ECE 494: Laboratory Manual

Electrical Engineering Laboratory IV
(Part A: Energy Conversion)

Version 1.3

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Contents

Laboratory Practice

There are four core electrical engineering laboratories, beginning with EE 291. Each laboratory is designed to fill specific needs in the curriculum while insuring that each student grows into a responsible, competent professional person. Since each laboratory is unique, operating policies differ, but there are certain universal requirements for all Electrical and Computer Engineering (ECE) laboratories.

1. All ECE laboratory reports shall follow the format outlined on the ECE laboratory Cover Sheets (bookstore).

2. No food or beverage is to be brought into the ECE laboratories. Smoking is not permitted in the laboratory.

3. Safe engineering practice shall be followed in all experimental work. Particular care shall be taken around line voltages, electrical machinery and special apparatus. All instructors and students shall know the location of the **main disconnect** for their laboratory area.

4. Laboratory periods are assigned for specific classes. The heavy use of the laboratory facilities makes it virtually impossible to reschedule any laboratory. Instructors shall weigh laboratory participation as part of the course grade.

5. Students may work in the laboratory only with proper supervision. Students wishing to use an operating laboratory shall request permission from the instructor assigned for those periods. Work accomplished outside the normal class period shall be signed by the instructor who is assigned for those periods.

6. Defective test equipment shall be tagged by the instructor after verification that the item is not functioning properly. Instruction books for all equipment may be borrowed from the ECE stockroom library for use during the laboratory period. They must be returned to the ECE stockroom before the end of the period.

We intend to provide the best experimental and test facilities within our resources for every student doing laboratory work in the ECE department. Please help us by learning to check your test equipment and being able to troubleshoot your experimental setups quickly and accurately.

ECE Laboratory Goals

1. The main goal of these laboratories is to introduce the student to a broad range of basic engineering practice.
2. Another goal is to develop, for each student, practical technological skills used to solve engineering problems.
3. The student will learn the art and practice of technical communications by writing technical reports that are clear, concise and correct.
4. Oral presentations, group discussions and informal critiques will be used to stimulate critical thinking while in the laboratory environment.
5. Finally, the laboratory provides an understanding of physical magnitudes, and the opportunity to examine elements of system behavior which are not explained by idealized mathematical treatment.

The Purpose of a Technical Report

1. A good technical report should demonstrate to the supervisor that the required experimental work was performed with satisfactory results.
2. An engineering college report provides practice in the art of technical writing.
3. The individual discussions and conclusions in a group laboratory report allow each student to develop a deeper understanding of the laboratory work, and to use creativity in improving or applying practical laboratory experiences.
4. The technical report is usually written with the aid of references. Skills in learning *how to find out* are valuable professional assets that are associated with professional engineering and technical communications.

Laboratory Grades

It is very difficult to evaluate individual performance where a group effort is involved unless methods are employed to provide some *individualization* to the laboratory work.

Each instructor has the responsibility to insure that all students are provided the best opportunities to develop their technological skills. To maintain reasonable standards of performance, the instructor may assign students with unique skills to various laboratory groups. In essence, this arrangement becomes a *student helping student* proposition.

College should be a unique experience for everyone. To make the most of this opportunity, it is necessary to learn *how to learn.* One's peers can be of great assistance here. Communication with them can be very rewarding and is distinctly encouraged.

There is no violation of professional ethics in studying the reports of other persons. It is a violation of professional ethics to use another's work without direct reference or written permission. Professional responsibility does require that credit be given to others from whom concepts, ideas and quotations have been used.

Where students have jointly prepared a group report, each part of the report should bear the name and signature of the person responsible for that part of the report.

The Formal Laboratory Report

The purpose of the laboratory report is:

1. To provide an accurate account of the work that was performed in the laboratory.

2. To present in a clear manner the data that was accumulated, and the conclusions that were drawn from it.

3. To interpret the results and discuss them in the light of the underlying theory.

For a report to be useful, it must be logically arranged so that it is clear to the reader. The description of the various procedures must be accurate and the results obtained must be as precise as the measurements permit.

The format of a formal laboratory report is somewhat flexible depending on the particular requirements of the persons concerned, (company policy, government specifications, course requirements, and so on). For the laboratory work in the Department of Electrical and Computer Engineering the following format and sequence of presentation will be required for a *formal* report.

1. **Title Sheet and Cover**
   The appropriate title sheet-cover is available at the college bookstore. This cover provides spaces for the experiment title, names of the group members, data and other information. It should be completed in *ink* or *typewritten.* All other parts of the report should be written in ink or typewritten unless otherwise specified.

2. **Abstract of Synopsis**
   This summary includes the apparatus tested, the type of results obtained and a summary of conclusions reached. The purpose is to provide a *concentrated* survey of what experimental work was accomplished.

3. **Procedure**
   The section consists of a concise description of the apparatus used, the manipulations made, and the observations taken. Reference should be made to the appropriate circuit diagrams that follow later in the report. The procedure *should not* be a mere copy of the "Instructions" printed in the laboratory manual.

4. **Final connection Diagram**
   The connection diagrams should be complete within themselves. All pertinent information concerning ratings and stockroom numbers of the measuring equipment and apparatus tested should be included. Standard electrical symbols as listed in the EE 11 Manual should be used. A *neat* pencil diagram will be acceptable, if suitable for photocopying.

5. **Data Sheets**

   (a) The observed laboratory data should be placed at the end of the report. The original laboratory data should be taken in ink or ball point pen and should have no erasures. All information including meter numbers, meter scales, meter factors, must be recorded. Correction of recorded data is made in the laboratory by drawing a *line* through the incorrect entry and writing in the new entry.

   (b) The translated laboratory data should follow the connection diagrams. This data should be a summary of the laboratory measurements in final form. All meter multiplying factor computations should be carried out before entering readings on the final data sheet. All reports of the experiment should be identified on the data sheet by a *descriptive title* and reference made to the proper circuit diagram. The use of such references as "Part I" should be avoided.

6. **Computations and Results**
   The computations should be made in a logical manner in *simple computation* form, with a table of results that follows. The method should be *explained to the reader* and all terms and symbols defined; any formulas or equations taken from reference material should be properly footnoted. The final results should appear in tabular form presented in a manner that makes them stand out. This usually requires some individual planning. In general all curves that are plotted in a report are preceded by a supporting table of results found in the "results" section.

7. **Curves**
   See "Instructions for Graphs."
   Note: In some cases special graph paper (semi-log, etc.) will be required. This will be pointed out in the "procedure" portion of the laboratory manual.

8. **Phasor Diagram**
   When phasor diagrams are required they should be plotted, to scale, on quadrille ruled paper. A scale should be chosen so that a quantitative appraisal of the shortest vector can be made. A *neat* pencil diagram will be acceptable if it is suitable for photocopying.

9. **Discussion and Conclusions**
   Topics for discussion are usually suggested in the instructions. These suggestions provide a minimum framework around which the student should build a discussion. The discussion section provides the student with the greatest opportunity for originality in thought and logical reasoning. A thoughtfully clear discussion can greatly increase the value of a report.

   It is often possible to provide clear explanations by means of curves or diagrams, and these should be used where applicable.

   Conclusions, results, comments on sources of error and their probable magnitude should be made. In some instances recommendations are in order. *The discussion of results should be a student's individual effort.*

10. **Bibliography**
    A complete bibliography presented in standard form must be included. This bibliography must appear if footnotes are used. The bibliography should also include any credits to the work of other individuals, even if unpublished, unless this was accomplished through footnotes.

11. **English Style**
    The report should be written in past tense third person *impersonal*.

