

ECE 431

Electric Machinery

COURSE GUIDE AND LABORATORY INFORMATION

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Preface

The Grainger Electrical Machinery Laboratory is dedicated in memory of University of Illinois alumnus W. W. Grainger, B.S. 1919. In his name, the Grainger Foundation funded the reconstruction of the electrical machinery laboratory in the Department of Electrical and Computer Engineering at the University of Illinois. A grant of \$500,000 provided the facility. The authors gratefully acknowledge this generous support.

Additional donations from the Tektronix Foundation and from the John Fluke Manufacturing Company have ensured that the laboratory is equipped with instruments of the highest quality.

Conceptual design of the Grainger Electrical Machinery Laboratory was done by P. T. Krein and P. W. Sauer. Henneman, Rauf Eisen, and Associates completed the detailed design and supervised construction work. Laboratory workstations were designed by P. T. Krein, and were constructed by the Department. A complete upgrade was conducted by P. L. Chapman and P. T. Krein in 2003. Additional changes are included for 2014. The extensive efforts of personnel in The Department's Electronics Shop and also the Machine Shop are deeply appreciated.

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Contents

1. Introduction	1
1.1 Why Electric Machinery?	1
1.2 Laboratory Team	1
1.3 The Laboratory Report	2
2. Safety	6
2.1 Safety Precautions	6
2.2 Summary of Laboratory Safety Features	7
2.3 First Aid	8
3. Lab Orientation	9
3.1 Objectives	9
3.2 Introduction	9
3.3 Map of the Facility and Electrical Panels	9
3.4 Tour of the Electrical System	11
3.5 The Lab Workbenches	12
3.6 Nameplate Machine Data	15
4. Lab Experiments	16
Experiment #1: Three-Phase AC Measurements	16
Experiment #2: Single-Phase Transformer Tests	21
Experiment #3: Stepper Motors (Reluctance Machines)	30
Experiment #4: Induction Machine Characterization	41
Experiment #5: Advanced Induction Machine Topics	50
Experiment #6: Synchronous Machine Tests and Synchronization	54
Experiment #7: Synchronous Machine Power Characteristics	59
Experiment #8: Synchronous Machine Dynamic Simulation	66
Experiment #9: Brushless DC Motor Equivalent Circuit and Performance	70
Experiment #10: DC Machine Equivalent circuit	77
Experiment #11: DC Machine Torque-Speed Characteristic	82
Experiment #12: A Model Power System	87
5. References	90

Introduction

Why Electric Machinery?

Today almost half of all energy worldwide is delivered in the form of electricity. Globally, about 2/3 of all electrical energy is delivered to electric machinery, and nearly 100% is produced by machines. It is well known that growth in electrical energy production has been closely correlated with economic growth in nearly all countries over the past several decades. The reasons are not just those of increases in energy consumption. The fundamental advantages of electrical energy—the convenience with which it is converted, the ease with which it is transmitted, and the high density of it as an energy source—continue to drive global growth in electric power.

The study of electric machinery and electromechanics offers a wide range of opportunities in such diverse areas as manufacturing process control, control systems, electrical energy generation, electromechanical systems and actuators, electric and hybrid transportation, disk drives, electronic power conversion, and others. Electric machinery and electromechanics provides an area for the generalist, in that expertise in electromagnetic field theory, circuit analysis, communication principles, information theory, electronics, computers, control systems, and energy areas must come together to create a complete working system. The need for expertise in this area continues to broaden and remains strong even during economic slumps.

The study of electric machinery is long established within electrical engineering. New technologies and materials, the economics of energy, the use of sophisticated computer hardware and software, and rapid advances in power electronics for energy and motion control offer inviting topics for new engineers.

1.2 Laboratory Team

Laboratory experiments normally will be done in groups of two or three students. Duties are assigned to help keep experiments organized and efficient. The duties are as follows:

- Leader: In charge of the experiment. Responsible for being familiar with procedures in depth and with any special safety considerations for the experiment. Acts as the link between group members and the instructor for questions. Responsible for decisions concerned with procedural details for the experiment. Responsible for ensuring that all equipment is properly put away at the end of the session.
- Recorder: Records all experiment data and observations in a formal notebook. Responsible for providing each group member with a copy of the data at the end of the session. Responsible for accuracy, completeness, and neatness of the data record.
- Helper: Other group members help with setup, cleanup, and actual performance of the experiments, as directed by the group leader.

Of course, all group members are active in the preparation, setup, and performance of each experiment. Be sure to return all equipment to the proper locations at the end of the session. These duties rotate among group members from session to session in the following manner: The recorder for a given experiment is leader for the next; the helper, if one is assigned, becomes the recorder. The leader becomes the helper or recorder.

1.3 The Laboratory Report

Individual reports on *each* experiment are required. They are due at the next laboratory session after the experiment. Reports are to be written based upon the group data furnished by the Recorder.

The format to be used for reports is as follows:

1. Title Page, with the following, (centered and in order)
 - a. Course number
 - b. Experiment number
 - c. Experiment title
 - d. Date of experiment and date of report write-up
 - e. Your name
 - f. In the lower right-hand corner, list all group members with their assigned duties
2. Introduction: State what your report covers (i.e., objectives, etc.) – roughly 100 words
3. Body
 - a. The body of the report should be broken into logical subsections based on the material covered in the experiment. For example, in the first experiment, a logical choice of subsections might be Wye-Connected Resistive Load, Delta-Connected Complex Impedance Load, and Induction Motor Load.
 - b. One sample calculation must be shown for each set of calculations. First show any equations used in their general form. Equations must be properly formatted using MS Equation Editor or a similar tool. Be sure to indicate the purpose behind each calculation.
 - c. Results of repetitive calculations should be tabulated in a neat, organized manner. Be sure to tabulate any data you intend to plot. Be certain to label each table with a table number and descriptive caption. It is important to remember that poor results are often caused by errors in calculations or simple data-recording mistakes, such as scale mis-readings. Be sure to examine your calculations to see whether they are reasonable, and try to find the difficulty if they are not.
 - d. All graphs must be electronically generated. Be sure to label your graphs completely. Include a figure number, legend, and a title block as shown in the example below. Add x and y labels with units.
 - e. *The most important aspect is discussion of the results.* The report should show that you understand the results and can explain them to another engineer who did not conduct the experiment. It should be more than a listing of data and observations. Discuss the results of your experiment and draw any deductions that are reasonable based on your results. The discussion should be brief and should not repeat procedures or data. Cite your own calculations, graphs, and data by figure number, table number, or page number for clarity. You are encouraged to use additional references if you feel the need, but be sure to provide complete bibliographic information (use IEEE format) at

the end of the discussion. The discussion should be concise but complete. Be sure to address any questions included in the experiment manual.

