}$ when the transformer operates at the nominal primary voltage (48 V) and when the transformer operates at the primary voltage maximizing transformer efficiency. Use the results you recorded in the previous exercise and in this exercise to do so.

Observe the graph. Does operating at a lower primary voltage have any effect on the transformer power losses P_{Losses} ? If so, explain.

40. Plot on the same graph curves of the transformer efficiency η as a function of the secondary (load) current I_{Sec} , when the transformer operates at the nominal primary voltage (48 V) and when the transformer operates at the primary voltage maximizing transformer efficiency. Use the results you recorded in the previous exercise and in this exercise to do so.

Observe the graph. Does operating at a lower primary voltage have any effect on the transformer efficiency η ? If so, explain.

41. Compare the transformer secondary (load) voltage E_{Sec} , measured at 50% of the nominal full-load current, i.e., at 50% of the nominal secondary current (1 A), when the transformer operates at the nominal primary voltage (48 V) and when the transformer operates at the primary voltage maximizing transformer efficiency. Use the results you recorded in the previous exercise and in this exercise to do the comparison.

What happens to the secondary (load) voltage E_{Sec} , when operating at a lower primary voltage? Does this have any effect on the transformer power rating?

Transformer operating temperature

In this section, you will measure the initial temperature of the transformer. You will start the ac power source and set the load resistance so that the load current is equal to about 75% of the nominal full-load current. You will let the ac power source operate for 20 minutes. You will then record the transformer temperature and calculate the transformer temperature increase. These results will be used in the next exercise.

42. Connect the *Thermistor Input* of the Four-Quadrant Dynamometer/Power Supply to the *Thermistor Output* of the Transformer module.



You can also use an external thermometer to achieve the same results if your Transformer module is not equipped with a thermistor input. If so, attach the thermometer probe to the transformer core in order to measure the transformer core temperature.

43. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Thermistor Type** parameter to **LV Type 2**, then observe the transformer temperature indicated by the temperature meter. Record the value below.

Transformer initial temperature = _____

44. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Voltage** parameter to 48 V, then start the **AC Power Source**. Readjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 48 V.

On the **Resistive Load**, adjust the resistance so that the transformer secondary (load) current $I_{Sec.}$ increases to about 1.5 A (75% of the transformer nominal full-load current).

In the **Four-Quadrant Dynamometer/Power Supply** window, readjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 48 V.

45. Let the **AC Power Source** operate for 20 minutes.

After 20 minutes of operation, observe the power transformer temperature indicated by the temperature meter in the **Four-Quadrant Dynamometer/Power Supply** window. Record the value below.

Transformer temperature after 20 minutes of operation = _____

Calculate the transformer temperature increase from the two transformer temperature values you measured. Record the value below.

Transformer temperature increase = _____

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

CONCLUSION

In this exercise, you saw what the voltage, current, and power ratings of a power transformer are, and how they can be determined. You also saw the effects of saturation on the magnetizing current and no-load power losses of a power transformer.

REVIEW QUESTIONS

1. A power transformer has two primary windings connected in series: one whose voltage and current ratings are 50 V and 1 A, respectively, and the other whose voltage and current ratings are 100 V and 1 A, respectively. Calculate the power rating of the transformer.

2. What factor limits the current rating of a power transformer? Explain briefly.

3. What happens to the waveform of the magnetizing current of a power transformer as the transformer primary voltage is increased and the transformer becomes more and more saturated? What is the effect on the harmonic content of the transformer magnetizing current?

4. What are the effects of saturation on the magnetizing current, no-load power losses, and efficiency of a power transformer?

5. What are the advantages and disadvantages of operating a power transformer with little or no saturation?

Effect of Frequency on Transformer Rating

EXERCISE OBJECTIVE

When you have completed this exercise, you will know the effects of the ac power source frequency on the saturation of a power transformer, as well as on the voltage and power ratings of the transformer.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Transformer saturation versus frequency
- Transformer rating versus frequency

DISCUSSION

Transformer saturation versus frequency

The equation that relates the rms value of the voltage across a power transformer winding to the number of turns in the winding, the surface area of the transformer core, the flux density in the transformer core, and the frequency of the ac power source is given below.

$$E = \frac{2\pi}{\sqrt{2}} N A B_{Max}. f \quad (7)$$

where

E	is the voltage across the transformer winding, expressed in volts (V).
N	is the number of turns in the transformer winding.
A	is the surface area of the transformer core, expressed in square meters (m ²).
$B_{Max.}$	is the maximum flux density in the transformer core, expressed in teslas (T).
f	is the frequency of the ac power source to which the transformer is connected, expressed in hertz (Hz).

Parameters N and A in the above equation are constants whose values depend on the transformer construction. When a fixed-frequency ac power source is used, the frequency parameter is also a constant. Consequently, as was stated in the previous exercise, for a given power transformer operating at a fixed frequency, the maximum value of the flux density $B_{Max.}$ in the transformer core is directly proportional to the rms value of the voltage E across the transformer winding.

Equation (7) also reveals that for a given winding voltage E , the maximum flux density $B_{Max.}$ increases when the frequency f is decreased. Therefore, at a lower operating frequency f , a lower voltage E is required across a transformer winding to produce a certain maximum flux density $B_{Max.}$ and, consequently, transformer saturation occurs at a lower voltage E . Conversely, for a given winding voltage E , the maximum flux density $B_{Max.}$ decreases when the frequency f is increased. Therefore, at a higher operating frequency f , a higher voltage E is required

across a transformer winding to produce a certain maximum flux density $B_{Max.}$, and, consequently, transformer saturation occurs at a higher voltage E . This is illustrated in Figure 32, which shows the saturation curves, i.e., curves of the primary voltage $E_{pri.}$ as a function of the magnetic field intensity H (proportional to the peak magnetizing current $I_{0,max.}$), of a power transformer operating at various frequencies.

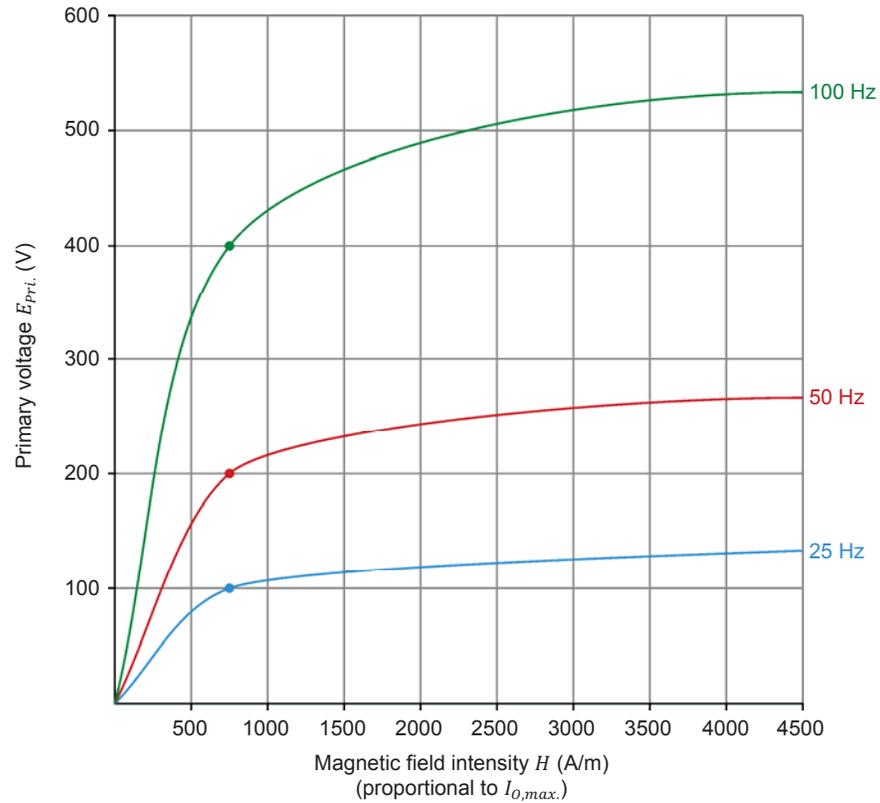


Figure 32. Saturation curves of a power transformer operating at various frequencies.

At the operation points shown on the three saturation curves in Figure 32, the magnetic field intensity H , and thus the peak magnetizing current $I_{0,max.}$, has the same values at all three frequencies. Similarly, the maximum flux density $B_{Max.}$ has the same value at all three frequencies. However, the values of the primary voltage $E_{pri.}$ differ, the primary voltage $E_{pri.}$ increasing in direct proportion to the operating frequency f .

Transformer rating versus frequency

Equation (7) in the previous section can be rearranged as follows:

$$\frac{E}{f} = \frac{2\pi}{\sqrt{2}} N A B_{Max.} \quad (8)$$

Since voltage can also be symbolized with the letter V , the E/f ratio can also be designated as the V/f ratio.

Since parameters N and A are constants, this form of the equation reveals that the ratio of winding voltage E over the ac power source frequency f determines the maximum flux density $B_{Max.}$, and thus, the amount of saturation of the transformer core (i.e., the operating point on the saturation curve of the transformer). Consequently, when the frequency f is decreased, the winding voltage E has to be decreased in the same proportion to keep the E/f ratio constant, and thus, to keep the same operating point on the saturation curve of the transformer. On the other hand, when the frequency f is increased, the winding voltage E has to be increased in the same proportion to keep the E/f ratio constant and to keep the same operating point on the saturation curve of the transformer.

This means that increasing the operating frequency f of a power transformer allows the winding voltage E to be increased without changing the operating point on the saturation curve of the transformer. In other words, increasing the operating frequency f allows the voltage rating of transformer windings to be increased without changing the values of the maximum flux density $B_{Max.}$ and magnetic field intensity H in the transformer (i.e., without moving the point of operation on the saturation curve of the transformer).

Since the operating frequency f does not affect the current rating of transformer windings, increasing the frequency f allows the power rating of a given transformer to be increased. For instance, doubling the operating frequency f doubles the voltage rating of the transformer windings, while the current rating remains unchanged. The transformer power rating thus also doubles. This, however, holds true up to a certain frequency for reasons that are beyond the scope of this manual.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Transformer operation at a frequency of 50 Hz
- Effect of frequency on transformer saturation
- Saturation curve of the power transformer at a frequency of 75 Hz
- Effect of frequency on the voltage rating of transformer windings and on the transformer power rating
- Transformer operating temperature (OPTIONAL)

PROCEDURE



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 section, you will set up a circuit containing a step-up transformer without load. You will then set the measuring equipment required to study the effect of the operating frequency on the transformer voltage and power ratings.

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.



Make sure you use the same *Transformer* module, Model 8353, as in Exercises 3 and 4 of this manual by confirming that the module's serial number is the same as the serial number you recorded in the first step of Exercise 3.

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.

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

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

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

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

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

In the *Module Selector* 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 selected. Also, 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 *Module Selector* window.

6. Connect the equipment as shown in Figure 33. In this circuit, the two 24 V primary windings of the *Transformer* module are connected in series to form a primary winding rated 48 V and 5 A. Also, the two 120 V secondary windings are connected in parallel to form a secondary winding rated 120 V and 2 A. These ratings are for an operating frequency of either 50 Hz or 60 Hz.