Instructions For Graphs

Materials

Graphs are to be consistent with good drafting style. Curves should be drawn on an adequate standard co-ordinate paper. They should be turned to be readable from left to right or from bottom to top (*never* from top to bottom). All figures should be captioned in a manner similar to that used in this manual.

Preparing Graphic Sheets

Graphs must indicate where, when and by whom the work was done. They must have a descriptive title. The graph sheets must contain enough information to make them sufficiently complete to be considered separately from the rest of the report.

Whenever possible, the meaning of the graph should be clarified by the addition of a small drawing somewhere on the sheet indicating, for example, how voltages were applied to the circuit or what measurements were made.

Place axes inside the printed edge; do not write in the white margins. Both axes of a graph must be marked with the scale and name of the quantity e.g., voltage (not V), and the corresponding units.

Choose a scale interval such that each main division represents 1, 2, or 5 units or a multiple of ten times 1, 2, or 5.

Enlargement of a graph scale sometimes provides greater precision. However, nothing will be gained if, at the smaller scale, the plotted points already exhibit scattering about the "average" line. It is also useless to expand the scale to the point where one unit in the last significant figure is represented by much more than a few divisions of the graph paper.

Start both scales at the origin (0, 0). In the case where a large part of the graph sheet, say 50 %, would be left unused, the origin may be omitted provided it has no significance in the interpretation of the graph.

When the range of the horizontal variable is very broad, a uniform scale may result in an overcrowding of the experimental points taken in the lower part of the scale. This problem may be solved by dividing the horizontal range into several parts and plotting a separate graph for each of these parts, using a uniform scale. However, a single plot covering the whole range is often desirable and a logarithmic scale is then found to be more convenient than a uniform scale. Semilog graph paper is recommended in this case.

Before using a semilog graph paper it is important to ascertain that it has a suitable number of cycles. A cycle represents a decade, that is, the numerical value of the variable at the end of the cycle is equal to ten times its value at the beginning of the cycle. Thus if the variable to be plotted takes on values from 2 to 425, three decades will be used, namely, 1 to 10, 10 to 100, and 100 to 1000. In this case a 3-cycle semilog paper is needed. Likewise, if the values go from 14 to 35000, four cycles are needed to show the intervals 10 to 100, 100 to 1000, 1000 to 10,000, and 10,000 to 100,000.

Plotting Points

In plotting a graph from experimental data, the plotted points should always be identified by a small circle, square or similar item. In plotting a graph from an analytical expression, use enough points to determine a smooth curve. The curve should go exactly through the points, which should *not* be circled or distinguished in any way.

Drawing Curves

In plotting a graph of experimental values, draw a *smooth average* curve which may or may not pass through most of the plotted points. When the proper curve is drawn, the plotted points will exhibit a random scattering on each side of the curve and will, on average, be as close as possible to the curve. An *experimental* curve should never show a special wave or bump by virtue of a single plotted point. Such complications in the curve would require that several points indicate the trend.

Interpreting Graphs

One of the purposes for a graph is to provide the writer of the report (as well as the reader) an overall picture of the data. Sometimes it is this picture which is the desired conclusion. A direct proportion is indicated by a graph only when the graph is a straight line *passing through the origin*. Frequently, there is a simple explanation available to show why the graph misses the origin. A note to that effect in the discussion of the graph is desirable in such cases.

In determining the slope of a tangent or of a straight line graph, use as long a straight segment as possible. Read values off the straight line; do not use plotted values.

Remember that tabulated experimental values contain experimental errors. The graph is a means of *averaging out* this error. A value read from the "smooth average" curve is likely to be closer to the "true" value than the plotted values which the curve misses.

Multiple Graphs

Whenever any information can be derived from the comparison of two graphs, or whenever two curves represent the same of similar tests, they should be plotted on the same sheet *with the same axes*. When several graphs are plotted on the same axes, distinguish between them by lettering a descriptive word or phrase along each curve. If the plotted points of two graphs tend to mingle, use different identifying marks for each set of points.

ECE 494A Laboratory Safety Rules

Read **ALL** of the following rules carefully, and remember them while working in the laboratory.

1. Never hurry. Haste causes many accidents.
2. **Always** see that power is connected to your equipment through a circuit breaker.
3. Connect the power source **last**. Disconnect the power source **first**.
4. Never make wiring changes on live circuits. Work deliberately and carefully and check your work as you proceed.
5. Before connecting the power, check your wiring carefully for agreement with the wiring diagram for an accidental short-circuit and for loose connections.
6. Check out the supply voltage to make sure that is what you expect. For example: AC or DC, 120V, 208V or 240V.
7. Do not cause short-circuits or high currents arcs. Burn from arcs may be very severe even at a distance of a few meters. Report all electrical burns to your instructor.
8. Be careful to keep metallic accessories of apparel or jewelry out of contact with live circuit parts and loose articles of clothing out of moving machinery.
9. When using a multiple range meter always use the high range first to determine the feasibility of using a lower range.
10. Check the current rating of all rheostats before use. Make sure that no current overload will occur as the rheostat setting is changed.

11. Never overload any electrical machinery by more than 25% of the rated voltage or current for more than a few seconds.
12. Select ratings of a current coil (CC) and potential coil (PC) in a wattmeter properly before connecting in a test circuit.
13. Do not permit a hot leg of a three phase 208V supply, or of a 240V or 120V supply to come in contact with any grounded objects, as a dangerous short-circuits will result.

Experiment 1 — Three Phase Power Measurements

Objectives

- To demonstrate the line and phase relations in 3-phase balanced networks.
- To study and demonstrate the two wattmeter method of measuring the power in 3-phase networks.

Equipment

- Five digital multi-meters from the stockroom.
- Two wattmeters with 0 - 300 watts scale.
- Three resistors with values very close to each other.
- One three-phase variac. (The one mounted on a small platform with casters which looks like a transformer with a wheel on top.)

References

- Richard Dorf, *Introduction to Electric Circuits*, pp. 777-793, 2nd edition, John Wiley & Sons, Inc., 1993.
- D. Johnson, J. Johnson, J. Hilburn, *Electric Circuit Analysis*, pp. 409-432, 2nd edition, Prentice Hall, N. J., 1992.

Background

Three-phase balanced networks are used in the power industry for reasons of economy and performance. Three-phase generators and motors run smoothly, with no torque pulsations, unlike single phase machines. In addition balanced three phase systems may be operated as three wire or four wire systems, with much less copper needed for the power delivered as compared with three single phase systems.

At a power generating plant, the windings of a three phase machine are arranged to provide three voltages, each 120° apart in time and, in the common *balanced* system, usually all of the same magnitude. These three voltage sources may be connected in a wye (Y) or a delta (Δ) configuration. Three phase loads may also be connected in wye or delta connections. The wye connection has a central node to which a neutral wire may be joined, but the delta connection is a three wire system without a node for a neutral (or ground) connection.

To measure power in a 3-phase system, it would seem necessary to use three wattmeters, each connected to neutral for a common terminal, and each responding to a line-to-neutral voltage and a line current. One would then add up the powers indicated on each wattmeter. Analysis of such a circuit shows that one wattmeter is redundant, hence the two-wattmeter method of measuring 3-phase power was developed for three wire systems. This method is satisfactory even if the loads are unbalanced. It is necessary to connect the wattmeters taking into account the polarity of their coils. When the current enters the marked terminal of the current coil and the voltage positive is connected to the marked terminal of the voltage coil, the reading represents power absorbed. In that case the *algebraic* sum of the wattmeters determines the total load power. In reactive circuits it may be necessary to reverse the current coil of one wattmeter in order to get an upscale deflection. This reading is taken as negative when the total power is determined algebraically.