6. Conclusions

Summarize your overall findings and suggest what additional experimental work might be a logical next step.

7. Appendix

Complete data should be maintained during the experiment in a proper laboratory notebook with the information shown below. A legible photocopy must be submitted with the laboratory report as an appendix. For all data, exactly the same information is to be shared among all group members. The notebook data should include:

- a. Date of the experiment
- b. Names of group members present, and their duties
- c. Wiring diagrams actually used in the experiment *if they differ from those provided in the laboratory manual*. Discussion in the report can refer to figures in the manual or in your datasheet.
- d. Serial number of the lab workbench used
- e. Serial numbers of any large equipment used which is not normally stored at your workbench
- f. All laboratory data and observations

Other information for the report

1. Use 8 ½" x 11" paper, single-sided printing, double-spaced format.
3. Everything in the reports must be typewritten or electronically generated.
4. Sloppy work or poor grammar will lower the report grade.

Evaluation Criteria for Lab Reports:

Format: Report conforms to specified overall format

Quality of text: Report is well-written and concise. Figures are useful and easy to read.

Technical merit: The observations, discussion, etc., are technically accurate.

Quality of results: The data taken are sensible and consistent with the theory, to the extent the theory is valid, and the discussion is consistent and effective in explaining the results.

Based on this list, most of the evaluation is based on the discussion.

Sample title page

ECE 431

Experiment #1

Three-phase ac measurements

PERFORMED 1/28/2020

WRITTEN 2/3/2020

Joan Illini

LEADER – Joan Illini
RECORDER – Leo Hand
HELPER – Hual Dunn

Sample graph and table

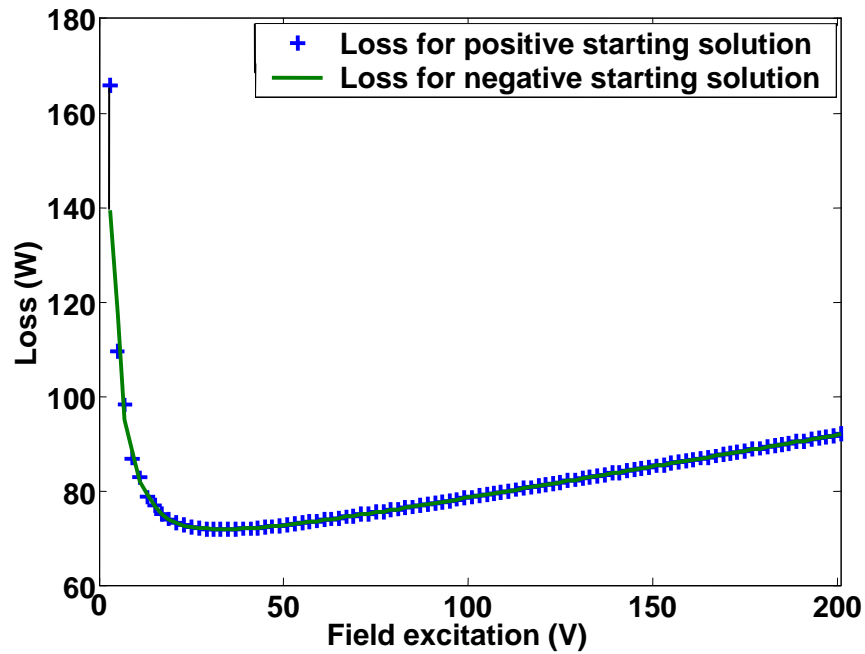


Figure 1.1. Power loss as a function of excitation voltage for offset dc machine.

Table 1.1
Measured power at various resistor values

Condition	Resistor value (Ω)	Measured power (kW)
Series connection, 1 ϕ	14	1.50
Series connection, 3 ϕ	14	4.61
Parallel connection, 1 ϕ	14	6.15
Parallel connection, 3 ϕ	21	12.3

2 Safety

The Grainger Electrical Machinery Laboratory has been designed with safety in mind. However, the power levels and rotating machines used in ECE 431 are potentially hazardous. Please use thought and care in the laboratory. Observe obvious safety rules by making measurements with proper caution and by avoiding circuit changes when power is on. Do not defeat guards and bench features which prevent contact with rotating parts and live connections. Familiarize yourself with lab safety features. If an accident does occur, *shut off power* and call for help. A summary of recommended safety precautions and safety features is given below. While no such list can be complete, you are *required* to be familiar with these precautions.

Safety Precautions

Primary rules

1. *Do not make circuit changes or perform any wiring when power is on.*
2. *When in doubt, turn power off.*
3. *Assume that panel jacks on your bench are electrically live unless power is off.*
4. *Be sure you understand the function and wiring of an instrument before using it in a circuit.*
5. *Do not repeat the same mistake.*
6. *Do not guess—know! If in doubt, see 2 above.*
7. *Do not wear loose-fitting clothing or jewelry in the lab. Rings and necklaces are usually excellent conductors in excellent contact with your skin.*
8. *It is wise in electrical labs to wear pants rather than shorts or skirts. Ties are also dangerous.*
9. *Powered equipment can be hot! Use caution when handling equipment after it has been operating.*

Additional key precautions

1. Acquaint yourself with disconnect switches, especially those at your bench.
2. Work slowly and deliberately. Think as you act.
3. Do your wiring, setup, and a careful circuit checkout *before* applying power.
4. *Use wires of appropriate length.* Do not allow them to drape over your equipment. Avoid splices, which create live surfaces. When running a pair of wires to adjacent terminals, twist the wires together so they do not dangle. This also neatens your work and will *save* time.
5. Keep your bench organized and neat. It should be clear of coats, extra books and papers, and unused equipment.
6. *Use your bench.* Avoid long connections by using the bench transfer wires. Plug instruments into the bench, not into the wall. This gives you the protection of the bench switches.

7. No smoking in the lab, and no food or beverages on or near the workbenches. *If you smell smoke, turn off power.*
8. Do not touch anything if your hands are wet. The “one-hand” approach is safest.
9. Do not pull wires out until you are absolutely sure that the circuit is completely dead. Shocks can occur if an inductive load (motor or transformer) is disconnected while conducting.

In the event of an accident or emergency:

- Do not panic.
- Shut off all power.
- Call for assistance. Fire Department and emergency services 9-911.