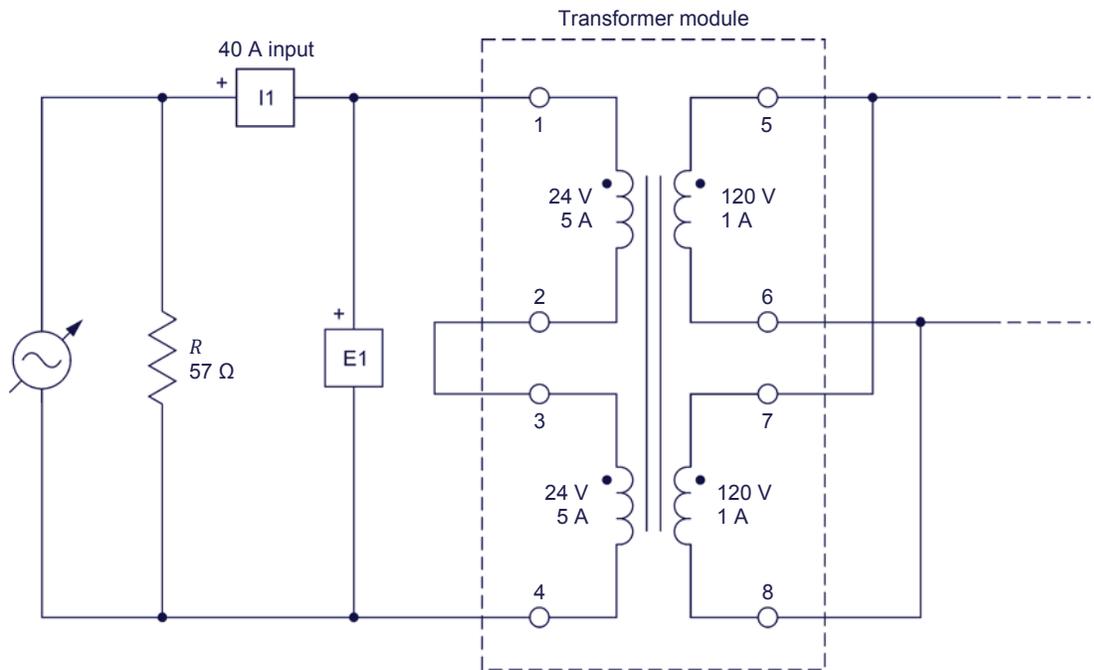


Figure 33. Step-up transformer without load.



The resistive load in the circuit of Figure 33 is used to improve the appearance of the voltage waveforms. As the resistive load is connected in parallel to the ac power source, it has no effect on the measured voltages.

In LVDAC-EMS, set the *Range* setting of current input *I1* to high.

7. 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* parameter to 48 V.
 - Set the *Frequency* parameter to 50 Hz.

8. In LVDAC-EMS, open the **Metering** window. Make the required settings in order to measure the rms values (ac) of the transformer primary voltage E_{pri} and current I_{pri} (inputs *E1* and *I1*, respectively). Set another meter to measure the primary active power P_{pri} from inputs *E1* and *I1*.

Transformer operation at a frequency of 50 Hz

In this section, you will start the ac power source. You will display on the Oscilloscope the waveforms of the transformer primary voltage and magnetizing current. You will then measure the transformer primary voltage and magnetizing current when operating at an ac power source frequency of 50 Hz.

9. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **AC Power Source**. Adjust the **Voltage** 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, temporarily set the meter measuring the transformer primary current so that it indicates dc current values. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **DC Offset Correction** parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it indicates ac current values.

10. In **LVDAC-EMS**, open the **Oscilloscope**, and display the waveforms of the transformer primary voltage $E_{Pri.}$ and current $I_{Pri.}$ (which corresponds to the magnetizing current I_o as the transformer is operating without load).

The waveform of the magnetizing current I_o should be virtually symmetrical, as the average (dc) value of the magnetizing current I_o has been set as close as possible to zero.

11. In the **Metering** window, measure the transformer primary voltage $E_{Pri.}$ and magnetizing current I_o (primary current $I_{Pri.}$). Record the values below.

Primary voltage $E_{Pri.}$ at a frequency of 50 Hz = _____ V

Magnetizing current I_o at a frequency of 50 Hz = _____ A

Effect of frequency on transformer saturation

In this section, you will gradually decrease the ac power source frequency to 35 Hz. While doing so, you will observe on the Oscilloscope what happens to the waveforms of the primary voltage and magnetizing current. You will measure the transformer primary voltage and magnetizing current when operating at an ac power source frequency of 35 Hz. You will set the ac power source frequency back to 50 Hz, then increase it gradually to 75 Hz. While doing so, you will observe on the Oscilloscope what happens to the waveforms of the primary voltage and magnetizing current. You will measure the transformer primary voltage and magnetizing current when operating at an ac power source frequency of 75 Hz, and compare the values to those you obtained at an ac power source frequency of 35 Hz.

12. In the **Four-Quadrant Dynamometer/Power Supply** window, gradually decrease the **Frequency** parameter to 35 Hz. While doing so, slightly readjust the **Voltage** parameter so that the primary voltage $E_{Pri.}$ remains

constant (48 V), and observe the waveform of the magnetizing current I_o on the Oscilloscope.

What happens to the waveform of the transformer magnetizing current I_o when the frequency of the ac power source is decreased while the primary voltage remains constant? Explain briefly why it is so.

- 13.** In the **Metering** window, measure the transformer primary voltage $E_{Pri.}$ and magnetizing current I_o (primary current $I_{Pri.}$). Record the values below.

Primary voltage $E_{Pri.}$ at a frequency of 35 Hz = _____ V

Magnetizing current I_o at a frequency of 35 Hz = _____ A

What happens to the rms value of the transformer magnetizing current I_o when the frequency of the ac power source is decreased while the primary voltage remains constant? Briefly explain why.

- 14.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Frequency** parameter back to 50 Hz, then adjust the **Voltage** parameter so that the primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 48 V.

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

On the **Data Acquisition and Control Interface**, disconnect all leads from the high current (40 A) terminal of input **I1** and connect them to the low current terminal (4 A) of input **I1**.

In **LVDAC-EMS**, set the **Range** setting of current input **I1** to low.

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

In the **Metering** window, temporarily set the meter measuring the transformer primary current so that it indicates dc current values. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **DC Offset**

Correction parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it indicates ac current values.

- 16.** In the *Four-Quadrant Dynamometer/Power Supply* window, gradually increase the *Frequency* parameter to 75 Hz. While doing so, slightly readjust the *Voltage* parameter so that the primary voltage $E_{pri.}$ remains constant (48 V), and observe the waveform of the magnetizing current I_o on the Oscilloscope.

What happens to the waveform of the transformer magnetizing current I_o when the frequency of the ac power source is increased while the primary voltage remains constant? Explain briefly why it is so.

- 17.** In the *Metering* window, measure the transformer primary voltage $E_{pri.}$ and magnetizing current I_o (primary current $I_{pri.}$). Record the values below.

Primary voltage $E_{pri.}$ at a frequency of 75 Hz = _____ V

Magnetizing current I_o at a frequency of 75 Hz = _____ A

What happens to the rms value of the transformer magnetizing current I_o when the frequency of the ac power source is increased while the primary voltage remains constant? Briefly explain why.

Saturation curve of the power transformer at a frequency of 75 Hz

In this section, you will reduce the transformer primary voltage to 18 V then you will increase the transformer primary voltage to 81 V by steps. For each voltage step, you will record in the Data Table the transformer primary voltage, current (magnetizing current), and active power (no-load power losses), as well as the peak magnetizing current. You will plot on the same graph the power transformer saturation curve at ac power source frequencies of 50 Hz (from results recorded in the previous exercise) and 75 Hz, and compare the two saturation curves.

18. In the Four-Quadrant Dynamometer/Power Supply window, adjust the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 18 V.

On the **Oscilloscope**, set a horizontal cursor to measure the peak value of the transformer magnetizing current ($I_{O,max.}$), which corresponds to the peak value of the primary current $I_{Pri.}$.

19. In LVDAC-EMS, open the **Data Table** window.

Set the **Data Table** to record the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$ (magnetizing current I_O), and active power $P_{Pri.}$ (transformer no-load power losses) indicated in the **Metering** window.

Also, set the **Data Table** to record the peak value of the transformer magnetizing current $I_{O,max.}$ measured using one of the horizontal cursors of the **Oscilloscope**.

In the **Data Table** window, click on the **Record Data** button to record the values of the transformer primary voltage $E_{Pri.}$, current $I_{Pri.}$ (magnetizing current I_O), and active power $P_{Pri.}$ (transformer no-load power losses), as well as the peak magnetizing current $I_{O,max.}$.

20. In the Four-Quadrant Dynamometer/Power Supply window, increase the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window increases by steps of 6 V up to 42 V. For each voltage step, adjust the horizontal cursor on the **Oscilloscope** to measure the peak value of the magnetizing current ($I_{O,max.}$) then record the transformer parameters in the **Data Table**.

21. In the Four-Quadrant Dynamometer/Power Supply window, continue to increase the **Voltage** parameter so that the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window increases by steps of 3 V up to 81 V. For each voltage step, adjust the horizontal cursor on the **Oscilloscope** to measure the peak value of the magnetizing current ($I_{O,max.}$) then record the transformer parameters in the **Data Table**.

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

In the **Data Table** window, save the recorded data, then export it to a spreadsheet application.

- 23.** On the same graph, plot the transformer saturation curves (i.e., curves of the primary voltage E_{Pri} as a function of the peak magnetizing current $I_{O,max}$.) measured at ac power source frequencies of 50 Hz and 75 Hz. Use the results you recorded in the previous exercise and in this exercise to do so.

Observe the graph. What is the effect of increasing the frequency of the ac power source on the saturation of the power transformer?

Effect of frequency on the voltage rating of transformer windings and on the transformer power rating

In this section, you will set up a circuit containing a step-up transformer connected to a resistive load. You will make the transformer operate at the nominal voltage and at an ac power source frequency of 50 Hz. You will measure the transformer magnetizing current. You will decrease the resistance of the resistive load so that a current of 1.5 A (75% of the nominal full-load current) flows in the secondary winding. While doing so, you will maintain the transformer primary voltage constant. You will measure the transformer secondary voltage and active power. You will set the resistive load back to infinite. You will then make the transformer operate at an ac power source frequency of 75 Hz, and adjust the primary voltage so that the transformer magnetizing current is virtually equal to the magnetizing current value you recorded at an ac power source frequency of 50 Hz. You will measure the transformer primary voltage, and compare the value with the nominal voltage at an ac power source frequency of 50 Hz. You will decrease the resistance of the resistive load so that a current of 1.5 A flows in the secondary winding. While doing so, you will maintain the transformer primary voltage constant. You will measure the transformer secondary voltage and active power, and compare the values with those obtained at an ac power source frequency of 50 Hz

24. Connect the equipment as shown in Figure 34.

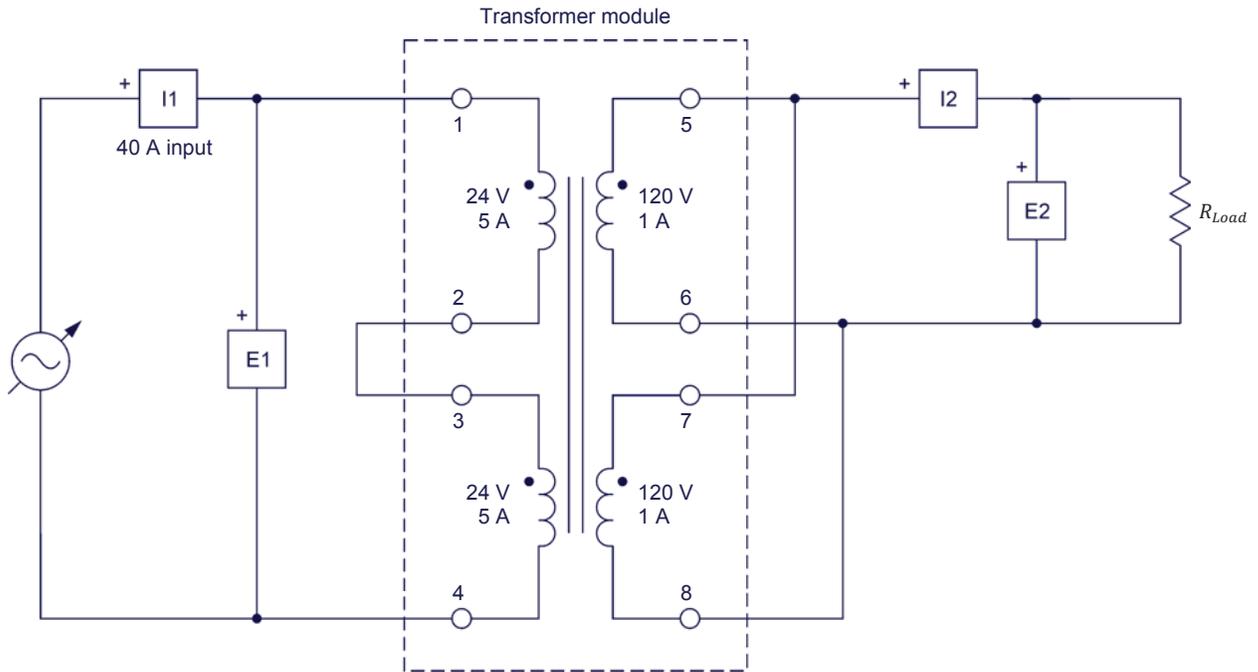


Figure 34. Step-up transformer connected to a resistive load.