If a 3-phase system has four wires, it is necessary to use three wattmeters, unless it is known that the system is balanced and therefore no current is flowing in the neutral wire. For any balanced N wire system it is necessary to use $N-1$ wattmeters to measure the total power.

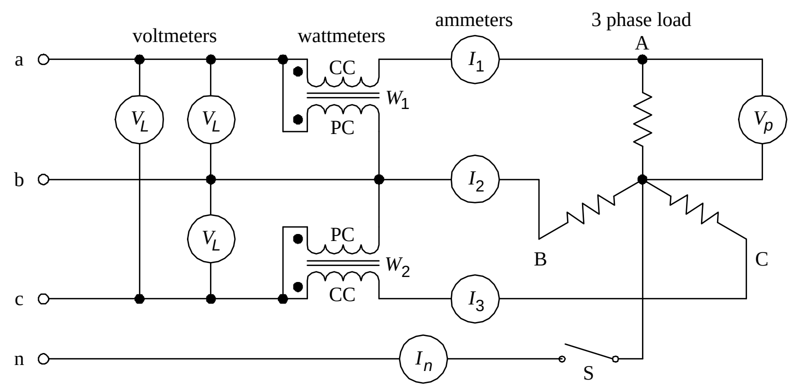

Figure 1.1: The balanced three phase wye connection.

Power Measurements on 3-ϕ Systems

1. Measure resistor values before the experiment; their values should be closely matched.

2. A voltage distribution panel is located on the side of the bench. Use a voltmeter to verify that the voltage is 208 volts between phases.

3. Connect the three-phase wye circuit as shown in figure 1.1. Note that all measurements in this experiment are AC. Estimate all instrument readings for a source voltage of 100 V between phases. Select your meter scales accordingly.

4. Read the wiring diagram on the three-phase variac carefully and adjust the output to be 100 volts between phases.

5. Without connecting the neutral, measure and record all currents, voltages (line and phase), and power. Record the results in table 1.1.
   Note: There are two sets of connections needed for a wattmeter to work. The terminals marked *Amp* should be in series with the load whose power is to be measured. The terminals marked *Volts* should be in parallel with the load whose power is to be measured. The *Volt* side has three connectors. When the 150 volt connector is used with the connector marked $\pm$, the wattmeter will read up to 300 watts. When the connector marked 300 volts is used with the one marked $\pm$, the wattmeter reading must be doubled. For example, if 120 watts is read on the meter and the 300 volt and $\pm$ connectors were used, then the power measured will be 240 watts.
   Note: If the deflection of the wattmeter is in the wrong direction (the

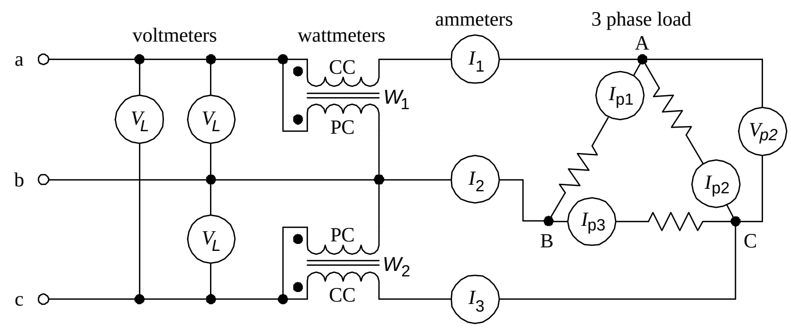

Figure 1.2: The balanced three phase Delta connection.

needle wants to go below the scale), disconnect the power supply and simply reverse the connection on the current side of the wattmeter. The wattmeter reading is then negative.

6. Connect an ammeter from the neutral of the resistor circuit to the neutral of the three-phase variac and observe the current flow. The current should be read on the 300 mA (or lower) scale.

7. Measure all currents, voltages and power readings. Record all measurements in table 1.1.

8. Connect the 3-phase circuit as shown in figure 1.2. Measure and record all currents, voltages and power readings.
   Note: There will not be enough ammeters for measuring all the line and phase currents at the same time. Measure the line currents first, then reconnect to measure the phase currents.

Report

1. Calculate the total load power, using the current and voltage data, by two different methods.

2. Tabulate the total load power from the calculations and from the two-wattmeter measurement method.

3. Verify phase and line voltage/current relationship.

Discussion Questions

1. Discuss any differences or similarities for the data obtained for the Y connection with or without neutral connection.

Table 1.1: Data sheet for Y and Δ connected load.

		Y w/o neutral	Y w/ neutral	Δ connection
Line Voltage in volts	V_{ab}			
	V_{bc}			
	V_{ca}			
Phase Voltage in volts	V_{AN}			—
	V_{BN}			—
	V_{CN}			—
Powers in watts	W_1			
	W_2			
Line/Phase Currents in amps	I_1/I_{p1}			
	I_2/I_{p2}			
	I_3/I_{p3}			
	I_N	—		—
Resistor in ohms	R_A			
	R_B			
	R_C			

2. Would the results be affected if wattmeter 2 were placed to measure the line current b-b' and both wattmeter potential coils were brought to line c, instead of line b.

3. Show a diagram for using only one wattmeter to measure the power in one phase of a balanced three-phase load.

Experiment 2 — Separation of Eddy Current and Hysteresis Losses

Objectives

To separate the eddy-current and hysteresis losses at various frequencies and flux densities using the Epstein Core Loss Testing equipment.

Equipment

- One low-power-factor (LPF) wattmeter from the stockroom.
- Two digital multimeters from the stockroom.
- One Epstein piece of test equipment. (It is mounted on a 3 ft×3 ft slide-equipped square platform stored in a cabinet and weighs 22 lbs.)
- Single Phase Variac. (Of cylindrical shape, it weighs about 15 lbs, and is about 10 inches in diameter and about 12 inches tall.)

References

- M. I. T. Staff, *Magnetic Circuits and Transformers,* pp. 144-154, John Wiley and Sons, 1985.
- Vincent Del Toro, *Basic Electric Machines*, pp. 34-38, Prentice Hall, 1990.

Background

Designers of electrical machines must know the magnetic characteristics of the material they use in order to predict the performance of their finished products. In this experiment core losses resulting from eddy currents and hysteresis in steel sheets will be measured. The Epstein test frame is a special one-to-one transformer having provisions for inserting the sample where it serves as a core. The testing procedure is specified by the American Society for Testing Materials (ASTM).

Description of the Apparatus

The windings are on four sections of hollow square fiber, each 1.57 × 1.57 inches square and about 17.25 inches long. Each section is wound with 150 turns of No. 18 wire. These turns are wound parallel to each other and in the same plane so that the primary and secondary turns lie alternately adjacent to each other in order to improve their magnetic coupling. The core material used is Armco 6M (USS Transformer 66).

The four sections are arranged to form a square. Primary turns on all sections are connected in series. The secondary turns are also connected in series.

The sample to be tested consists of 10 kg (22 lbs) of strips 3 cm wide and 59 cm long. One half of the sample is cut with the grain and the other half is cut across the grain. Four equal bundles are made of the specimen and each bundle is tightly taped and placed in a section of the winding. The four ends are then butted together in the form of a square with a piece of 0.004 inch thick paper in each joint, and all joints made as tight as possible.