2.2 Summary of Laboratory Safety Features

The laboratory is equipped with an emergency electrical shutoff system. This can be activated by any of the large red buttons located on panels and benches throughout the room. When *any* button is pushed, power is disconnected from *all* panels in the room. The regular wall duplex outlets and the room lights are not affected. *These buttons were designed to protect you. Use them when necessary.* If the emergency system operates, and you are without power, inform your instructor. **Do not try to restore power under any circumstances.** It is your instructor's responsibility and task to locate the trouble, resolve it, and restore power when it is safe to do so.

Each lab workbench is connected to power only through a set of line cords attached to the bench. The line cords are connected directly to two front panel switches labeled “3 ϕ ” and “dc mains,” and to the switch on the bench outlet column. Your bench can be de-energized by shutting off these three switches. Do not circumvent them by plugging instruments directly into the wall outlets.

The benches plug into lab station panels in any of eleven locations throughout the room. The panels are numbered 1 – 11. Each is supplied from a set of circuit breakers. Your instructor will assist you by turning on the necessary breakers when you are ready. Please realize that circuit breakers can only protect against extreme problems or mistakes. They cannot protect against electric shock.

The rotating parts of the machines on each bench are separated from laboratory workers by a plastic shield on the front and sides. Keep your bench close against a wall or against the rear of a second bench to prevent access to the rotating parts. The machines have been set up for your experiment, and no adjustment will be needed. Some experiments will be conducted with much smaller machines that will not require a shield. However, even with the small machines it is possible to get things tangled in the rotors (ties, hair, etc.).

Many panel jacks on your bench have been prewired for your convenience. Transfer connections throughout each bench provide convenient connections to meters. This allows short, organized connections, and helps to avoid the “rats nest” problem. It also means that many front panel cables will create electrical paths to several points on your bench. *Be aware of the labels, and respect them.*

2.3 First Aid

Training in standard first aid procedures and cardiopulmonary resuscitation (CPR) is a helpful skill. Call the local Red Cross for information about classes in Urbana-Champaign. The directions here serve as brief reminders. Review them *before* you need them.

Bleeding: *Pressure* is the key treatment. Press hard with a compress until bleeding stops. In severe cases, maintain pressure and call for help. For nosebleed, have victim sit down and pinch bleeding nostril. Seek help if bleeding is difficult to stop or if the wound is significant.

Burns: For mild burns, with unbroken skin, immerse in cold water or apply cold towels. If the skin is damaged or charred, have the victim lie down and keep warm to help prevent shock, and send for help. Flood chemical burns with clear water for fifteen minutes, and seek medical advice.

ABC of Life Support

ABC of Life Support:

A — Airway open. Lie victim on back if it is safe to do so. Quickly remove any objects from the mouth. Tilt the head back to provide an airway.

B — Breathing restored. If the victim is not breathing, place your mouth tightly over victim's, pinch the nostrils, and blow until you see the chest rise. Allow a few moments for the chest to deflate. Start with four quick breaths, then check for a pulse. If present, continue mouth-to-mouth breathing at 12 times per minute. If no pulse, alternate breathing with CPR.

C — Circulation maintained. Quickly feel for pulse at the next, under side angle of lower jaw. If none, begin external cardiac compressions as follows: Victim's back should be on a firm surface. Place the heel of your hand on the lower breastbone, about 1½ inches up from the lower tip, with fingers off the chest and your other hand on top. Gently rock forward, exerting pressure down, to force blood out of the heart. Release pressure. The rate should be about 60 compressions per minute.

Choking: If victim is actively coughing or choking, wait briefly, since the obstruction is often cleared. If the victim cannot choke or if choking continues, get behind victim. Place the thumb side of your fist just below the rib cage, grasp your fist with your other hand, and press into the victim's abdomen with a quick upward thrust. Repeat. If victim loses consciousness, pull tongue and jaw forward, and dislodge any visible objects. Perform mouth-to-mouth resuscitation or CPR until help arrives.

Electric shock: Turn off power or use an insulating object to break contact between victim and power source. If breathing has stopped, begin mouth-to-mouth resuscitation or CPR until help arrives. If victim is conscious, treat for burns or shock, and seek medical advice.



One Rescuer: Alternate CPR with breathing, giving two full breaths after each 15 compressions. Compressions should be somewhat faster, at 80 per minute.

Two Rescuers: Perform CPR and breathing simultaneously, as above.

For Small Children and Infants: Cover both the nose and mouth when performing breathing. Blow gently, but faster, at about 20 times per minute. For compression, use only one hand for children, and only the finger tips for infants. Give 80 to 100 compressions per minute.

This reminder is not intended as a training tool. To be able to perform CPR effectively, a practice course is *essential*.

3 Lab Orientation

3.1 Objectives

The objectives of the laboratory orientation are to familiarize the students with the Grainger Electrical Machinery Laboratory facility, its special safety features, and the custom power workbenches.

3.2 Introduction

The Grainger Electrical Machinery Laboratory was funded through a grant from the Grainger Foundation. This facility is among the best student power laboratories in the world, and rivals many modern industrial research counterparts in terms of safety and instrumentation.

The laboratory has three major components:

- A set of power lab-station panels which provide access to ac power, dc power, a central patch system, and an emergency disconnect system.
- A central panel which controls energy flow to each lab station panel. The panel provides full circuit-breaker protection for the facility. It also contains a central patch panel for interconnections among lab stations.
- A set of power workbenches. Each bench is a complete self-contained power test station, and requires only external electrical sources. The benches hold a set of rotating machines, a set of dedicated power meters, an instrument rack, a cable rack, and a set of connection panels. Extra instrumentation and equipment are stored in cabinets at the bottom of each bench.

In this orientation, a tour will be given of the facility, as well as a “wire tour” of the electrical system and the workbenches.

3.3 Map of the Facility and Electrical Panels

The laboratory is located in room 4024 in the Electrical and Computer Engineering Building (ECEB). A lab map is shown in Figure 3.1. The Design Lab Annex and Power Projects Lab are in 4022 ECEB, and the Advanced Power Applications Laboratory, in 4020 ECEB, is a research facility which shares many of the same features as 4024 ECEB..

The laboratory is supplied by two dedicated transformers which convert building power at 480 V ac to a 60 Hz ac power supply of up to 150 kVA each (or about 400 A at 208 Vac three-phase). A set of industrial power supplies provides dc power of ± 120 V at up to 24 kW, on a separate feed. These ac and dc supplies are distributed to the laboratory through a main panel.

