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.

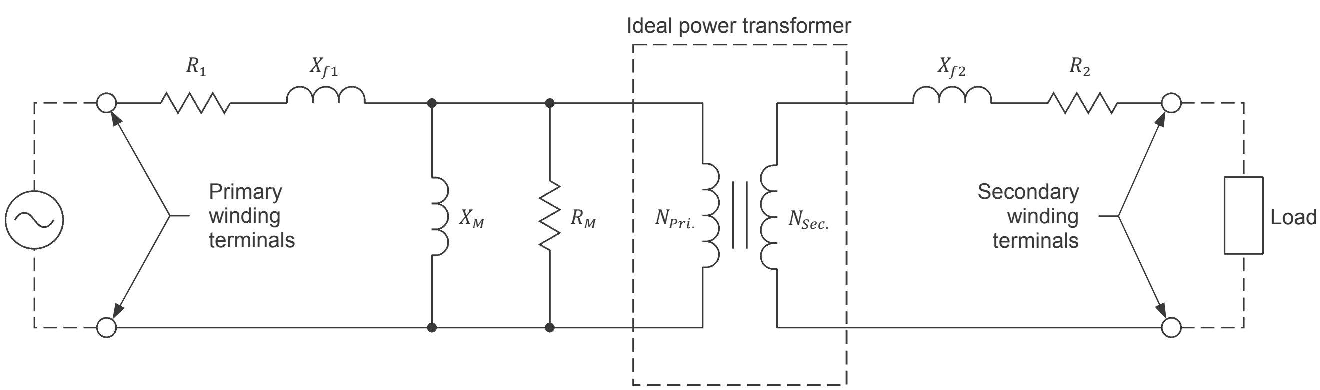

Figure 21. Equivalent circuit of an actual power transformer.

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

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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.

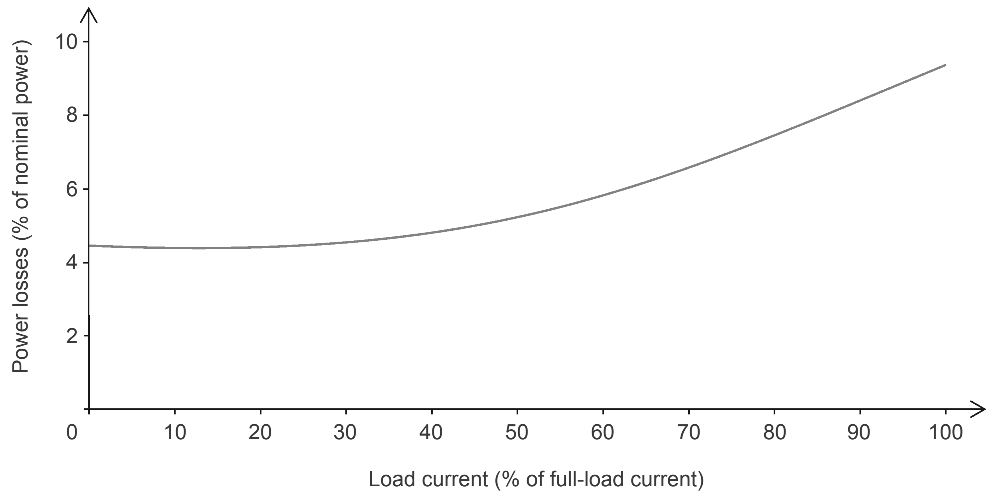

Figure 22. Typical curve of the power losses in a low-power transformer as a function of the load current.

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}.

$$\eta = \frac{P_{Load}}{P_S} \times 100\% \tag{5}$$

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.

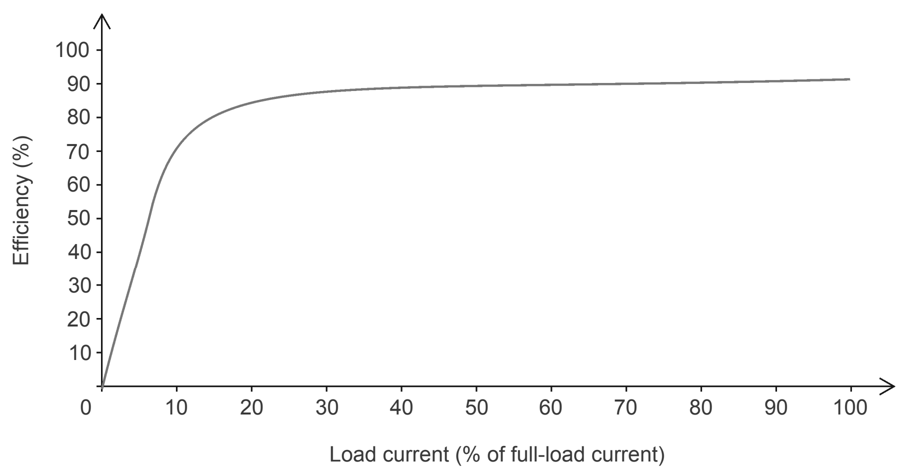

Figure 23. Typical curve of the efficiency of a low-power transformer as a function of the load current.