In LVDAC-EMS, set the *Range* setting of current input *I1* to high.

25. Make the necessary switch settings on the *Resistive Load* so that the resistance of the resistive load is infinite.
26. In the *Metering* window, make the required settings on additional meters in order to measure the rms values (ac) of the transformer secondary voltage $E_{Sec.}$ and current $I_{Sec.}$ (inputs *E2* and *I2*, respectively). Set another meter to measure the secondary active power $P_{Sec.}$ from inputs *E2* and *I2*.
27. In the *Four-Quadrant Dynamometer/Power Supply* window, set the *Voltage* parameter to 48 V and the *Frequency* parameter to 50 Hz, then start the *AC Power Source*. Readjust the *Voltage* 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, temporarily set the meter measuring the transformer primary current so that it indicates dc current values. Then, in the *Four-Quadrant Dynamometer/Power Supply* window, adjust the *DC Offset Correction* parameter so that the dc current flowing in the transformer primary winding is as close as possible to 0 A. Once this is done, set the meter measuring the transformer primary current so that it indicates ac current values.

- 28.** In the **Metering** window, measure the transformer magnetizing current I_O (primary current $I_{Pri.}$) when operating at the nominal primary voltage $E_{Pri.}$ of 48 V and at an ac power source frequency of 50 Hz. Record the value below.

Magnetizing current I_O at a frequency of 50 Hz = _____ A

- 29.** On the **Resistive Load**, gradually decrease the load resistance R_{Load} so that the secondary current $I_{Sec.}$ value indicated in the **Metering** window increases to 1.5 A (75% of nominal secondary current or full-load current of the transformer). While doing so, readjust the **Voltage** parameter of the ac power source so that the primary voltage $E_{Pri.}$ remains as close as possible to 48 V.

- 30.** In the **Metering** window, measure the transformer secondary voltage $E_{Sec.}$ and active power $P_{Sec.}$ when operating at the nominal primary voltage $E_{Pri.}$ of 48 V and at an ac power source frequency of 50 Hz. Record the values below.

Secondary voltage $E_{Sec.}$ at a frequency of 50 Hz = _____ V

Secondary active power $P_{Sec.}$ at a frequency of 50 Hz = _____ W

- 31.** On the **Resistive Load**, make the necessary switch settings so that the load resistance R_{Load} is infinite.

- 32.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Frequency** parameter to 75 Hz. Adjust the **Voltage** parameter so that the rms value of the transformer magnetizing current I_O (primary current $I_{Pri.}$) indicated in the **Metering** window is as close as possible to the transformer magnetizing current I_O you recorded in step 28. This makes the transformer operate at the same point on the saturation curve (i.e., at the same level of saturation) as when the transformer operates at a primary voltage $E_{Pri.}$ of 48 V and at an ac power source frequency of 50 Hz.

- 33.** In the **Metering** window, measure the transformer primary voltage $E_{Pri.}$ when operating without load and at an ac power source frequency of 75 Hz. Record the value below.

Primary voltage $E_{Pri.}$ at a frequency of 75 Hz = _____ V

34. Compare the transformer primary voltage $E_{Pri.}$ you recorded in the previous step when operating at an ac power source frequency of 75 Hz to the primary voltage $E_{Pri.}$ (48 V) when operating at an ac power source frequency of 50 Hz. What do you observe?

What can you conclude concerning the effect of the ac power source frequency on the nominal voltage of a transformer winding.

35. On the **Resistive Load**, gradually decrease the load resistance R_{Load} so that the secondary current $I_{Sec.}$ value indicated in the **Metering** window increases to 1.5 A (75% of nominal secondary current or full-load current of the transformer). While doing so, readjust the **Voltage** parameter of the ac power source so that the primary voltage $E_{Pri.}$ remains constant (i.e., as close as possible to the voltage value recorded in step 33).



*The voltage and power ratings of the **Resistive Load** are significantly exceeded in this manipulation. It is therefore important that you perform the remainder of this step in less than 2 minutes to avoid damaging the **Resistive Load**.*

In the **Metering** window, measure the transformer secondary voltage $E_{Sec.}$ and active power $P_{Sec.}$ when operating at 75% of the full-load current and at an ac power source frequency of 75 Hz. Record the values below.

Secondary voltage $E_{Sec.} =$ _____ V

Secondary active power $P_{Sec.} =$ _____ W

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

36. Compare the transformer secondary voltage $E_{Sec.}$ and active power $P_{Sec.}$ you recorded in the previous step when operating at an ac power source frequency of 75 Hz to the values you recorded in step 30 when operating at an ac power source frequency of 50 Hz. What do you observe?

What can you conclude concerning the effect of the ac power source frequency on the nominal power of a transformer.

Transformer operating temperature (OPTIONAL)



This section can only be performed if a second Resistive Load is available. For this reason, it is considered optional.

In this section, you will connect a second load resistor in series with the one in the circuit you set up in the previous section to allow continuous operation at higher voltages. You will measure the initial temperature of the transformer. You will start the ac power source. You will make sure that the transformer primary voltage is equal to the nominal primary voltage determined when operating at an ac power source frequency of 75 Hz and that the load current is equal to about 75% of the nominal load current. You will let the ac power source operate for 20 minutes. You will record the transformer temperature, and calculate the transformer temperature increase. You will then compare the transformer temperature increase when the transformer operates at ac power source frequencies of 50 Hz and 75 Hz using the results you recorded in the previous exercise and in this exercise.

- 37.** Connect the *Thermistor Input* of the Four-Quadrant Dynamometer/Power Supply to the *Thermistor Output* of the Transformer module.

You can also use an external thermometer to achieve the same results if your Transformer module is not equipped with a thermistor input. If so, attach the thermometer probe to the transformer core in order to measure the transformer core temperature.

- 38.** Using two Resistive Load modules, modify the resistive load in the circuit of Figure 34 so that it consists of two resistors in series. This doubles the voltage that can be applied to the resistive load as well as the power which the resistive load can dissipate. To do so, connect the three resistor sections on each Resistive Load in parallel, connect the two Resistive Load modules in series, then set the resistance on each Resistive Load to 60 Ω . The total resistance of the resistive load R_{Load} is thus equal to 120 Ω .

- 39.** In the Four-Quadrant Dynamometer/Power Supply window, set the *Thermistor Type* parameter to *LV Type 2*, then observe the transformer temperature indicated by the temperature meter. Record the value below.

Transformer initial temperature = _____

- 40.** In the Four-Quadrant Dynamometer/Power Supply window, start the *AC Power Source*. Adjust the *Voltage* parameter so that the transformer primary voltage E_{pri} , indicated in the *Metering* window is as close as possible to the transformer nominal primary voltage E_{pri} , measured at an ac power source of 75 Hz (i.e., the voltage value recorded in step 33). The transformer

secondary current $I_{Sec.}$ should now be close to 1.5 A (about 75% of the transformer nominal full-load current). If required, adjust the resistance of the resistive load so that the transformer secondary current $I_{Sec.}$ is as close as possible to 1.5 A while maintaining the primary voltage constant.

- 41.** Let the *AC Power Source* operate for 20 minutes.

After 20 minutes of operation, observe the transformer temperature indicated by the temperature meter in the *Four-Quadrant Dynamometer/Power Supply* window. Record the value below.

Transformer temperature after 20 minutes of operation = _____

Calculate the transformer temperature increase from the two transformer temperature values you measured. Record the value below.

Transformer temperature increase = _____

- 42.** Compare the transformer temperature increase you recorded in the previous step when operating at an ac power source frequency of 75 Hz to the temperature increase you recorded in step 45 of Exercise 4 when operating at an ac power source frequency of 50 Hz. In both cases, the transformer was loaded at 75% of the nominal full-load current. What do you observe? Explain briefly.

- 43.** 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 the effects of the ac power source frequency on the saturation of a power transformer, as well as on the voltage and power ratings of the transformer.

REVIEW QUESTIONS

1. Explain why transformer saturation occurs at a lower voltage value when the frequency of the ac power source is decreased?

2. What are the effects of decreasing the frequency of the ac power source on the waveform and the rms value of the magnetizing current of a power transformer?

3. What are the effects of increasing the frequency of the ac power source on the waveform and the rms value of the magnetizing current of a power transformer?

4. What does the E/f (or V/f) ratio of a power transformer determine?

5. What is the effect of increasing the frequency of the ac power source on the voltage and power ratings of a power transformer?

The Autotransformer

EXERCISE OBJECTIVE

When you have completed this exercise, you will know what an autotransformer is. You will be able to connect an autotransformer so that it operates as either a step-up or a step-down unit. You will also be able to determine the primary and secondary voltages and currents of an autotransformer. You will know how the power rating of an autotransformer compares with the power rating of a similarly sized conventional power transformer.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Autotransformer operation
- Autotransformer circuit analysis
- Power rating of conventional transformers and autotransformers

DISCUSSION

Autotransformer operation

An **autotransformer** is a special type of transformer in which only one winding serves as both the primary and the secondary windings. Autotransformers operate according to the same principles as conventional power transformers. Like conventional power transformers, autotransformers can be used either as step-up or step-down transformer. When an autotransformer is used as a step-up transformer, only part of the single winding acts as the primary winding, while the complete winding serves as the secondary winding. On the other hand, when an autotransformer is used as a step-down transformer, the use of the single winding for the primary and secondary windings is reversed. This means that the whole winding is used as the primary winding, while only part of the single winding is used as the secondary winding. Figure 35 shows the autotransformer connections that are necessary for step-up and step-down operation.