Because of the tight coupling between the primary and secondary coils, the voltage induced in them by the AC magnetic flux is the same. Since the primary winding carries the current which establishes the magnetic flux in the core, the voltage applied to the primary winding includes the ohmic voltage drop due to the resistance of that winding. The secondary winding, on the other hand, is open-circuited; hence, its terminal voltage is equal to the induced voltage. The latter is given by

$$E_s = 4.44 f N_s (B_m A) \tag{2.1}$$

with

$$A = \frac{m}{l \cdot p} \tag{2.2}$$

where,

$$N_s \doteq \text{number of secondary turns} = 600 \tag{2.3}$$

$$B_m \doteq \text{maximum flux density in } Wb/m^2 \tag{2.4}$$

$$m \doteq \text{weight of bundle of strips} = 10 \text{ kg} \tag{2.5}$$

$$l \doteq \text{total length of strips} = 2 \text{ m} \tag{2.6}$$

$$p \doteq \text{density of steel in kg/m}^3 = 7700 \tag{2.7}$$

$$A \doteq \text{cross-sectional area of bundle strips} \tag{2.8}$$

$$f \doteq \text{frequency of AC supply.} \tag{2.9}$$

Substituting the values for N_s, m, l and p, we get

$$E_s = 1.73 \times f \times B_m \tag{2.10}$$

In order to separate the eddy-current loss (P_e) and hysteresis losses (P_h) when only total power loss (W) is measured, the following calculations must be performed.

$$\begin{aligned} P_h &= K_h \times B_m^n \times f && (2.11) \\ P_e &= K_e \times B_m^2 \times f^2 && (2.12) \\ \frac{W}{f} &= \frac{P_h + P_e}{f} = K_h B_m^n + K_e B_m^2 \times f && (2.13) \end{aligned}$$

where K_h and K_e are constants related to the material of the transformer core and its volume.

In (2.13) we see that if (W/f) is plotted against f for fixed B_m, a straight line is obtained whose slope is $K_e B_m$ and y-axis intercept $K_h B_m^n$. The hysteresis power loss for that value of B_m is then obtained by multiplying the y-intercept by the frequency. The corresponding eddy-current loss is the slope multiplied by the frequency squared. The procedure is repeated for each value of B_m.

To obtain the value of K_h, the logarithmic values of $K_h B_m^n$ obtained above are plotted against $\log B_m$. The slope of the resulting straight line is n and its y-intercept is $\log K_h$. Thus K_h and n can be obtained. Similarly, by plotting $\log K_e B_m^2$ against $\log B_m$ as a straight line of slope 2, $\log K_e$ can be obtained and, hence, K_e.

An alternator-dc motor set is used as a variable frequency AC voltage supply. The frequency can be changed by varying the motor speed. The magnitude of voltage can be altered by varying the alternator field current.

Note: Only the instructor can change the frequency and the maximum AC voltage. The students can then obtain fractions of the supplied voltage by turning the single-phase variac.

Eddy Current and Hysteresis Losses

1. Complete table 2.1 using (2.10).
2. Connect the circuit as shown in figure 2.1.
3. Connect the power supply from the bench panel to the *INPUT* of the single phase variac and connect the *OUTPUT* of the variac to the circuit.
4. Wait for the instructor to adjust the frequency and maximum output voltage available for your panel.
5. Adjust the variac to obtain voltages E_s as calculated in table 2.1. For each applied voltage, measure and record E_s and W in table 2.2.

Table 2.1: $E_s = 1.73 \cdot f \cdot B_m$.

B_m	$f = 30\,\text{Hz}$	$f = 40\,\text{Hz}$	$f = 50\,\text{Hz}$	$f = 60\,\text{Hz}$
0.4				
0.6				
0.8				
1.0				
1.2				

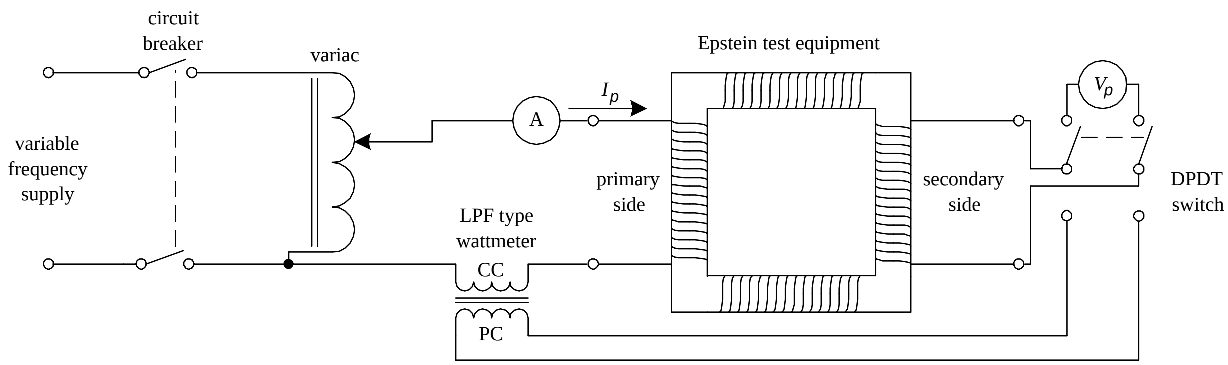

Figure 2.1: Circuit for Epstein core loss test set-up.

6. Perform the previous steps for frequencies of 30, 40, 50 and 60 hertz.

Report

1. Plot a graph of kg core loss (W/10), against the frequency f at different flux densities B_m on the same graph.

2. Separate the Eddy-Current P_e and hysteresis P_h losses at different flux densities B_m and frequencies f. Complete table 2.3.

3. Plot graphs for P_e and P_h against the frequencies for different flux densities on the same graph.

Discussion Questions

1. Discuss how eddy-current losses and hysteresis losses can be reduced in a transformer core.

2. Using the hysteresis loss data, compute the value for the constant n.

Table 2.2: Core Loss Data.

	$f = 30\,\text{Hz}$		$f = 40\,\text{Hz}$		$f = 50\,\text{Hz}$		$f = 60\,\text{Hz}$	
B_m	E_s Volts	W Watts	E_s Volts	W Watts	E_s Volts	W Watts	E_s Volts	W Watts
0.4								
0.6								
0.8								
1.0								
1.2								

Table 2.3: Data Sheet for Eddy-Current and Hysteresis Losses.

	$f = 30\,\text{Hz}$		$f = 40\,\text{Hz}$		$f = 50\,\text{Hz}$		$f = 60\,\text{Hz}$	
B_m	P_e Watts	P_h Watts	P_e Watts	P_h Watts	P_e Watts	P_h Watts	P_e Watts	P_h Watts
0.4								
0.6								
0.8								
1.0								
1.2								

3. Explain why the wattmeter voltage coil must be connected across the secondary winding terminals.

Experiment 3 — Performance Characteristics of DC Generators

Objectives

- To obtain the no-load magnetization characteristics.
- To obtain the external characteristics of DC shunt and compound generators.

Equipment

- Three digital multimeters from the stockroom.
- One tachometer from the stockroom.
- Rheostat with 175 Ω and 1.69 Amp rating.
- Loading resistors consisting of a rack painted green with four switches on top.
- A bench mounted motor-generator set.

References

- Vincent Del Toro, *Basic Electric Machines*, pp. 303-320, Prentice-Hall, 1990.
- A. Fitzgerald, C. Kingsley Jr., and S. Umans, *Electric Machinery*, pp. 390-414, 5th Edition, McGraw-Hill, 1990.

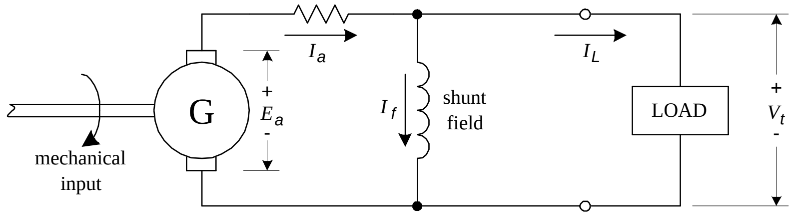

Figure 3.1: Schematic diagram of a self-excited DC generator.