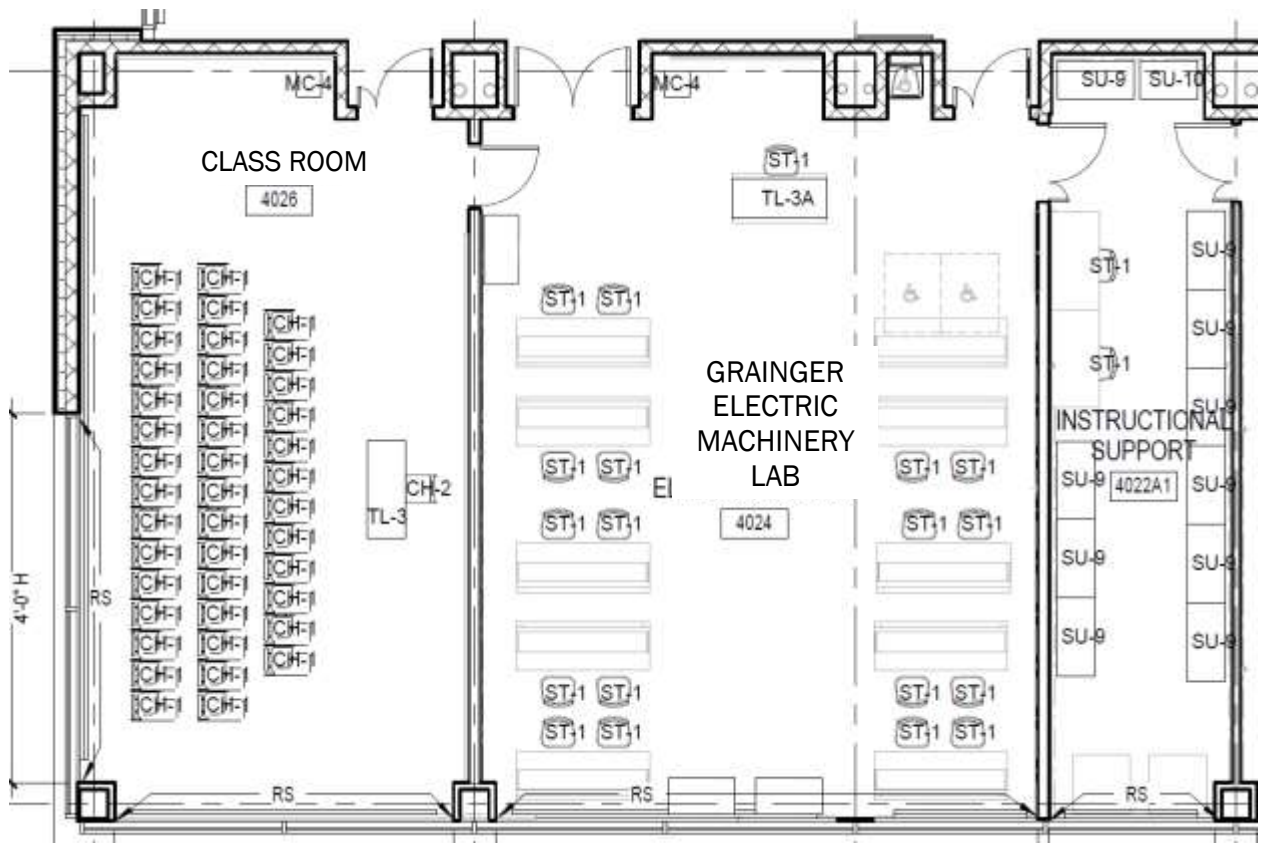


Figure 3.1. The Grainger Electrical Machinery Laboratory and supporting areas

The master circuit breakers have what is called a *shunt trip* mechanism. They can be turned off internally with a short pulse of ac power. This mechanism is used for the laboratory emergency disconnect system as follows: When any of the red *panic buttons* throughout the room is pushed, all master breakers are forced to shut off. When this occurs, power is cut off at all lab station panels throughout the room. This important safety feature will be tested often and can be used whenever necessary. The panels are not connected to lights or to regular wall outlets in the lab. Use of the panic buttons will not disturb any sensitive equipment.

Power access at workbenches is provided through a set of eleven identical *lab station* panels, located throughout the laboratory. A view of one such panel is given in Figure 3.2. The panel contains two power outlets for convenient access to our most commonly used power sources. A set of duplex outlets connected to one of the sources is also provided. The center of the panel holds eight *transfer jacks* which are wired to the patch area. There is also a ground jack for access to a solid earth ground. Line cords on each lab workbench make connections to the various power sources convenient.



Figure 3.2. Front view of lab station panel

3.4 Tour of the Electrical System

The electrical system provides access to several voltage levels from the dedicated ac supply, and to both polarities of the dc supply. The following supplies are available for use:

- 120/208 V three-phase four-wire. This is a common commercial electrical supply level. The three phases each carry 120 V ac RMS relative to a common neutral point, which means the line-to-line potentials are 208 V ac RMS. The neutral point is connected to earth ground at a central location, so the source is not a floating one.
- 120 V single-phase power for the three duplex outlets for each lab station's panel is taken from each phase of the 120/208 V source, as in a typical commercial installation.
- An independent 120 V single-phase source is connected to regular wall outlets in the room. This source is not part of the room's emergency disconnect system and is recommended for computers and electronic instruments.
- ± 120 V dc three-wire. This supply is a set of two Magna-Power Electronics dc power supplies (240 V dc 80A). The third *central* wire is a grounded neutral point. The supply can provide 240 V dc for ungrounded loads such as motor windings.

The lab station panels have direct access to the 120/208 V ac three-phase, and ± 120 V sources.

3.5 The Lab Workbenches

Overview

The power lab workbenches are the central feature of the laboratory. Each bench is designed as a complete test station, with its own safety features and protective mechanisms. The benches have space for instrument operation and for storage, rotating machines, and power connections. The benches are mobile, and can be placed at any suitable location within the room. A layout appears in Figure 3.3. There are two functionally identical bench versions: a right-hand unit and a left-hand unit.

The benches are divided into four major sections: input power handling and distribution, rotating machine access panels, the instrument rack, and the load patch area. There is storage in the cabinets beneath each bench. Input power is supplied through any of three line cords, stowed in the *window* area at one end of the bench. (This window has been arranged to allow access to a wall lab station panel.) The line cords have incompatible plugs to prevent errors in power—please do not try to force connections. They are of the twist-lock style to prevent accidental removal.