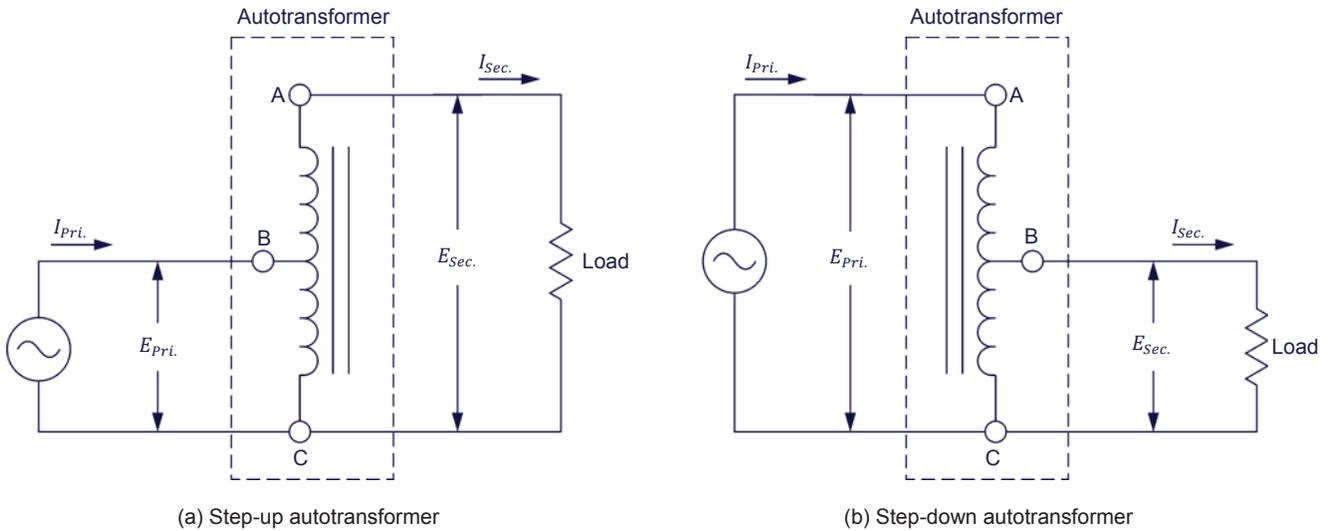


Figure 35. Autotransformer step-up and step-down operation.

To determine the turns ratio of an autotransformer, each winding is considered as separate, even though a certain proportion of the turns are common to both the primary and the secondary windings. The primary and secondary voltages and currents of an autotransformer are related through the same equations as those presented for conventional power transformers (see Exercise 1 of this manual). Using the circuits illustrated in Figure 35, it is thus possible to determine that, in step-up operation, the relationship between the voltage ratio, the current ratio, and the turns ratio of an autotransformer is equal to:

$$\frac{E_{Pri.}}{E_{Sec.}} = \frac{I_{Sec.}}{I_{Pri.}} = \frac{N_{B-C}}{N_{A-C}} = \frac{N_{Pri.}}{N_{Sec.}}$$

In step-down operation, on the other hand, the relationship between the voltage ratio, the current ratio, and the turns ratio of an autotransformer is equal to:

$$\frac{E_{Pri.}}{E_{Sec.}} = \frac{I_{Sec.}}{I_{Pri.}} = \frac{N_{A-C}}{N_{B-C}} = \frac{N_{Pri.}}{N_{Sec.}}$$

These relationships are true only when voltages E_{B-C} and E_{A-C} of the autotransformer are in phase (this is usually the case in any autotransformer), and thus, add together. As for conventional power transformers, the relationship between the current ratio and the turns ratio of an autotransformer is the inverse of the relationship between the voltage ratio and the turns ratio of the autotransformer. Furthermore, the apparent power at the primary winding of an autotransformer is virtually equal to the apparent power at the secondary winding of the autotransformer, as for any conventional power transformer.

Autotransformers, however, have one major disadvantage when compared to conventional power transformers: the lack of electrical isolation between the primary and secondary windings. This is due to the fact that, in autotransformers, the primary and the secondary windings are not separate. Because of this, autotransformers cannot be used in applications requiring electrical isolation between the primary and the secondary windings.

Autotransformer circuit analysis

The rules that apply to the operation of conventional power transformers also apply to autotransformers. This means that:

1. The voltage ratio (i.e., the ratio of the primary voltage to the secondary voltage) of an autotransformer is equal to its turns ratio $N_{Pri.}/N_{Sec.}$.
2. The voltage-current product at the primary winding of an autotransformer equals the voltage-current product at the secondary winding.

These two rules allow the operation of autotransformers to be analyzed.

Step-up autotransformer circuit analysis

Figure 36 shows an example of a step-up autotransformer.

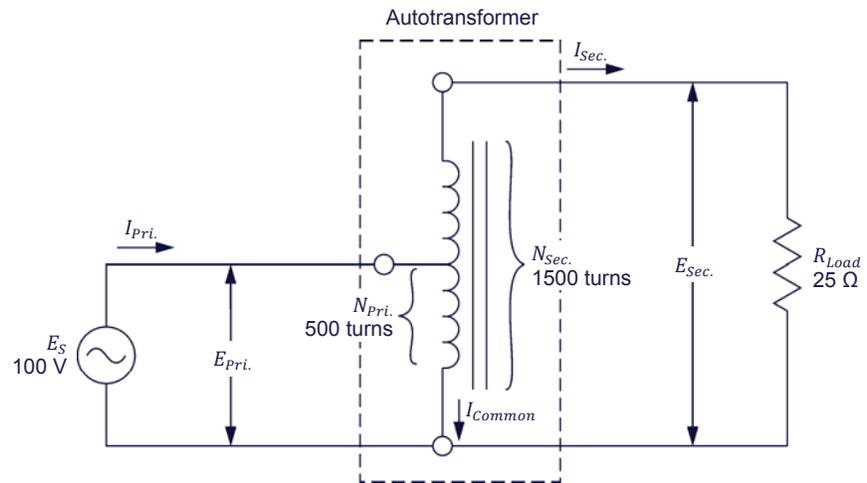


Figure 36. Step-up autotransformer.

The circuit of the autotransformer shown in Figure 36 can be resolved as follows:

$$\frac{E_{Pri.}}{E_{Sec.}} = \frac{N_{Pri.}}{N_{Sec.}}$$

$$E_{Sec.} = \frac{E_{Pri.} \times N_{Sec.}}{N_{Pri.}} = \frac{100 \text{ V} \times 1500 \text{ turns}}{500 \text{ turns}} = 300 \text{ V}$$

$$I_{Sec.} = \frac{E_{Sec.}}{R_{Load}} = \frac{300 \text{ V}}{300 \Omega} = 1.00 \text{ A}$$

$$E_{Pri.} \times I_{Pri.} = E_{Sec.} \times I_{Sec.}$$

$$I_{Pri.} = \frac{E_{Sec.} \times I_{Sec.}}{E_{Pri.}} = \frac{300 \text{ V} \times 1.00 \text{ A}}{100 \text{ V}} = 3.00 \text{ A}$$

$$I_{Common} = I_{Pri.} - I_{Sec.} = 3.00 \text{ A} - 1.00 \text{ A} = 2.00 \text{ A}$$

As you can see from the above calculations, the current (i.e., the primary current $I_{Pri.}$) flowing in the autotransformer winding tap is equal to the sum ($I_{Sec.} + I_{Common}$) of the currents flowing in the two sections of the autotransformer winding. Consequently, the value of current I_{Common} flowing in the turns of the winding that is common to the primary and secondary is equal to the difference ($I_{Pri.} - I_{Sec.}$) between the primary and secondary current values. This must be taken into account when selecting the size of the wire used for this section of the autotransformer winding. The lower the turns ratio, the higher the difference between the primary and secondary current values, and thus, the higher the value of current I_{Common} .

Step-down autotransformer circuit analysis

Figure 37 shows an example of a step-down autotransformer.

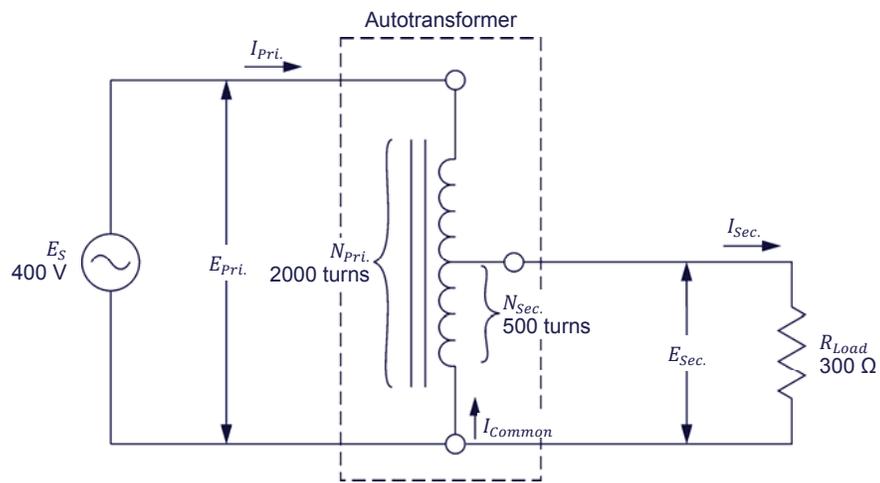


Figure 37. Step-down autotransformer.

The circuit of the autotransformer shown in Figure 37 can be resolved as follows:

$$\frac{E_{Pri.}}{E_{Sec.}} = \frac{N_{Pri.}}{N_{Sec.}}$$

$$E_{Sec.} = \frac{E_{Pri.} \times N_{Sec.}}{N_{Pri.}} = \frac{400 \text{ V} \times 500 \text{ turns}}{2000 \text{ turns}} = 100 \text{ V}$$

$$I_{Sec.} = \frac{E_{Sec.}}{R_{Load}} = \frac{100 \text{ V}}{25 \Omega} = 4.00 \text{ A}$$

$$E_{Pri.} \times I_{Pri.} = E_{Sec.} \times I_{Sec.}$$

$$I_{Pri.} = \frac{E_{Sec.} \times I_{Sec.}}{E_{Pri.}} = \frac{100 \text{ V} \times 4.00 \text{ A}}{400 \text{ V}} = 1.00 \text{ A}$$

$$I_{Common} = I_{Sec.} - I_{Pri.} = 4.00 \text{ A} - 1.00 \text{ A} = 3.00 \text{ A}$$

As you can see from the above calculations, the current (i.e., the secondary current $I_{Sec.}$) flowing in the autotransformer winding tap is equal to the

sum ($I_{pri.} + I_{Common}$) of the currents flowing in the two sections of the autotransformer winding. Consequently, the value of the current flowing in the turns of the winding that is common to the primary and secondary is equal to the difference ($I_{sec.} - I_{pri.}$) between the primary and secondary current values, as in step-up autotransformers. This time, however, the higher the turns ratio, the higher the difference between the primary and secondary current values, and thus, the higher the value of current I_{Common} .

Power rating of conventional transformers and autotransformers

Figure 38 represents a conventional power transformer with a power rating of 100 VA.