Background

A DC generator, whose schematic is shown in figure 3.1, is an electrical machine which converts the mechanical energy of a prime mover (e.g. DC motor, AC induction motor or a turbine) into direct electrical energy. The generator shown in figure 3.1 is self exciting. It uses the voltage E_a generated by the machine to establish the filed current I_f, which in turn gives rise to the magnetic-field flux Φ. When the armature winding rotates in this magnetic field so as to cut the flux, the voltage E_a is induced in the armature. This voltage is commonly referred to as the armature electromotive force or EMF. The induced EMF is proportional to the rate of cutting the flux and is is given by

$$E_a = \frac{pZ}{60a}\Phi n \tag{3.1}$$

where

$$\Phi = \text{flux in webers} \tag{3.2}$$
$$n = \text{armature speed in rpm} \tag{3.3}$$
$$Z = \text{total number of armature conductors} \tag{3.4}$$
$$p = \text{number of poles} \tag{3.5}$$
$$a = \text{number of parallel paths} \tag{3.6}$$
$$\tag{3.7}$$

The magnetic field necessary for generator action may be provided by (a) permanent magnets, (b) electromagnets receiving their exciting current from an external source, and (c) electromagnets being excited from the current obtained from the generator itself (like that shown in figure 3.1). The use of permanent magnets is confined to very small generators. The electromagnetic excitations listed in (b) and (c) above give rise to generators having somewhat different types of characteristics.

In the case of a compound generator, the series and shunt fields may be connected so as to aid each other, i.e. the fluxes set up by each will add up.

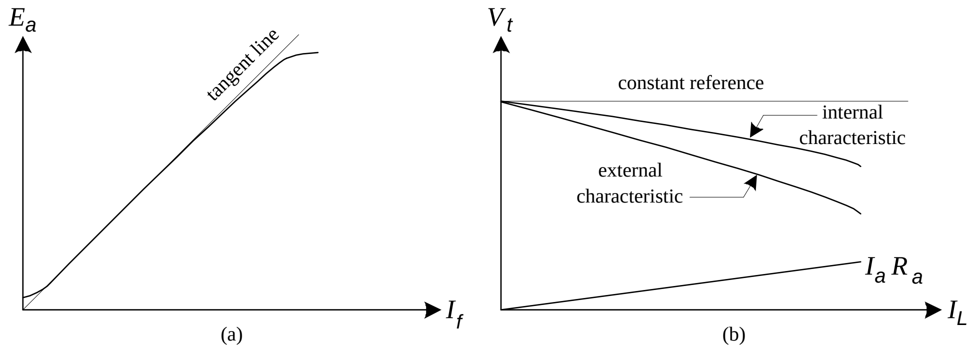

Figure 3.2: Magnetization characteristic (a) and internal and external characteristics of a DC shunt generator (b).

An increase in the total flux will generate a greater EMF. Such a connection is know as *cumulative*. If, however, the shunt and series winding are so connected that the flux set up by one opposes the other, then the induced EMF will be smaller. This type of connection is called *differential*.

Magnetization Characteristics

The typical magnetization curve for a shunt DC generator is shown in figure 3.2a. The generated voltage E_a is related to the field winding current I_f. This generator generates a voltage E_a even in the absence of a current I_f. The small voltage at zero excitation is due to residual magnetism in the pole material. Thus a self excited shunt generator is self exciting provided that an external voltage of the *proper polarity* is momentarily applied to the field winding to create the residual magnetic field at the time the generator is put into service for the first time.

The magnetization curve rises very steeply while the magnetic circuit is unsaturated. As the magnetic circuit saturates the curve flattens out. There is a critical field resistance R_c that allows a self excited shunt generator to be self exciting. In order to build up voltage in the generator, the total resistance in the field must be less than the critical resistance.

The critical resistance R_c, for the rated speed of the machine, can be determined from the magnetization curve. To do this, a tangent line is drawn to the magnitization curve starting from the origin. The slope of the tangent line represents the critical field resistance R_c.

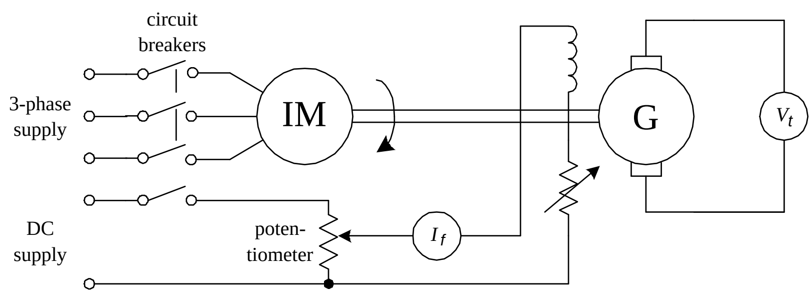

Figure 3.3: Circuit for checking the magnetization curve of a DC generator.

Observable Characteristics of a Shunt Generator

The voltage induced in the armature of a shunt generator is due to the armature wires cutting the magnetic field established by the field current. The induced voltage E_a, and hence the terminal voltage V_t, would be constant if other factors did not affect them. But the armature current I_a affects the terminal voltage V_t in two manners. The armature current distorts the magnetic field thus reducing the terminal voltage V_t. This effect is called *armature reaction*. In addition to the above there is the *ohmic voltage drop* $I_a R_a$, the product of the armature current I_a passing through the armature resistance R_a.

The graph of terminal voltage V_t versus load current I_L is called the "External Characteristic" as shown in figure 3.2b. It is directly measurable by observing the terminal voltage V_t for different load currents I_L. As is obvious form figure 3.1, the load current I_L and the armature current I_a differ by the field current I_f, which can also be measured.

The armature resistance R_a is a measurable quantity. As a consequence the ohmic voltage drop $I_a R_a$, which is a straight line, can be added to the external characteristic for the calculation of the internal generated EMF of the machine, which is shown plotted as the *internal characteristic* in figure 3.2b. The drop in voltage of the internal characteristic as the load current I_L (and hence armature current I_a) is increased is due to armature reaction.

Magnetization Characteristics

Procedure

1. Record the name-plate data of the DC generator.
2. Connect the circuit as shown in figure 3.3.
3. Run the generator at rated speed (1730 rpm) and no load.

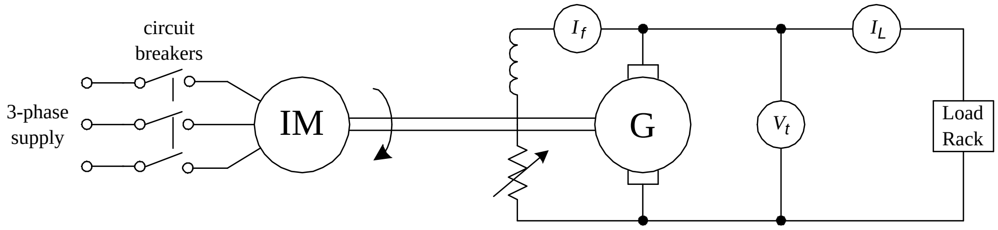

Figure 3.4: Circuit for measuring the characteristics of a shunt generator.

4. Connect the 240 volts DC source to the potentiometer to generate the field current I_f.

5. Record the voltage generated when I_f is zero.

6. Adjust the field current I_f (300 mA scale, DC) only in an ascending direction and in approximate 20 mA increments, then record the generated voltage V_a (DC). Repeat until the generated voltage is (almost) at 220 volts. (The rated value is 240 volts.)
Note: The maximum field current is about 230 mA. If the reading goes over the desired value, **do not** turn the potentiometer back as the DC generator will follow another hysteresis loop pattern.