Three-phase ac power to the bench is taken from the 120/208 V wye source and wired to the 3ϕ mains switch on the bench front panel. When this switch is off, no three-phase power will appear at the bench panels.

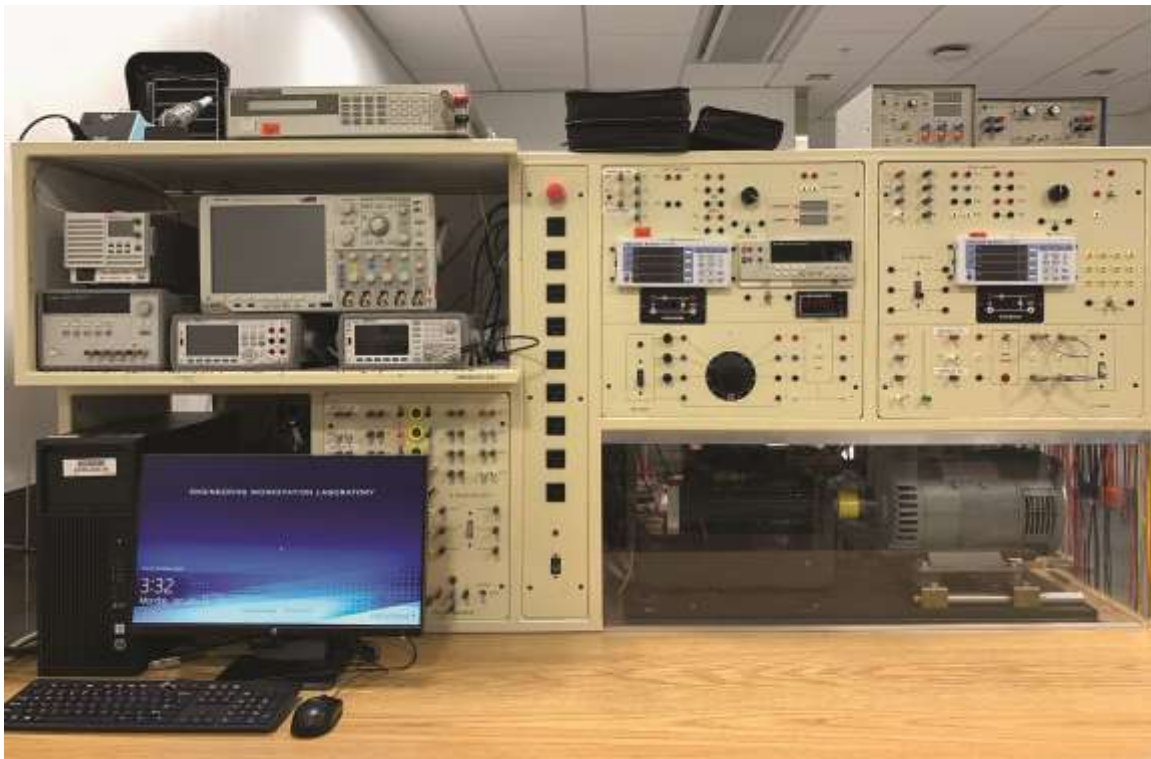


Figure 3.3. The laboratory power workbench

Dc power to the bench is routed from the line cord, through a fuse box and then to the *dc mains* switch on the bench front panel. As with ac power, turning this switch off will remove all panel access to the dc source.

The single-phase ac instrument power is routed from the familiar 1 ϕ line cord to the outlet column near the center of the bench through a front-panel circuit breaker. Instrument power also supplies outlets in the instrument rack, along with internal outlets for permanent instruments. The single-phase line cord should be plugged into the regular wall duplex outlet on the wall so that computers and instruments will not be affected by use of the room panic buttons. The other cords should be plugged in only as necessary for power access.

Each bench can be shut off by turning off the 3 ϕ mains switch, the dc mains switch, and the instrument power switch. Alternatively, the line cords can be removed.

Inventory

Each bench is permanently equipped with the following:

- Variable three-phase ac transformer, 0-230 V, 0-10 A
- Yokogawa WT310 Power Meter (four display) RMS V A Watts, PF, dc to 100 kHz 20 A
- Fluke Model 45 dual multimeter
- Speed and torque meters connected to the machine set
- Westinghouse Power Miser ac motor start box
- Three-phase transformer set 120 V/25.2 V
- Variable power resistors 0-300 Ω , 150 W
- Power resistor, 100 Ω , 150 W
- Three three-pole 30 A switches
- Two one-pole switches, one rated 30 A, one rated 6 A for meter shunting
- Kollmorgen *Goldline* brushless servo motor and drive (B-206-C21 + SR20200), 0-4900 RPM and 0-19 N-m torque

In addition, each bench is supplied with the following equipment:

- Tektronix Model MS04304B scope, 350 MHz 2.5 GS/s, 4 CH Analog and 16 CH Digital
- Tektronix current and isolated voltage probes
- Keithley 2260B-80-27, 720 W
- Agilent 34461A 6½ Digit Display, Multimeter
- Agilent 3350B Waveform Generator Series Trueform
- Agilent E 3631A Triple Output DC Power Supply 6 Vdc 5 A, ± 25 Vdc 1 A
- Hewlett-Packard 6060B electronic load
- General Electric Model CD186AT 1.5 HP dc machine

- TECO/Westinghouse 2 HP 1.5 kW three-phase induction motor
- Advanced Motor Tech 1.5 kW wound-rotor synchronous machine
- Additional dc and ac machines
- Three power resistor boxes, each with ten 500 Ω resistors
- Three capacitor boxes, each with eight 6 μF capacitors
- Three 1 kVA, 240/120 V transformer boxes
- Computer with LabVIEW Dynamometer Control, GPIB, USB, Network, NI 6014 cards
- Lead rack with banana leads of various lengths

Additional instruments available in the laboratory for shared use include:

- Hewlett-Packard Model 4195A network/spectrum analyzer
- Tektronix Model 371 power semiconductor curve tracer
- Hewlett-Packard plotter and printer
- Philips Model PM6303 automatic RCL meter
- Laser printer and copier

The laboratory also has a tool set and selections of electronic parts.