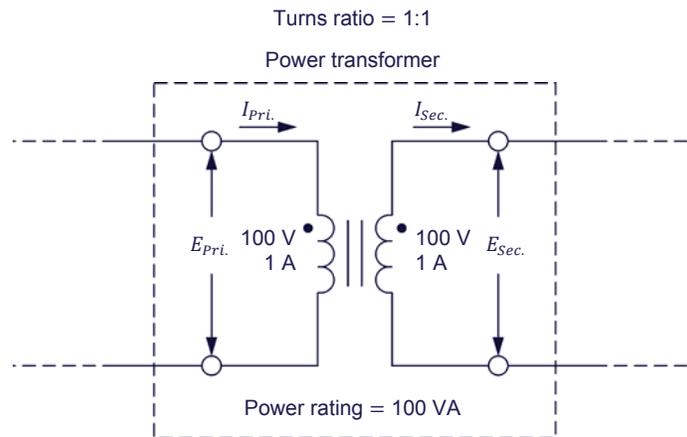
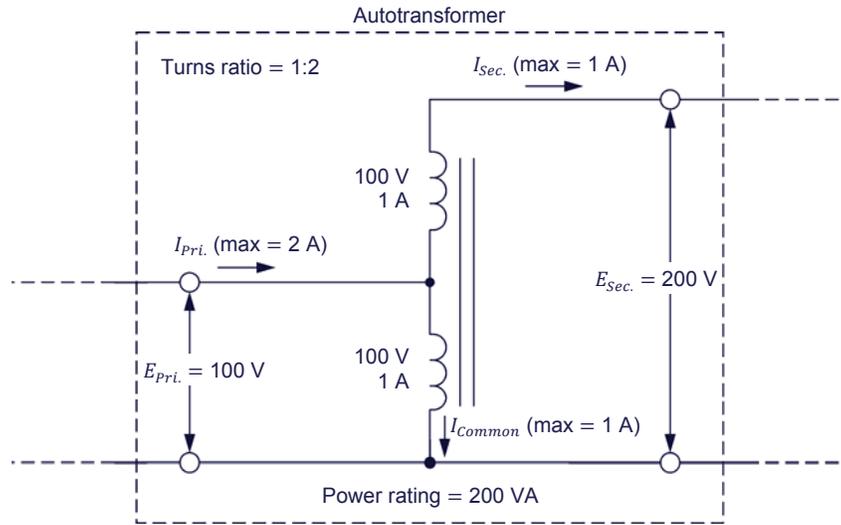
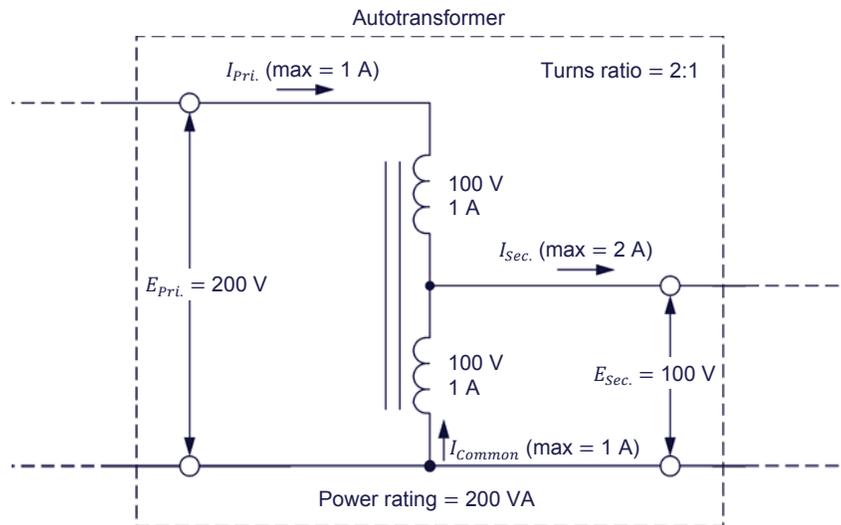


Figure 38. Conventional power transformer with a power rating of 100 VA.

A step-up or step-down autotransformer can be built using the primary and secondary windings of the conventional power transformer above. This is shown in Figure 39.



(a) Step-up autotransformer



(b) Step-down autotransformer

Figure 39. Step-up and step-down autotransformers built using the conventional power transformer in Figure 38.

As you can see in Figure 39, the power rating of each autotransformer is higher (twice in this particular case) than that of the conventional power transformer in Figure 38. This is an advantage that all autotransformers have over conventional power transformers. Consequently, for a given power rating, autotransformers are always smaller, lighter, and cheaper than conventional power transformers. However, autotransformers do not provide electrical isolation between the primary and secondary windings.

The difference between the power rating of a conventional power transformer and that of an autotransformer built with the same windings depends on the turns ratio of the autotransformer. The power rating of the autotransformer is twice that of the conventional power transformer when the turns ratio of the autotransformer

is 2:1 or 1:2, as demonstrated above. Both of these turns ratios allow for a maximum increase in the power rating of the autotransformer. The difference between the power rating of the autotransformer and that of the conventional transformer decreases as the turns ratio of the autotransformer diverges from the optimal values of 2 and 0.5 (voltage ratios of 2:1 and 1:2, respectively). This is illustrated in Figure 40. Using the conventional power transformer with a power rating of 600 VA in Figure 40a, an autotransformer with a turns ratio of 1:3 can be built, as illustrated in Figure 40b. Because the turns ratio of the resulting autotransformer is not optimal, the power rating of the autotransformer is less than two times the power rating of the conventional transformer, i.e., the power rating of the autotransformer is only 150% that of the conventional transformer.

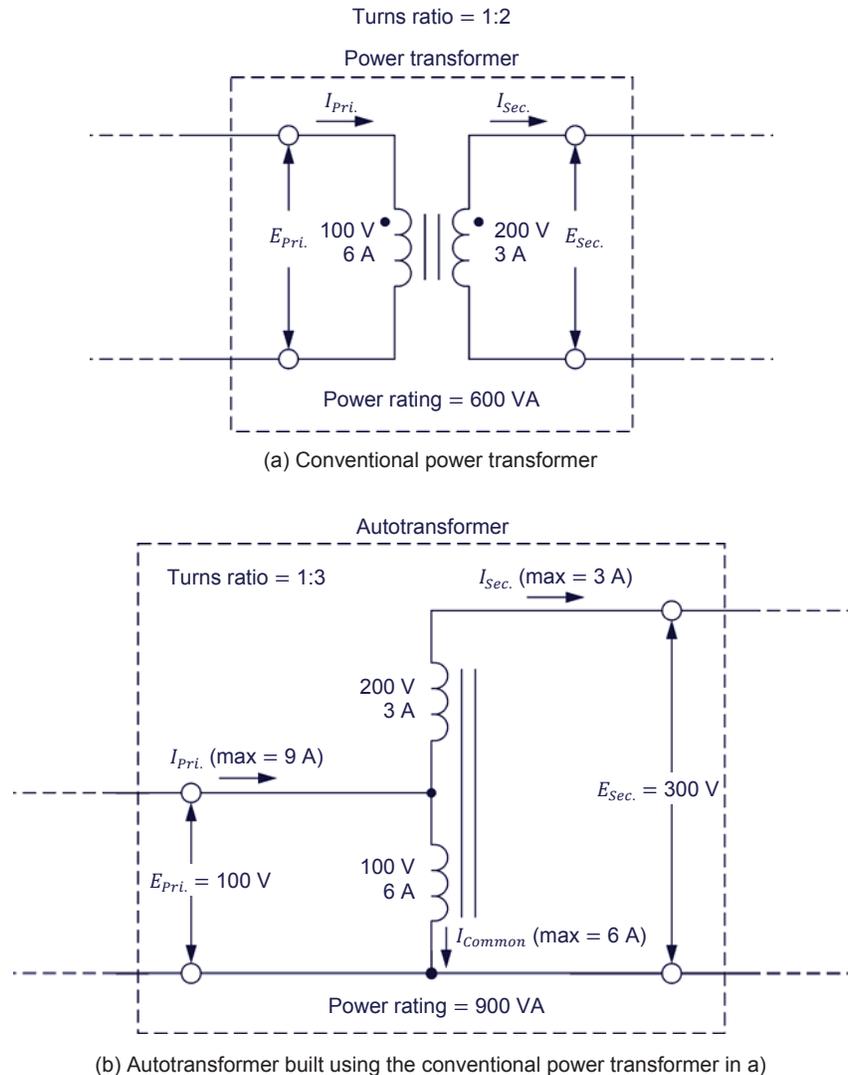


Figure 40. Autotransformer with a power rating of 900 VA built using a conventional power transformer with a power rating of 600 VA.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Operation of a step-down autotransformer
- Operation of a step-up autotransformer
- Comparing the power rating of an autotransformer to that of a conventional power transformer of the same size
- Effect of the turns ratio on the power rating of autotransformers

PROCEDURE



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 section, you will set up a circuit containing a step-down autotransformer connected to a resistive load. You will determine the autotransformer turns ratio and the secondary voltage when a voltage of 100 V is applied to the primary. You will then set the measuring equipment required to study the operation of autotransformers.

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.

Connect the *Power Input* of the [Data Acquisition and Control Interface](#) to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.

Connect the USB port of the [Four-Quadrant Dynamometer/Power Supply](#) to a USB port of the host computer.

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

5. Turn the host computer on, then start the [LVDAC-EMS](#) software.

In the [Module Selector](#) 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 selected. Also, 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 *Module Selector* window.

6. Connect the equipment as shown in Figure 41. Notice that, in this circuit, the two 120 V - 1 A windings are connected in series-aiding configuration to form the single winding of the autotransformer.

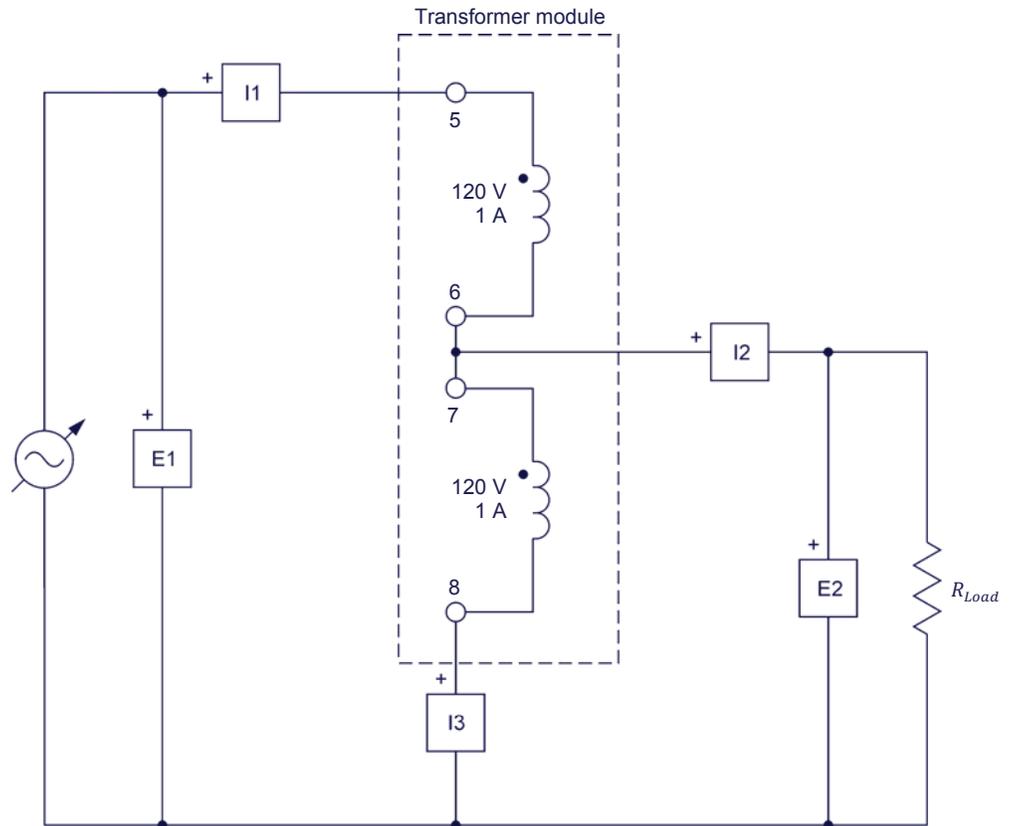


Figure 41. Step-down autotransformer connected to a resistive load.

7. Make the necessary switch settings on the *Resistive Load* so that the resistance of the resistive load is infinite.
8. Determine the turns ratio of the autotransformer you just set up, as well as the voltage at the secondary winding when a voltage of 100 V is applied to the primary.

Turns ratio = _____

Secondary (load) voltage $E_{Sec.}$ = _____ V



The number of turns in each of the two 24 V – 5 A windings of the power transformer in the *Transformer* module is 57 turns. The number of turns in each of the two 120 V – 1 A windings of the transformer is 285 turns.

Do your calculations confirm that the autotransformer is currently in step-down operation?

Yes No

9. 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* parameter to 100 V.
 - Set the *Frequency* parameter to the frequency of your local ac power network.