7. After reaching the maximum voltage generated, decrease the field current I_f in the same manner in 20 mA increments until 0 mA is reached. At each I_f, measure and record the voltage V_a.
Note: Again, if the reading goes under the desired value, **do not** turn the potentiometer back up, just record the values of I_f and V_a.

Report

1. Plot the curves between the generated voltage V_a and field current I_f both for ascending and descending currents.

2. Obtain the mean magnetization curve by using the above curve.

3. Compute the value of the critical resistance R_c.

Characteristics of a Shunt Generator

Procedure

1. Measure the load rack resistor values for 8 different combinations.
Suggestions: Leave the first switch half way down and measure the resistor

value, then all the way down and measure the resistor value. While the first switch is closed all the way, put the second switch half way down, measure the resistor value then all the way down and measure again. Do the same thing for the other switches. This way, there should be 8 resistor load values available, ranging from 500 Ω down to about 50 Ω. Each two-stage switch represents 500 Ω when closed halfway and 250 Ω when closed all the way.

2. Complete the circuit as shown in figure 3.4.
3. Run the generator at no load and rated speed (1730 rpm).
   Note: If the measured voltage V_t is only 6 or 7 volts, simply reverse the connection of the field winding. The *expected* voltage generated at no load should be around 220 volts.
4. Connect the loading rack to the DC shunt generator. With each load resistor value-change, record the field current I_f (on 300 mA range, DC), the generated voltage V_t (DC), generator speed N and load current I_L (on 10 A range, DC).
5. Measure the resistance of the armature winding R_a at the end of the experiment by inserting the probes across the generator armature connector with all other wires disconnected.

Report

1. Plot the external curve of the terminal voltage V_t against load current I_L.
2. On the same graph draw the voltage drop line $I_a R_a$ against the load current I_L.
3. Obtain the internal curve using the curves above.

Characteristics of a Compound Generator

Procedure

1. Connect the circuit as shown in figure 3.5.
2. Run the generator at no load and rated speed. Reverse the shunt field connection if the generated voltage is substantially below the rated voltage of about 210 volts.
3. Connect the load rack to the circuit and with each load resistor value measure the motor speed N, terminal voltage V_t (DC), load current I_L (10 A scale, DC) and field current I_f (300 mA scale, DC).
4. Reverse the series field connection and repeat the last part.

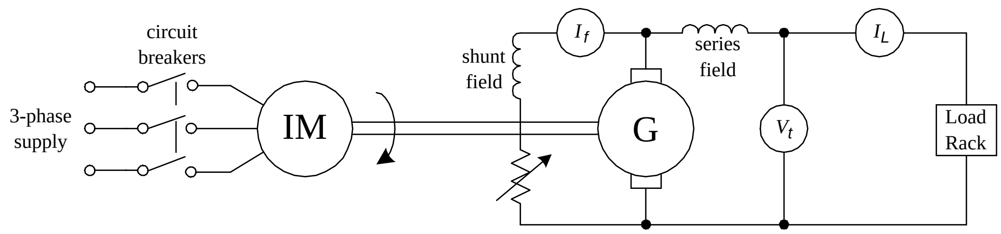

Figure 3.5: Circuit for measuring the characteristics of a compound generator.

Report

From the above data, plot the external characteristics for a compound generator.

Discussion Questions

1. Obtain the mean magnetization curve at 125% of rated speed.
2. Explain why the total resistance of the field circuit must be less than its critical resistance in a DC shunt generator.
3. Explain why an internal characteristic of a shunt generator is not a flat curve.

Experiment 4 — Load Tests on a Three-Phase Induction Motor

Objectives

To obtain the load performance characteristics of a three-phase squirrel-cage induction motor.

Equipment

- Four digital multimeters from the stockroom.
- One tachometer from the stockroom.
- Two wattmeters. (Use the ± and 300 V terminals for readings up to 600 watts).
- One resistor load rack.
- One Three-Phase Variac.

Background

The three-phase induction motor carries a three-phase winding on its stator. The rotor is either a wound type or consists of copper bars short-circuited at each end, in which case it is known as squirrel-cage rotor. The three-phase current drawn by the stator from a three-phase supply produces a magnetic field rotating at synchronous speed in the air-gap. The magnetic field cuts the rotor conductors inducing electromotive forces which circulate currents in them. According to Lenz's Law, the EMFs must oppose the cause which produces them; this implies that the rotor must rotate in the direction of the magnetic field set up by the stator. If the rotor could attain synchronous speed, there would be no induced EMF in it. But on account of losses, the speed is always less than the synchronous speed.

In this experiment the induction motor drives a DC generator. The field of the DC generator is excited separately. Loading the generator by means of a resistor load rack in turn loads the motor. When the motor drives a load, it has to exert more torque. Since torque is proportional to the product of flux and current, with increasing load the relative speed (slip) between the rotor and the rotating magnetic field must also increase.

The three-phase induction motor behaves as a transformer whose secondary winding can rotate. The basic difference is that the load is mechanical. Besides, the reluctance to the magnetic field is greater on account of the presence of the air-gap across which the stator power is transferred to the rotor. The no-load current of the motor is sometimes as high as 30 % to 40 % of the full-load value. The performance of an induction motor may be determined indirectly by loading a DC generator coupled to its shaft as is done in this experiment.

Relevant Equations

1. No-load data:

$$I_{a0} \doteq \text{Line current in amps.} \quad (4.1)$$
$$V_t \doteq \text{Terminal voltage in volts.} \quad (4.2)$$
$$P_0 \doteq \text{Input power (sum of both wattmeter readings).} \quad (4.3)$$
$$N_0 \doteq \text{Motor speed in rpm.} \quad (4.4)$$

2. Load test data:

$$I_a \doteq \text{Line current in amps.} \quad (4.5)$$
$$V_t \doteq \text{Terminal voltage in volts.} \quad (4.6)$$
$$P \doteq \text{Input power (sum of both wattmeter readings).} \quad (4.7)$$
$$N \doteq \text{Motor speed in rpm.} \quad (4.8)$$

3. Other data:

$$R_a \doteq \text{measured stator per phase resistance} \quad (4.9)$$

4. Core losses (including friction and windage loss) given by

$$P_c = P_0 - 3I_{a0}^2 R_a \quad (4.10)$$

5. The mechanical power output is

$$P_m = (P - P_c - 3I_a^2 R_a)(1 - s) = P_g(1 - s) \quad (4.11)$$

where

$$P_g \doteq P - P_c - 3I_a^2 R_a = \text{gap power} \tag{4.12}$$

$$s \doteq \frac{N_s - N}{N_s} = \text{slip of rotor} \tag{4.13}$$

$$N_s \doteq 120f/p = \text{synchronous speed} \tag{4.14}$$

$$f \doteq \text{frequency} = (60\,\text{Hz}) \tag{4.15}$$

$$p \doteq \text{Number of poles} = 4 \tag{4.16}$$

6. Since one horsepower equals 746 watts, we use the conversion

$$P_m\,(\text{HP}) = P_m(\text{watts})/746 \tag{4.17}$$

7. Torque is

$$T_m = \frac{P_m(\text{watts})}{2\pi N/60} = \frac{P_g(\text{watts})}{2\pi N_s/60} \tag{4.18}$$

8. Power factor at any load is calculated using

$$pf = \frac{P(\text{watts})}{\sqrt{3}V_t I_a} \tag{4.19}$$

9. Efficiency is given by

$$\eta = \frac{P_m(\text{watts})}{P(\text{watts})} \tag{4.20}$$

Three-Phase Induction Motor — Load tests

1. Arrange and measure the resistance of the load rack in the same manner as in the previous experiment for 4 different readings. It should range from 500 Ω down to about 100 Ω.