3.6 Nameplate Machine Data

Brand	TECO Westinghouse	GE	Dayton	Hampden	Advanced Motor Tech	Yaskawa Minertia	SKC
Type	Induction motor	Dc motor – wound compound	Induction motor	Synchronous motor/ generator	Synchronous motor/ generator	Brushed dc pancake servo	Brushless dc servo PM rotor
Output	2 HP 1.5 kW	1.5 HP	1/3 HP	2 HP	1.5 kW	10.7kW/ sec	40 W
Hz	60		60	60	60		
Phase	3		3	3	3		
Volts	230/460	Arm 240 FLD 240/120	208 230/460	133/230	230		24/75
Amps	5.21/2.60	Arm 5.6 R = 466/3	1.5 – 1.5/0.75	15.5/9	3.8	37.1 peak	2.5/0.9
Ohms		I _f = 0.37x3					
RPM	3450	1150/2000	1725	1200	1800	3000 rated 4000 max	3000 rated 4000 max
Torque Rated/peak						1.26/6.28 Nm	12.7/13.28 Ncm
Voltage Constant						17.8 V/ 1000 rpm	5.2/15.5V/ 1000 rpm
Duty Ratio	N/A	Cont	Cont	Cont	Cont		
Service Factor	1.15		1				
Field					240 Vdc, 1.3A, 135Ω		
Model	Asheuw DH0022	GEH 3967/CD186AT	3N842BA		A002- D0120L085		

4. Lab Experiments

Experiment #1: Three-Phase AC Measurements

Objective

The objectives of this experiment are to become familiar with the laboratory equipment and 3ϕ ac power circuits. Specifically, 3ϕ voltage, current, and complex power relationships will be verified.

Introduction

We are all familiar with single-phase (1ϕ) ac circuits, particularly for domestic uses. The number of phases encountered in a power circuit should not be confused with the number of different voltages available from the source. For example, domestic 120/240 V sources are single-phase since they are usually obtained from one phase of a 3ϕ electric power distribution network. Three-phase power circuits are predominant in commercial and industrial uses, mostly for economic reasons, although the very existence of three-phase circuits can be attributed to their amenability to rotating magnetic fields. In terms of output power, a polyphase circuit is somewhat like a multi-cylinder internal combustion engine. The power in all cylinders is summed to obtain the total shaft power, but the construction is such that each cylinder is important because the power portion of the engine stroke does not occur at the same time in each cylinder.

The total real and reactive power delivered to or consumed by a load is the algebraic sum of that consumed by each element regardless of connection type. Three-phase real and reactive power consumption may be measured in many ways. This experiment uses the classical two-wattmeter method for the total 3ϕ real power. Many types of wattmeter have been invented. Ours use analog and digital electronic circuits to multiply current and voltage. They then compute and display the average of this product.

Procedure

NOTE: Unless otherwise specified, all measurements should be RMS values.

NOTE: Always zero the voltage probes and degauss the current probes before measurements.

NOTE: Color coding is very helpful in this lab.

Part A: Wye-connected resistive load

1. Set up a balanced wye-resistive load, as shown in Figures 1.1., 1.2, and 1.3.
2. Measure the following:

- Line current magnitudes (two measurements)
- Line-to-line voltage magnitudes (two measurements)
- Phase current magnitudes (current through load, two measurements)
- Phase voltage magnitudes (voltage across each leg of the load, two measurements)
- Phase shift between the phase voltage and phase current (choose any one). Save a screenshot of the waveforms.
- The total real power supplied to the load using the two-wattmeter method (Figure 1.2)
- The total reactive power supplied to the load using the one-wattmeter method (see Figure 1.3). Danger: The wattmeter may have metal leads exposed; be very careful not to touch them or let them touch anything!

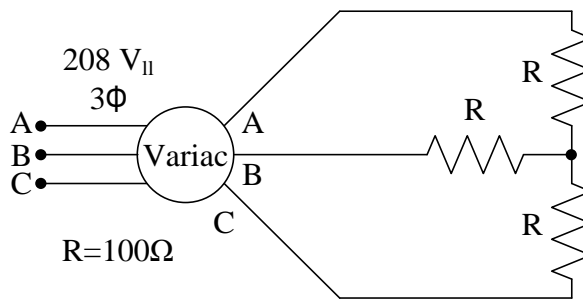


Figure 1.1. Balanced wye connected resistive load

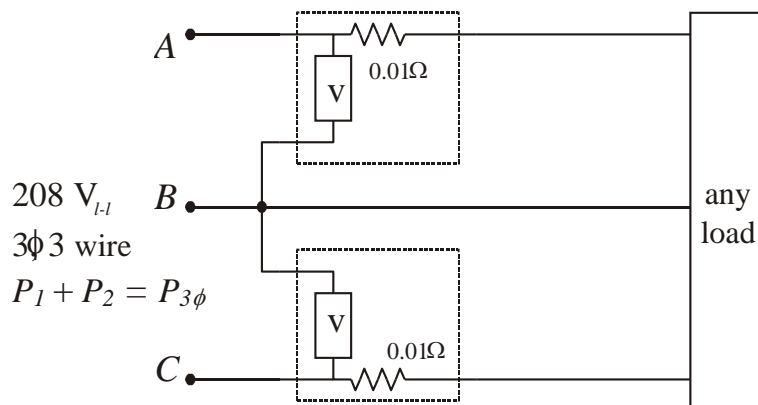


Figure 1.2. Two-wattmeter connection for sequential A-B-C

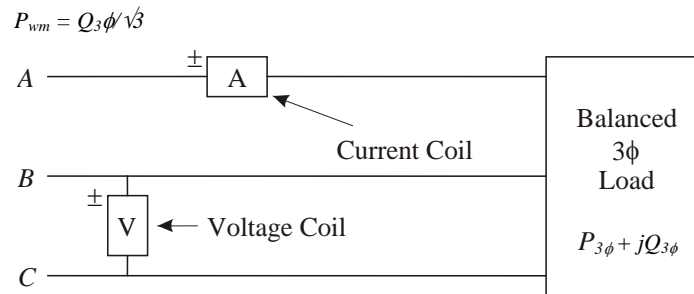


Figure 1.3. One-wattmeter connection for seq. A-B-C

Part B: Delta-connected complex impedance load

1. Set up a balanced delta impedance load as shown in Figure 1.4. Group the capacitor boxes. Be sure to ground capacitor boxes.
2. Repeat Step 2 of Part A.