10. In LVDAC-EMS, open the *Metering* window. Make the required settings in order to measure the rms values (ac) of the autotransformer primary voltage $E_{Pri.}$ and current $I_{Pri.}$ (inputs *E1* and *I1*, respectively), secondary (load) voltage $E_{Sec.}$ and current $I_{Sec.}$ (inputs *E2* and *I2*, respectively), and current I_{Common} (input *I3*) flowing in the lower portion of the autotransformer winding.

Operation of a step-down autotransformer

In this section, you will start the ac power source. You will set the resistance of the resistive load to 57 Ω . You will measure the autotransformer voltages and currents, and analyze the results. You will determine the autotransformer maximum secondary (load) voltage and current, as well as its power rating.

11. In the *Four-Quadrant Dynamometer/Power Supply* window, start the *AC Power Source*. Adjust the *Voltage* parameter so that the autotransformer primary voltage $E_{Pri.}$ indicated in the *Metering* window is as close as possible to 100 V.

In the *Metering* window, temporarily set the meter measuring the autotransformer primary current so that it indicates dc current values. Then, in the *Four-Quadrant Dynamometer/Power Supply* window, adjust the *DC Offset Correction* parameter so that the dc current flowing in the autotransformer primary winding is as close as possible to 0 A. Once this is done, set back the meter measuring the autotransformer primary current so that it indicates ac current values.

12. On the **Resistive Load**, decrease the resistance to $57\ \Omega$. In the **Four-Quadrant Dynamometer/Power Supply** window, readjust the **Voltage** parameter so that the autotransformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 100 V.



*It is possible that you may not be able to set the transformer primary voltage $E_{Pri.}$ indicated in the **Metering** window to 100 V because you have reached the voltage limit of the **Four-Quadrant Dynamometer/Power Supply**. If so, simply set the **Voltage** parameter to the highest possible value before proceeding to the next step.*

13. In the **Metering** window, measure the autotransformer primary voltage $E_{Pri.}$ and current $I_{Pri.}$, secondary (load) voltage $E_{Sec.}$ and current $I_{Sec.}$, and current I_{Common} flowing in the lower portion of the autotransformer winding. Record the values below.

Primary voltage $E_{Pri.} = \underline{\hspace{2cm}}$ V

Primary current $I_{Pri.} = \underline{\hspace{2cm}}$ A

Secondary (load) voltage $E_{Sec.} = \underline{\hspace{2cm}}$ V

Secondary (load) current $I_{Sec.} = \underline{\hspace{2cm}}$ A

Current $I_{Common} = \underline{\hspace{2cm}}$ A

14. Is the autotransformer secondary (load) voltage $E_{Sec.}$ you measured in the previous step virtually equal to the voltage you calculated in step 8?

Yes No

Is the secondary (load) current $I_{Sec.}$ you measured in the previous step virtually equal to the sum of the currents ($I_{Pri.}$ and I_{Common}) flowing in the two portions of the autotransformer winding?

Yes No

Do your measurements confirm that the autotransformer is currently in step-down operation?

Yes No

15. Determine the power rating of the autotransformer by calculating the autotransformer maximum secondary (load) voltage $E_{Sec.}$ and maximum secondary (load) current $I_{Sec.}$.

Maximum secondary (load) voltage $E_{Sec.} = \underline{\hspace{2cm}}$ V

Maximum secondary (load) current $I_{Sec.} = \underline{\hspace{2cm}}$ A

Power rating = $\underline{\hspace{2cm}}$ VA

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

Operation of a step-up autotransformer

In this section, you will set up a circuit containing a step-up autotransformer connected to a resistive load. You will determine the autotransformer turns ratio and the secondary voltage when a voltage of 50 V is applied to the primary. You will start the ac power source. You will set the resistance of the resistive load to 200 Ω . You will measure the autotransformer voltages and currents, and analyze the results. You will determine the autotransformer maximum secondary (load) voltage and current, as well as its power rating.

17. Connect the equipment as shown in Figure 42.

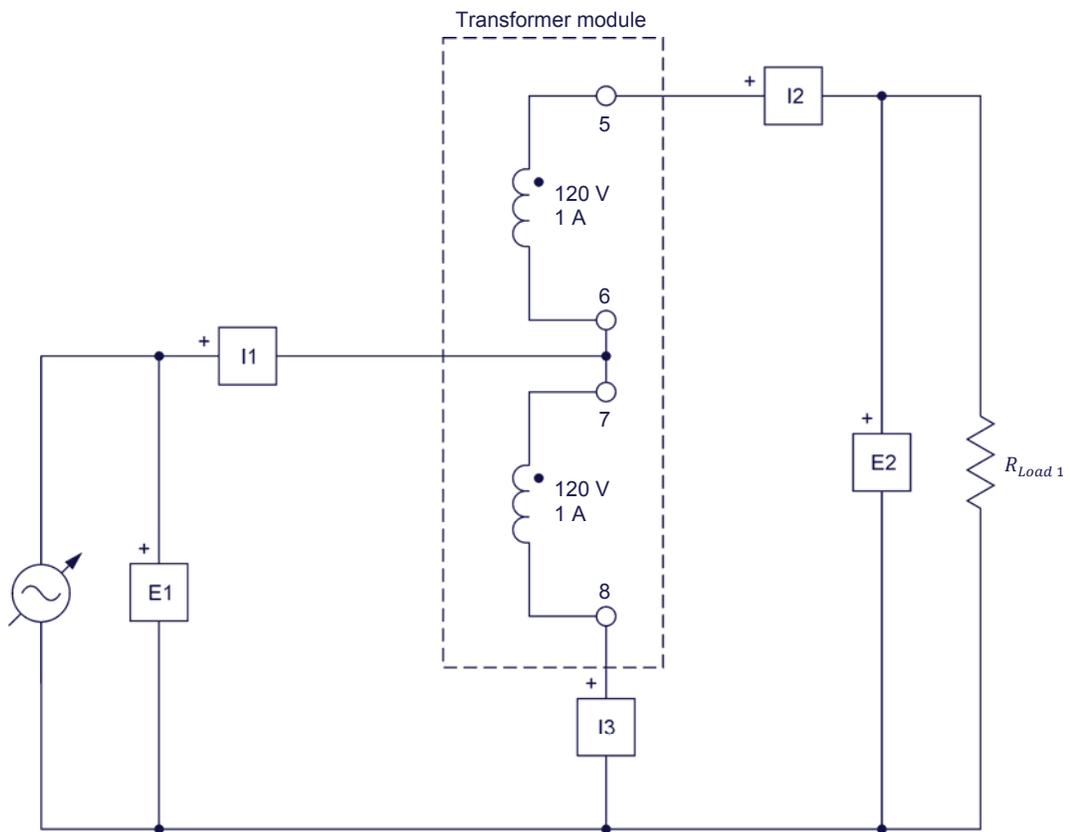


Figure 42. Step-up autotransformer connected to a resistive load.

18. Make the necessary switch settings on the Resistive Load so that the resistance of the resistive load is infinite.

19. Determine the turns ratio of the autotransformer you just set up, as well as the voltage at the secondary winding when a voltage of 50 V is applied to the primary.

Turns ratio = _____

Secondary (load) voltage $E_{Sec.}$ = _____ V

Do your calculations confirm that the autotransformer is currently in step-up operation?

Yes No

20. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Voltage** parameter to 50 V, then start the **AC Power Source**. Readjust the **Voltage** parameter so that the autotransformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 50 V.

In the **Metering** window, temporarily set the meter measuring the autotransformer primary current so that it indicates dc current values. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **DC Offset Correction** parameter so that the dc current flowing in the autotransformer primary winding is as close as possible to 0 A. Once this is done, set back the meter measuring the autotransformer primary current so that it indicates ac current values.

21. On the **Resistive Load**, decrease the resistance to 200 Ω . In the **Four-Quadrant Dynamometer/Power Supply** window, readjust the **Voltage** parameter so that the autotransformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 50 V.

22. In the **Metering** window, measure the autotransformer primary voltage $E_{Pri.}$ and current $I_{Pri.}$, secondary (load) voltage $E_{Sec.}$, and current $I_{Sec.}$, and current I_{Common} flowing in the lower portion of the autotransformer winding. Record the values below.

Primary voltage $E_{Pri.}$ = _____ V

Primary current $I_{Pri.}$ = _____ A

Secondary (load) voltage $E_{Sec.}$ = _____ V

Secondary (load) current $I_{Sec.}$ = _____ A

Current I_{Common} = _____ A

23. Is the autotransformer secondary (load) voltage $E_{Sec.}$ you measured in the previous step virtually equal to the voltage you calculated in step 19?

Yes No

Is the primary current $I_{Pri.}$ you measured in the previous step virtually equal to the sum of the currents ($I_{Sec.}$ and I_{Common}) flowing in the two portions of the autotransformer winding?

Yes No

Do your measurements confirm that the autotransformer is currently in step-up operation?

Yes No

- 24.** Determine the power rating of the autotransformer by calculating the autotransformer maximum secondary voltage $E_{Sec.}$ and maximum secondary (load) current $I_{Sec.}$.

Maximum secondary (load) voltage $E_{Sec.} = \underline{\hspace{2cm}}$ V

Maximum secondary (load) current $I_{Sec.} = \underline{\hspace{2cm}}$ A

Power rating = $\underline{\hspace{2cm}}$ VA

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

Comparing the power rating of an autotransformer to that of a conventional power transformer of the same size

In this section, you will calculate the power rating of a conventional transformer built using the same windings of the transformer module that you used to implement the step-down and step-up autotransformers studied in the previous sections. You will compare the power rating of these autotransformers with the power rating of the conventional transformer built using the same windings.

- 26.** Determine what would be the power rating of a conventional 120 V:120 V power transformer implemented with the same two 120 V - 1 A windings as those used to implement the step-down and step-up autotransformers in Figure 41 and Figure 42, respectively.

Power rating = $\underline{\hspace{2cm}}$ VA

- 27.** Compare the power ratings of the step-down and step-up autotransformers you calculated in steps 15 and 24, respectively, to the power rating of the conventional transformer you calculated in the previous step. What conclusions can you draw?

Which size would the 120 V:120 V conventional transformer need to be in order to have a power rating similar to the power rating of the autotransformers used in the previous sections of this exercise? Briefly explain why.

Effect of the turns ratio on the power rating of autotransformers

In this section, you will set up a circuit containing a step-up autotransformer connected to a resistive load. You will determine the autotransformer turns ratio and the secondary (load) voltage when a voltage of 24 V is applied to the primary. You will start the ac power source. You will set the resistance of the resistive load to 257 Ω . You will measure the autotransformer voltages and currents, and analyze the results. You will determine the autotransformer maximum secondary (load) current, as well as its power rating. You will calculate the power rating of a conventional transformer built using the same windings as the autotransformer. You will confirm that the power rating of the autotransformer is still higher than that of the conventional transformer built with the same windings. Finally, you will compare the increase in the power rating for autotransformers with turns ratios of 2:1, 1:2, and 1:6 in comparison to a conventional transformer built using the same respective windings.

28. Connect the equipment as shown in Figure 43. Notice that the resistive load consists of two resistors ($R_{Load\ 1}$ and $R_{Load\ 2}$) connected in series. Connect two resistor banks of the Resistive Load in parallel to implement resistor $R_{Load\ 2}$.