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).

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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.

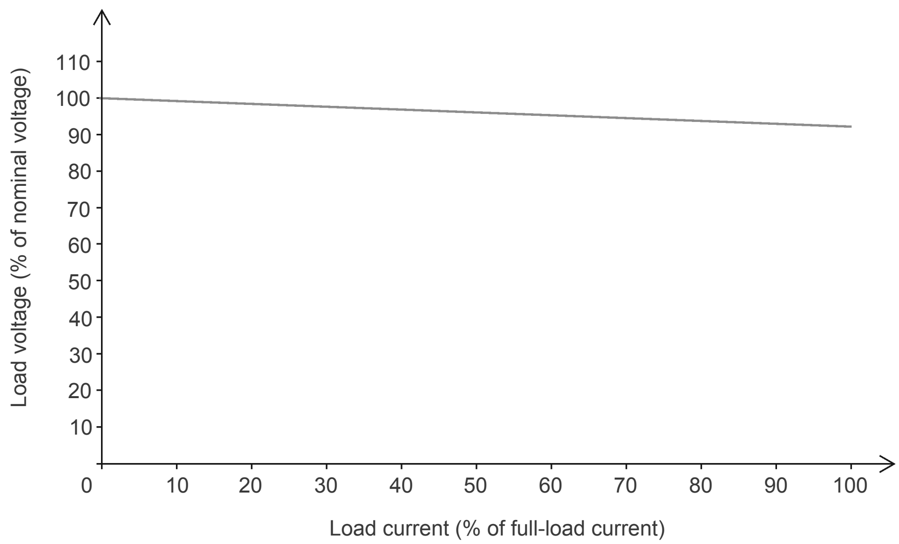

Figure 24. Typical voltage regulation curve of a low-power transformer.

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

⚠ WARNING

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

Set up and connections

In this 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.

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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.

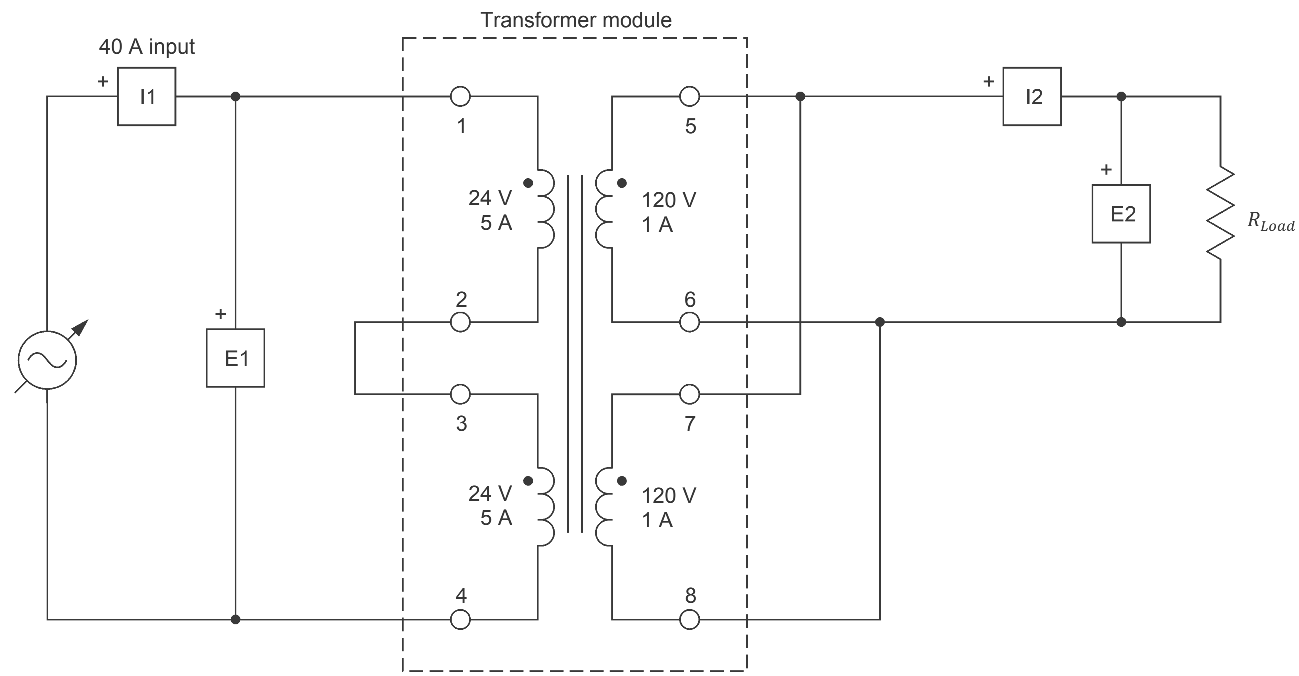

Figure 25. Transformer circuit used for studying transformer losses, efficiency, and voltage regulation.

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.

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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.

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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.

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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.

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Are power transformers high-efficiency devices? Explain briefly.

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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 $I_{Sec.}$.

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

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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.

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

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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.

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