2. Adjust the output of the three-phase variac to be 110 V between phases before the circuit is connected.

3. Connect the circuit as shown in figure 3.1.
Note: The current terminals of the wattmeter should be **shorted** before turning on the motor, otherwise the start-up current will blow the fuse in the wattmeter. The voltage terminals of the wattmeter to be used are ± and 300 V. The reading of the wattmeters should be **doubled** to obtain the actual wattage.

4. With no load connected to the resistor load rack, run the motor, disconnect the wire shorting the current coil of wattmeter to get power readings. If

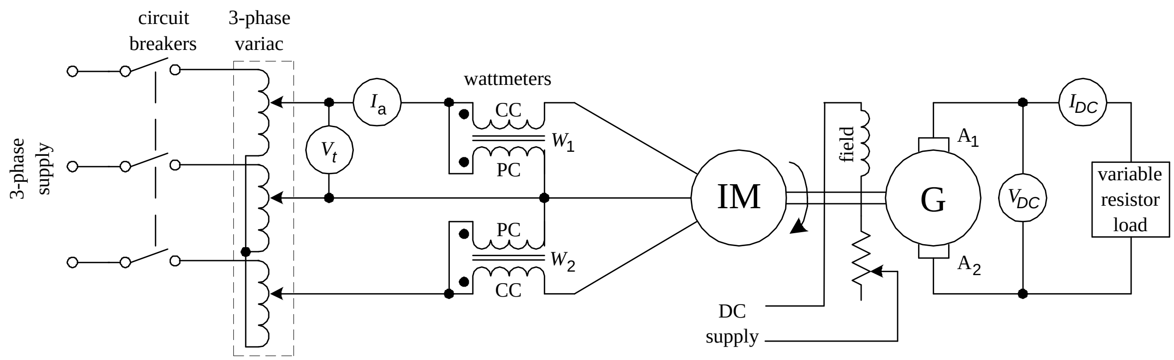

Figure 4.1: Connection for load testing of a there-phase induction motor.

the indicator of the wattmeter is deflected in the wrong direction, simply interchange the connections on the volt side of the meter. Record the terminal AC voltage V_t, the speed, the readings from both wattmeters and the DC load voltage V_{dc}.

5. Connect the resistor loading rack at the generator armature terminals. With each load value, record the reading of V_t, I_a, W_1, W_2, V_{dc} and I_{dc} (10 Amp scale) in table 4.1.
   Note: The load rack resistor value should not be under 100Ω or the wattmeter fuse will blow due to the excessive current.

6. Shut down the power, then disconnect all the wiring and turn on the motor starting switch. The stator winding resistor R_a is half the resistance value measured between the power supply terminals of the induction motor marked L_1 and L_2 on the bench. This is so because in a wye connection two phases are connected in series between terminals L_1 and L_2.

Report

1. Record the specifications of the induction motor.

2. Complete table 4.2.

3. Plot the efficiency η, power factor pf, speed N, horsepower and torque T_m against input current I_a on the same graph sheet.

Table 4.1: Experiment Data.

R_L Ohms	V_t Amps	I_a Amps	W_1 Watts	W_2 Watts	$P = W_1 + W_2$ Watts	I_{dc} Amps	V_{dc} Volts	N rpm

Table 4.2: Calculated Data.

I_a	pf	N	HP	T_m	η

Discussion

1. Discuss briefly any two methods of starting an industrial induction motor.
2. Report on the effect of interchanging any two terminals of the three-phase supply on the rotation.

Experiment 5 — Power Transformer Open and Short Circuit Tests

Objectives

- To conduct standard open and short circuit tests in order to find the parameters of the equivalent circuit of a transformer.
- Evaluate the regulation and efficiency of the transformer at a given load.
- Check the excitation characteristics of the transformer.

Equipment

1. Three digital multimeters from the stockroom.
2. One low power factor wattmeter from the stockroom.
3. Two scope leads from the stockroom.
4. One wattmeter (0 - 300 watts).
5. One single phase AC variac.
6. One four-winding single phase transformer.
7. One oscilloscope.
8. One 1 Ω resistor.

References

- Vincent Del Toro, *Basic Electric Machines*, pp. 51 - 88, Prentice Hall Inc., 1990.

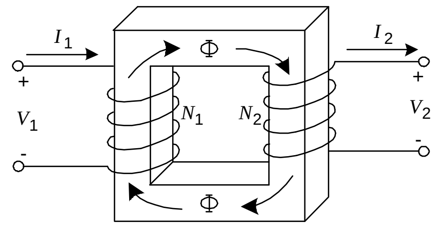

Figure 5.1: Ideal transformer.

- A. Fitzgerald, C. Kinsley, Jr., S. Umans, *Electric Machinery,* pp. 50 - 60, 5th Edition, McGraw-Hill Inc., 1990.

Background

A power transformer is usually employed for the purpose of converting power, at a fixed frequency, from one voltage to another. If it is used for converting power from a high voltage to a low voltage, it is called a step-down transformer. The conversion efficiency of a power transformer is extremely high and almost all of the input power is supplied as output power at the secondary winding.

Consider a magnetic core as shown in figure 5.1, carrying primary and secondary windings having N_1 and N_2 turns, respectively. When a sinusoidal voltage is applied to the primary winding, a flux Φ will exist in the core which links both the primary and secondary windings, inducing the RMS voltages

$$V_1 = 4.44 f N_1 \Phi \quad \text{in the primary winding} \tag{5.1}$$

$$V_2 = 4.44 f N_2 \Phi \quad \text{in the secondary winding} \tag{5.2}$$

The transformer is said to have a transformation ratio

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = a \tag{5.3}$$

Equivalent Circuit

The transformer may be represented by the equivalent circuit shown in figure 5.2. The parameters may be referred to either the primary or the secondary side. The series resistances R_1 and R_2 represent the copper loss in the resistance of the two windings. The series reactances X_1 and X_2 are leakage inductances and account for the fact that some of the flux established by one of the windings does not fully couple the other winding. These reactances would be zero if there were perfect coupling between the two transformer windings.

The shunt resistance R_p accounts for the core losses (due to hysteresis and eddy currents) of the transformer. The shunt inductance X_p is representative of

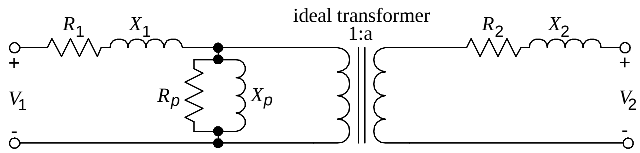

Figure 5.2: Equivalent circuit of a transformer.

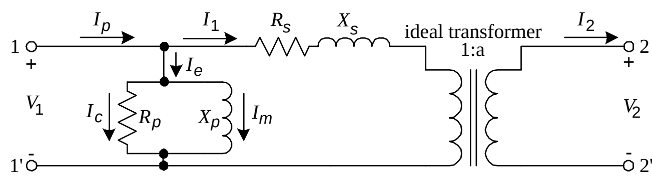

Figure 5.3: Simplified equivalent circuit of a transformer.

the inductances of the two windings and would be infinite in an ideal transformer if the number of turns of the two windings were to be infinite.

A knowledge of the equivalent circuit parameters permits the calculation of transformer efficiency and of voltage regulation without the need to conduct actual load tests. But experimental data must first be obtained in order to determine those parameters.

It will be confirmed at the conclusion of the first two parts of this experiment that the impedances of the series branch of the transformer equivalent circuit are substantially smaller than the impedances of the parallel branch. Because of this large discrepancy in the magnitudes of the elements we can redraw the equivalent circuit shown in figure 5.2 into that shown in figure 5.3. The errors introduced into calculations using figure 5.3 in place of figure 5.2 are quite insignificant. Furthermore, the large difference in the magnitudes of the transformer parameters allows for the determination of the elements in the series branch using one set of measurements and the elements in the parallel branch using another set of measurements.