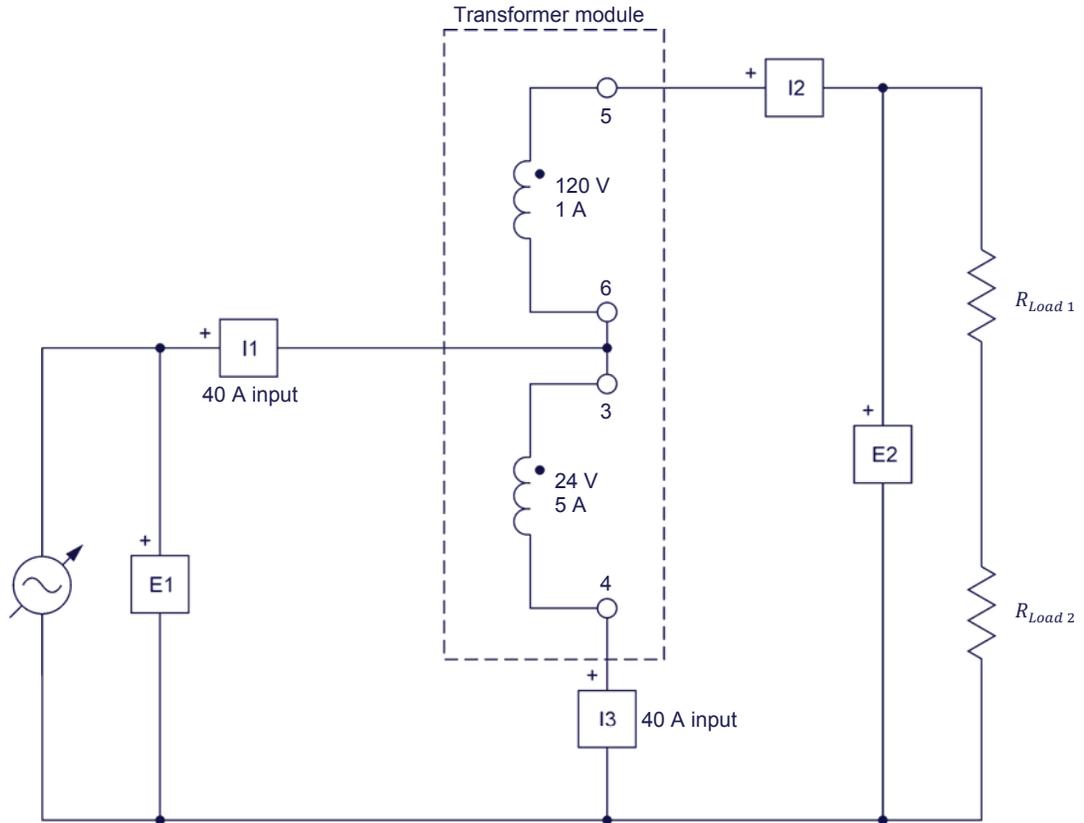


Figure 43. Step-up autotransformer connected to two resistive loads.

In LVDAC-EMS, set the *Range* setting of current inputs *I1* and *I3* to high.

29. Make the necessary switch settings on the Resistive Load so that the resistance of the resistive load is infinite.
30. Determine the turns ratio of the autotransformer you just set up, as well as the voltage at the secondary winding when the nominal voltage of 24 V is applied to the primary.

Turns ratio = _____

Secondary (load) voltage $E_{Sec.}$ = _____ V

31. In the Four-Quadrant Dynamometer/Power Supply window, set the *Voltage* parameter to 24 V, then start the *AC Power Source*. Readjust the *Voltage* parameter so that the autotransformer primary voltage $E_{Pri.}$ indicated in the *Metering* window is as close as possible to 24 V.

In the **Metering** window, temporarily set the meter measuring the autotransformer primary current so that it indicates dc current values. Then, in the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **DC Offset Correction** parameter so that the dc current flowing in the autotransformer primary winding is as close as possible to 0 A. Once this is done, set back the meter measuring the autotransformer primary current so that it indicates ac current values.

- 32.** On the **Resistive Load**, set the resistance values of $R_{Load\ 1}$ and $R_{Load\ 2}$ to 171 Ω and 86 Ω , respectively. In the **Four-Quadrant Dynamometer/Power Supply** window, readjust the **Voltage** parameter so that the autotransformer primary voltage $E_{Pri.}$ indicated in the **Metering** window is as close as possible to 24 V.
- 33.** In the **Metering** window, measure the autotransformer primary voltage $E_{Pri.}$ and current $I_{Pri.}$, secondary (load) voltage $E_{Sec.}$, and current $I_{Sec.}$, and current I_{Common} flowing in the lower portion of the autotransformer winding. Record the values below.

Primary voltage $E_{Pri.} = \underline{\hspace{2cm}}$ V

Primary current $I_{Pri.} = \underline{\hspace{2cm}}$ A

Secondary (load) voltage $E_{Sec.} = \underline{\hspace{2cm}}$ V

Secondary (load) current $I_{Sec.} = \underline{\hspace{2cm}}$ A

Current $I_{Common} = \underline{\hspace{2cm}}$ A

- 34.** Is the autotransformer secondary (load) voltage $E_{Sec.}$ you measured in the previous step virtually equal to the voltage you calculated in step 30?

Yes No

Is the primary current $I_{Pri.}$ you measured in the previous step virtually equal to the sum of the currents ($I_{Sec.}$ and I_{Common}) flowing in the two portions of the autotransformer winding?

Yes No

- 35.** Determine the maximum secondary (load) current $I_{Sec.}$ which this autotransformer can provide, as well as the resulting power rating of the autotransformer.

Maximum secondary (load) current $I_{Sec.} = \underline{\hspace{2cm}}$ A

Power rating = $\underline{\hspace{2cm}}$ VA

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

37. Determine what would be the power rating of a conventional 24 V:120 V or 120 V:24 V power transformer implemented with the same two windings as those used to implement the step-up autotransformer in Figure 43.

Power rating = _____ VA

38. Compare the power rating of the step-up autotransformer you calculated in step 35 to the power rating of the conventional transformer you calculated in the previous step.

Is the power rating of the autotransformer still higher than the power rating of the conventional transformer built with the same windings?

Yes No

39. Compare the increase in power rating obtained using the autotransformer with a 1:6 turns ratio to that obtained using the autotransformers with 2:1 and 1:2 turns ratios. What conclusions can you draw?

40. 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 an autotransformer is, and how to connect an autotransformer so that it operates as either a step-up or a step-down unit. You saw how to determine the primary and secondary voltages and currents of an autotransformer. You also saw how the power rating of an autotransformer compares with the power rating of a similarly sized conventional power transformer.

REVIEW QUESTIONS

1. What is the main difference between conventional power transformers and autotransformers?

2. What is the main advantage of autotransformers over conventional power transformers? Explain briefly.

3. What is the main drawback of autotransformers in comparison to conventional power transformers? Explain briefly.

4. Consider the step-up autotransformer shown in the following figure.

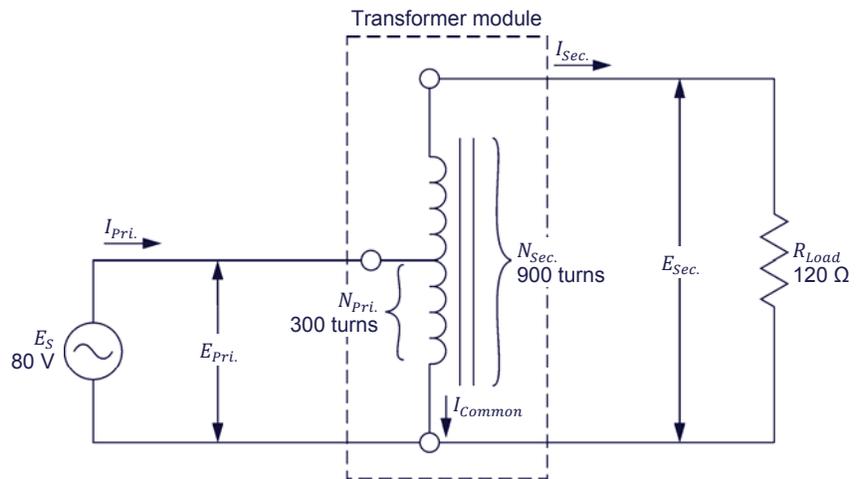


Figure 44. Step-up autotransformer.

Knowing that this autotransformer has 300 turns of wire in the primary winding and 900 turns of wire in the secondary winding, calculate the value of current I_{Common} flowing in the lower part of the autotransformer winding.

5. What are the two turns ratios which maximize the power rating increase of an autotransformer in comparison to a conventional power transformer built using the same windings? Explain briefly.

Equipment Utilization Chart

The following equipment is required to perform the exercises in this manual.

Equipment							
Model	Description	1	2	3	4	5	6
8134 ⁽¹⁾	Workstation	1	1	1	1	1	1
8216 ⁽²⁾	Wind Turbine Generator/Controller	1					
8311 ⁽³⁾	Resistive Load	1	1	1	1	2 ⁽⁴⁾	1
8353	Transformer	1	1	1	1	1	1
8946-2	Multimeter	1					
8951-L	Connection Leads	1	1	1	1	1	1
8960-C ⁽⁵⁾	Four-Quadrant Dynamometer/Power Supply	1	1	1	1	1	1
8990	Host Computer	1	1	1	1	1	1
9063-B ⁽⁶⁾	Data Acquisition and Control Interface	1	1	1	1	1	1
30004-2	24 V AC Power Supply	1	1	1	1	1	1
<p>⁽¹⁾ Workstation model 8110 can also be used.</p> <p>⁽²⁾ This model is optional.</p> <p>⁽³⁾ Resistive Load unit with low (120 V) voltage rating. Use model variant -00, -01, -02, or -0A.</p> <p>⁽⁴⁾ The second Resistive Load is optional as it is only required to perform an optional section of this exercise.</p> <p>⁽⁵⁾ Model 8960-C consists of the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, with functions 8968-1 and 8968-2.</p> <p>⁽⁶⁾ Model 9063-B consists of the Data Acquisition and Control Interface, Model 9063, with function 9069-1.</p>							

Glossary of New Terms

autotransformer	An autotransformer is a special type of power transformer in which only one winding serves as both the primary and the secondary windings, instead of two separate windings as in conventional power transformers. Because of this, autotransformers are smaller, lighter, and cheaper than conventional transformers for the same power rating. Autotransformers, however, do not provide electrical isolation between their windings.
copper losses	The copper losses in a power transformer are the power losses occurring in the transformer wires (typically made of copper). Copper losses are dissipated as heat.
current ratio	The current ratio of a power transformer represents the proportion between the current flowing in the transformer primary winding ($I_{Pri.}$) and the current flowing in the transformer secondary winding ($I_{Sec.}$). The current ratio of a power transformer is inversely proportional to its turns ratio.
efficiency	The efficiency η of a power transformer is a measure of the ability of the transformer to transfer power from the ac power source to the load with minimum power losses. The efficiency of a transformer thus expresses the percentage of power supplied by the ac power source to the transformer that is actually delivered to the load connected to the transformer.
exciting current	See magnetizing current.
harmonics	The Harmonics of a waveform are the frequency components of the signal. The frequency of each harmonic is a multiple of the fundamental frequency. Harmonics are highly undesirable in any ac power network because they can affect the operation of other equipment connected to the network. Also, harmonics decrease the power factor of the network, and thus, its efficiency.
iron losses	The iron losses in a power transformer are the power losses occurring in the transformer iron core. Iron losses primarily consist of hysteresis and eddy-current losses. They are mostly dissipated as heat.
magnetizing current	The magnetizing current (or exciting current) of a power transformer corresponds to the current that produces the magnetic field required for the operation of the transformer. Magnetizing current flows in the primary winding of a power transformer as soon as a voltage is applied to the primary winding, no matter whether the transformer is connected to a load or not. Magnetizing current is generally represented by the symbol I_0 .