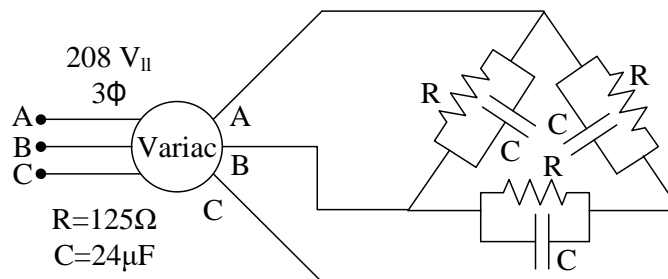


Figure 1.4. Balanced delta-connected impedance load

Part C: Induction motor load

1. Set up an induction motor as a load, as shown in Figure 1.5. Set up to measure real and reactive power. The sequencing of the supply will affect the direction of machine rotation. This will be important in future labs.
2. Connect a 250Ω across the 240 V dc bus, as shown in Figure 1.6.
3. Start the motor by turning on the 3φ mains and slowly turning up the Variac (1–2 seconds) from 0% to 100%.
4. Measure:
 - a. Line currents (two measurements)
 - b. Line-to-line voltages (two measurements)
 - c. Total real power supplied, using the two-wattmeter method
 - d. Total reactive power supplied, using the one-wattmeter method
 - e. Phase shift between the phase voltage and phase current. Save a screen shot of the waveforms.

Be careful not to create any open circuits while the motor is running!

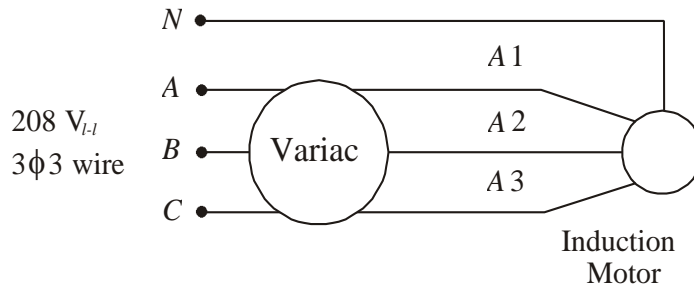


Figure 1.5. Induction motor load

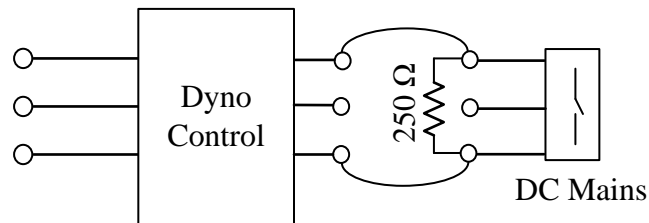


Figure 1.6. Dyno control wiring

Notes

1. Use a data sheet or notebook page to record all quantities measured. Make sure all information necessary to write the report is included and clearly labeled.
2. Remember that there will be exposed conductors and terminals in the experiment set up. These can cause serious physical harm. Take your time, and observe all safety precautions.

Report

1. Determine the total 3ϕ real and reactive power delivered to the loads in Parts A, B and C of the procedure.
2. For the two-wattmeter method, how does P_1 compare with P_2 in each part? Under what conditions does $P_2 = 0$? When does $P_1 = P_2$?
3. Verify the balanced wye connection relationships between the phase and line currents, and the phase and line-to-line voltages (use average value of two readings).
4. Repeat Step 3 for the balanced delta connection.
5. Determine the power factors for each of the three loads.

6. Consider the delta-connected load. Using the numerical values of R and C in ohms/phase, predict the power factor and compare with the answer of Step 5.
7. Compare the reactive power using the one-wattmeter method with the number computed using P_1 , P_2 and the voltmeter and ammeter readings for Part C.

Final Comments

It is interesting to conjecture what changes would be observed in modern power systems if 3ϕ circuits had not been developed. Thomas Edison never favored the use of ac circuits, and early publications show his doubt that 3ϕ would ever be used. Early power systems (1880-1900) were primarily dc, using ± 120 V with a grounded center conductor, still called the *Edison system*. George Westinghouse favored ac circuits owing to the ease in raising and lowering potentials. Most early circuits were 1ϕ . Nikola Tesla established the 3ϕ system, but after a time he favored higher frequency circuits and possible wireless transmission.

Bulk power demands and very rapid growth of electrical demand no doubt influenced the choice of 3ϕ transmission methods. These were attractive because of their low loss and economy as far as the amount of copper conductor required to transmit a given quantity of power. It is not at all certain that the best number of phases to be used is three. Research in this area has investigated the use of six-phase and twelve-phase systems. Motor research has suggested advantages of five-phase and fifteen-phase sources.

Actually, the Edison dc system did not really disappear. Large-scale dc distribution continues to be the power of choice for telephone and communication networks. It is essentially universal for telephone wire lines, cell towers, cable television, and other networks. Some researchers are discussing the revival of the Edison system. One reason is that electronic equipment nearly always operates on dc and requires an input rectifier to process incoming ac power. Another reason is that conversion among dc levels today is almost as routine as the use of transformers for conversion among ac levels. Single-phase power circuits have a fundamental disadvantage of double-frequency time-varying power not shared with either three-phase or dc systems. Dc power is making a major comeback for large-scale data centers and could become increasingly common.

Experiment #2: Single-Phase Transformer Tests

Objective

The objective of this experiment is to become familiar with more of the lab instrumentation by studying the characteristics of single-phase transformers. Specifically, tests will be performed to determine coil polarity, number of coil turns and the transformer steady-state equivalent circuit. Magnetic saturation will be observed.

Introduction

A single-phase transformer is a device which steps up or down a given voltage (although it can be thought of as stepping current up or down as well, in some cases). Typically, a transformer has two windings. One is called the *primary* (usually the source side) and the other is called the *secondary* (usually the load side). If there are more than two windings, the additional windings are called *tertiary windings*. The windings are wound on a core made of ferromagnetic material. There is usually no direct electrical connection between the pairs of windings. When a given time-varying voltage is applied to one of the windings, a time-varying magnetic flux is established in the core. The current required to produce this flux is called the *exciting current*. High permeability (μ) iron is usually used to facilitate the creation of this flux. The flux will link all other windings, which are wrapped around the core encompassing the flux path. The time-varying flux linking the windings induces a time-varying voltage in the other coils. This time variation is usually sinusoidal. The magnitude of the induced voltage is determined approximately by the number of turns in each coil. That is, if 120 V is applied to a coil of N turns, and 30 V is induced in a test coil of ten turns, then the source coil has $N = 40$ turns. This test is called the *coil turn test* and can be used to approximate the number of turns if the number is not known. A transformer with high voltage turns N_1 and low-voltage turns N_2 is considered an $a:1$ (a to one) transformer where $a = N_1 / N_2$. When two coils are connected in series or parallel, the physical direction of turn-wrapping determines how the respective induced voltages will behave relative to each other. The physical arrangement of the windings is not always easily determined after manufacturing. A method called the *polarity test* is used to determine if two coils have “additive” or “subtractive” polarity. This method is used to specify polarity marks for each winding.