Open Circuit Test

The open circuit test is used to determine the values of the shunt branch of the equivalent circuit R_p and X_p. We can see from figure 5.3 that with the secondary winding left open, the only part of the equivalent circuit that affects

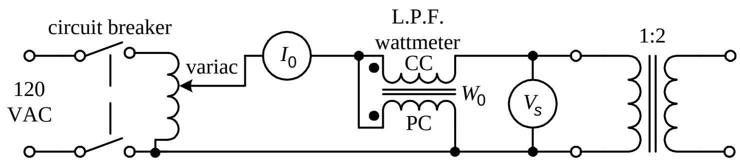

Figure 5.4: Circuit for open circuit test.

our measurement is the parallel branch. The impedance of the parallel branch is usually very high but appears lower when referred to the low voltage side. This test is therefore performed on the low voltage side of the transformer (terminals $1-1'$ in figure 5.3) to increase the current drawn by the parallel branch to a readily measurable level. Besides, the rated voltage on the low voltage side is lower and therefore more mangeable.

This transformer has four identical windings. Create a 1:2 ratio step up transformer by connecting the two primary windings in parallel and the two secondary windings in series. To make sure the secondary connection is made correctly, apply a voltage to the primary and make sure that the secondary voltages are connected in an aiding and not an opposing manner. This transformer will also be used in the next part of the experiment, so leave the connections intact when the present part is finished.

This transformer is rated at 0.5 KVA. The rated current is 500 VA/240 V = 2.08 A on the 240 V side and 500 VA/120 V = 4.16 A on the 120 V side. Be aware that the fuse used for each winding is rated at 2.5 Amps. In any case, the current in any of the four windings should never exceed 2.08 Amps.

Instructions

1. Connect the circuit as shown in figure 5.4. Make sure that the low voltage side of the transformer corresponds to the left side of the connection diagram. A low power factor wattmeter should be used.

2. Vary the input voltage starting at 0 V in 20 V increments to go up to 120 V. At each step change, record I_p, W_0 and V_1 in table 5.1.

Report

1. Compute the parameters R_p and X_p at the *rated* voltage by using

$$R_p = \frac{W_0}{I_c^2} = \frac{V_1^2}{W_0} \tag{5.4}$$

Table 5.1: Data for open circuit test.

V_1 Volts	I_p Amps	W_0 Watts	$I_c = W_0/V_1$ Amps	$I_m = \sqrt{I_p^2 - I_c^2}$ Amps	$\cos\phi = W_0/V_1 I_p$
20					
40					
60					
80					
100					
120					

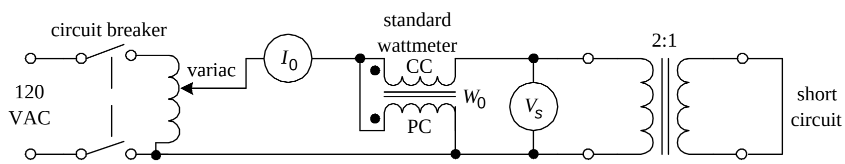

Figure 5.5: Circuit for short circuit test.

and

$$X_p = \frac{V_1}{I_m} \tag{5.5}$$

These parameters are referred to the low voltage side.

2. Find the values of R_p and X_p as referred to the high voltage side.

3. Plot the no-load current I_p, magnetizing current I_m and core loss W_0 and no-load power factor $\cos\phi$, against the applied voltage V_1 on the same graph paper.

Short Circuit Test

The short circuit test is used to determine the values R_s and X_s of the series branch of the equivalent circuit. These impedances are usually very low, but appear higher in value when referred to the high voltage side. This test is consequently performed on high voltage side of the transformer (terminals $2-2'$ in figure 5.3) in order to keep the current drawn by these impedances at a manageable level.

Table 5.2: Data for the short circuit test.

I_s Amps	V_s Volts	W_s Watts
4.0		
3.5		
3.0		
2.5		
2.0		
1.5		
1.0		
0.5		

Instructions

1. Using the 2:1 ratio transformer of the previous part connect the circuit as shown in figure 5.5. Make sure that the high voltage side of the transformer corresponds to the left side of the connection diagram. Use the voltage terminals $\pm$ and 150 V of the standard AC wattmeter.

2. Make sure that the variac is turned all the way down before starting this experiment.

3. Turn the variac up slowly until the current I_s (consult figure 5.5) is at the rated value (about 4 amps). Record I_s, V_s and W_s in table 5.2.

4. Repeat the previous step by reducing the current I_s in 0.5 A increments and record all values in table 5.2.

Report

1. Plot the copper losses W_s against the current I_s.

2. Compute the equivalent circuit parameter R_s and X_s at the *rated* high voltage winding current by first calculating

$$Z_s = \frac{V_s}{I_s} \tag{5.6}$$

$$\cos\phi_s = \frac{W_s}{V_s I_s} \tag{5.7}$$

The above results can then be used to find

$$R_s = Z_s \cos\phi_s \tag{5.8}$$

$$X_s = Z_s \sin\phi_s \tag{5.9}$$

These parameters are referred to the high voltage side.

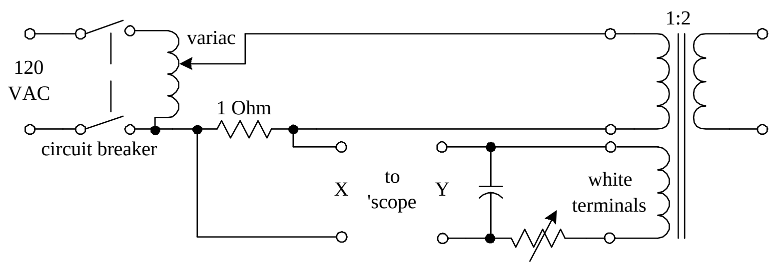

Figure 5.6: Circuit for obtaining transformer excitation characteristics.

3. Calculate the values of R_s and X_s referred to low voltage side.

4. Now that we have all the parameters for the transformer equivalent circuit, compute the voltage regulation at the rated power and at a lagging power factor of 0.8.

5. Calculate the per unit efficiency at the rated power and at a lagging power factor of 0.8.

Excitation Characteristics

Instructions

1. Connect the circuit as shown in figure 5.6.

2. Apply 20 volts (peak to peak) to the primary side of the transformer. Display and record the voltage waveform of both primary and secondary sides on a two channel oscilloscope.

3. Display the voltage across the 1 Ω resistor (which represents the excitation current of the primary winding) and the voltage of the secondary side on an oscilloscope and record their waveforms. Notice the non-symmetry of the excitation current waveform and the phase shift relative to the secondary voltage.

4. Apply the excitation current to channel I of the oscilloscope. Connect the info winding (the connectors are located on top of the primary winding) to an R-C passive integrator available on the back of the transformer and display the voltage across the capacitor on channel II of the oscilloscope. The purpose of the integrator is to integrate the voltage in order to get the flux since $e = N(d\phi/dt)$.

5. Press the X-Y button on the oscilloscope to see the hysteresis loop.
6. Increase the voltage applied to the primary winding and record the change in the shape of the hysteresis loop.

Discussion Questions

1. Calculate the value of the maximum efficiency of this transformer and determine the current at which it occurs.
2. Explain how the excitation current waveform can be graphically obtained from a hysteresis loop and flux waveform. Write a computer program to perform such an operation.
3. Using the laboratory data, determine percent efficiency at half rated power and 0.8 lagging power factor.