polarity	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. It has no meaning in itself and is only meaningful in relation to the polarity of the other windings. When one end of two windings of a transformer are of the same polarity, the polarity of the voltage at this end, with respect to the voltage at the other end of the winding, is the same for both windings, and thus, the ac voltages across these windings are in phase. Conversely, when one end of two windings of a transformer are of opposite polarity, the polarity of the voltage at this end for one winding is opposite that of the voltage at the end of the other winding, and thus, the ac voltages across these windings are 180° out of phase. Transformer winding polarity is especially important when connecting transformer windings in series or in parallel.
primary winding	The primary winding of a power transformer is the winding to which the ac power source supplying power to the transformer is connected.
secondary winding	The secondary winding of a power transformer is the winding that is connected to a load and that supplies power to it.
step-down transformer	A step-down power transformer is a transformer whose voltage across the secondary winding is lower than the voltage across the primary winding. Conversely, the current flowing in the secondary winding of a step-down transformer is higher than the current flowing in the transformer primary winding.
step-up transformer	A step-up power transformer is a transformer whose voltage across the secondary winding is higher than the voltage across the primary winding. Conversely, the current flowing in the secondary winding of a step-up transformer is lower than the current flowing in the transformer primary winding.
turns ratio	The turns ratio of a power transformer is the ratio between the number of turns of wire in the primary winding of the transformer ($N_{Pri.}$) and the number of turns of wire in the secondary winding of the transformer ($N_{Sec.}$). The turns ratio of a power transformer determines the transformer voltage and current ratios.
voltage ratio	The voltage ratio of a power transformer represents the proportion between the voltage across the transformer primary winding ($E_{Pri.}$) and the voltage across the transformer secondary winding ($E_{Sec.}$). The voltage ratio of a power transformer is directly proportional to its turns ratio.
voltage regulation	The voltage regulation of a power transformer expresses its ability to maintain the load voltage ($E_{Sec.}$) constant as the load current ($I_{Sec.}$) varies. There are two ways to define the voltage regulation of a power transformer: regulation down and regulation up. Regulation down is more commonly used for power transformers and indicates the extent of the variation in the load voltage of the power transformer as the load current increases.

Impedance Table for the Load Modules

The following table gives impedance values which can be obtained using either the Resistive Load, Model 8311, the Inductive Load, Model 8321, or the Capacitive Load, Model 8331. Figure 45 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

Table 1. Impedance table for the load modules.

Impedance (Ω)			Position of the switches								
120 V 60 Hz	220 V 50 Hz/60 Hz	240 V 50 Hz	1	2	3	4	5	6	7	8	9
1200	4400	4800									
600	2200	2400									
300	1100	1200									
400	1467	1600									
240	880	960									
200	733	800									
171	629	686									
150	550	600									
133	489	533									
120	440	480									
109	400	436									
100	367	400									
92	338	369									
86	314	343									
80	293	320									
75	275	300									
71	259	282									
67	244	267									
63	232	253									
60	220	240									
57	210	229									

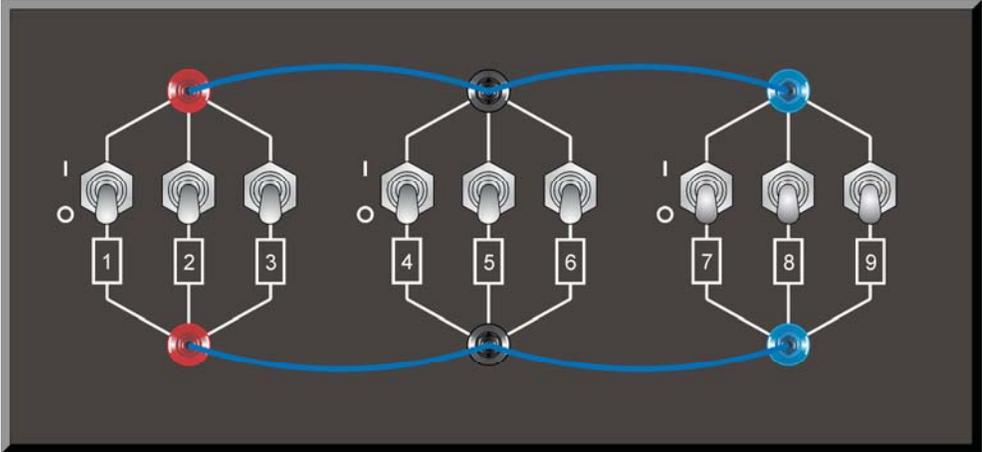


Figure 45. Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

Harmonics

Introduction to harmonics

The fundamental component of a periodic signal is a sine-wave component whose frequency is equal to the frequency of the periodic signal.

It is possible to demonstrate that any non-sinusoidal periodic signal consists of an infinite number of sine-wave components, the frequency of each sine-wave component being equal to a whole multiple of the frequency of the fundamental component. The sine-wave components are referred to as harmonics and they are identified in accordance with their multiple number.

For example, consider the distorted current waveform shown in Figure 46.

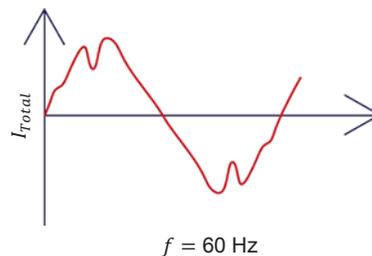


Figure 46. Distorted current waveform.

Even though the distorted current waveform in Figure 46 is not sinusoidal, it is possible to reproduce it by using only sinusoidal waveforms. This current waveform can thus be decomposed into the harmonics shown in Figure 47.

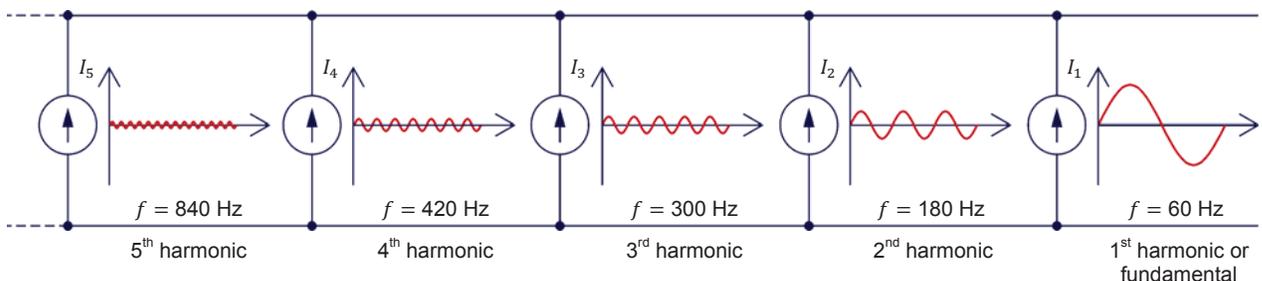


Figure 47. Harmonic decomposition of the distorted current waveform in Figure 46.

At first sight, nothing is gained by changing a source of non-sinusoidal current into many sources of sinusoidal current. The advantage of doing this, however, resides in the fact that it allows very complex circuits to be analyzed, since it is much easier to analyze these circuits with sinusoidal signals rather than with distorted signals. Furthermore, high frequency signals can be neglected when solving practical circuits.

The amplitude of the harmonics in any non-sinusoidal periodic signal can be determined by using instruments such as the LVDAC-EMS Harmonic Analyzer.

Effect of harmonics on the power factor

Consider a source of sinusoidal voltage operating at a frequency of 60 Hz and supplying a square-wave current to a non-linear load, as shown in Figure 48. The sinusoidal waveform representing the voltage across the load is shown in Figure 48b, while the square wave representing the current flowing in the load is shown in Figure 48c. Figure 48d shows the resulting waveform of the power supplied to the load ($E_{Load} \times I_{Load}$). By determining the power factor PF of the circuit, it is possible to demonstrate that the harmonics in the current waveform limit the power factor at a value lower than unity.

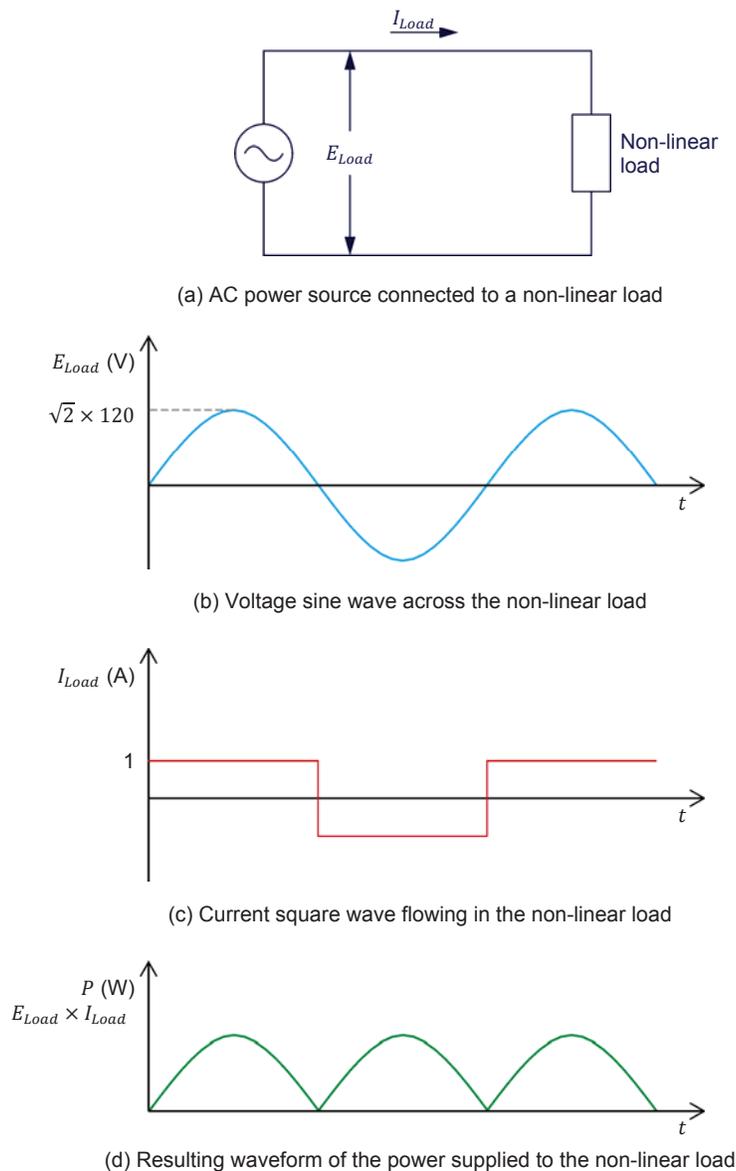


Figure 48. Determining the power factor of a circuit containing harmonics.

To determine the power factor PF , it is necessary to calculate the active power P and the apparent power S supplied to the load. The active power P is the average value of the product of the instantaneous values of the current I_{Load} flowing through the load and the voltage E_{Load} across the load. It is expressed by the following equation:

$$P = \frac{2}{\pi} \times \sqrt{2} \times E_{Load} \times I_{Load}$$

$$P = \frac{2}{\pi} \times \sqrt{2} \times 120 \text{ V} \times 1 \text{ A} = 108 \text{ W}$$



The average value of a rectified sine wave is expressed by $(2/\pi) \times A$, where A is the amplitude of the signal.

The apparent power S supplied to the load is the product of the rms values of the load voltage E_{Load} and the current I_{Load} . Apparent power S is calculated using the following equation:

$$S = E_{Load} \times I_{Load}$$

$$S = 120 \text{ V} \times 1 \text{ A} = 120 \text{ VA}$$

The power factor PF is expressed as the ratio of the active power P to the apparent power S :

$$PF = \frac{P}{S}$$

$$PF = \frac{108 \text{ W}}{120 \text{ VA}} = 0.90$$

The calculated power factor is less than unity even if the voltage and current waveforms are in phase. This is caused by the presence of harmonics in the current waveform, and clearly demonstrates that the presence of harmonics lowers the power factor in a circuit.

Index of New Terms



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