Based on this description of the transformer we can see there is resistance and inductance for each winding and a mutual inductance between the windings. There are also core losses caused by hysteresis and eddy currents. The latter are losses due to the currents induced in the ferromagnetic

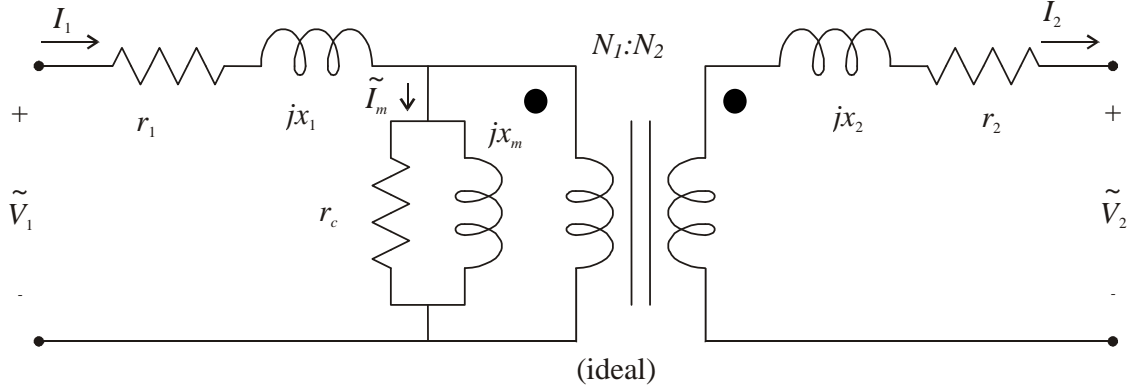
core material. Transformer cores are often laminated to reduce these losses. The amount of core loss is a function of the magnetic flux strength in the core. Thus if rated flux is produced in the transformer core while the transformer is unloaded, the majority of losses measured are the core losses. This is the purpose of the *open-circuit test*. In this test, the winding resistances and leakage reactance are neglected since only a small amount of current will flow in them, producing only small power loss. In order to determine the winding resistance and leakage reactance, it is necessary to reduce the core-losses effects. This can be done by short-circuiting one side and applying a reduced voltage to the other side to produce rated current. This is called the *short-circuit test*. The reduced voltage results in a low level of flux in the core, and thus the measurements made are dominated by losses resulting from the rated current in the series impedances. Basically, the shunt core losses and magnetizing reactance are negligible.

The performance characteristics of a transformer are specified by its voltage regulation, efficiency and percent impedance. Input voltage regulation is defined as the *load side voltage at no load minus the load side voltage at full load, divided by the load side voltage at full load* (where the load side voltage at full load is rated, and the source voltage remains fixed). It is expressed in percent, and zero percent is the ideal regulation. Efficiency is the ratio of real power out over real power in. It is expressed in percent, and 100% is the ideal efficiency. The per-unit impedance of a transformer is the magnitude of the impedance looking in one side (with the other side shorted) divided by the “base” impedance for that side. The per-unit impedance is called *percent impedance* when expressed in percent, and zero percent is ideal. The *base impedance* is the rated voltage divided by the rated current. These performance characteristics can all be found from the equivalent circuit of the transformer (see Figure 2.1). The voltage regulation and efficiency could also be found experimentally using the “load test.”

This introduction has mentioned five basic tests. We will perform them in the laboratory. References [1-4] discuss transformer tests and characteristics in detail.

The Saturation Problem

Any real magnetic material exhibits a maximum value of B , called the *saturation flux density* B_{sat} , beyond which it displays permeability equal to that of vacuum. Since the flux ϕ in a material is found as magneto motive force (Ni) divided by reluctance, the current in all windings ultimately determines whether the saturation flux density has been reached. Alternatively, the flux ϕ is given by λ/N , or $\int v \, dt/N$. The integral of voltage (*volt-seconds*) determines the flux, within some integration constant.



r_1, x_1 = Resistance and leakage reactance of “1” side

r_2, x_2 = Resistance and leakage reactance of “2” side

r_c = Core loss resistance referred to “1” side

x_m = Magnetizing reactance referred to “1” side

Figure 2.1: Single-phase transformer equivalent circuit

A real core has two limitations due to flux: the maximum value, determined by the integral of voltage, and the integration constant, which can be shown to equal Ni_{dc}/\mathcal{R} . Maximum volt•seconds and a maximum dc current result from the saturation limit. Hysteresis and eddy current loss can also be viewed as flux limitations. The applied voltages and currents must not cause excessive power loss in the material.

In a transformer, saturation must be avoided so that leakage flux and losses are low. For ac applications, this means that only the volt•second integral is relevant. But notice that if a dc current is applied, a second flux contribution will appear. In most power-frequency transformers, the number of turns is high, and tolerance for dc current is low. Dc current must be avoided.

The circuit in Figure 2.4 is intended for measuring hysteresis loops of magnetic materials. Recall that H is equal to Ni/ℓ for the core and that B is related to flux linkage as $B = \lambda/(NA)$. The flux linkage, λ , can be found as $\lambda = \int v dt$. Current can be readily measured. It is proportional to H . In the circuit shown, voltage v_c is approximately proportional to λ . This will be true provided the resistor value $R \gg X_c$.

Procedure

Part A: Polarity, coil turn, and dc resistance tests

1. Assume that the top terminal of the 115 V coil is marked with a dot. Perform the polarity test of Appendix A2 to determine the dot location on the 230 V coil. *Apply only 50 V to the 115 V coil.* Ignore any old dot markings. Note: this must be ac!

2. Apply 115 V across the 115 V coil. Measure the voltage on the 10-turn search coil and the 230 V coil to determine the respective number of coil turns.
3. Use a benchtop dc power supply to determine the dc resistance of the 115 V and 230 V coils at rated current. (Rated current can be calculated using transformer ratings.) Low voltages are required. Set current limit on supply to 80 % of rated value.

Part B: Open-Circuit Test

1. Connect the low side of the transformer through the Variac. Leave the high side open-circuited (see Figure 2.2).
2. Measure the following quantities at rated voltage (115 V)
 - a) Low-side current
 - b) Low-side voltage
 - c) Power into the low side

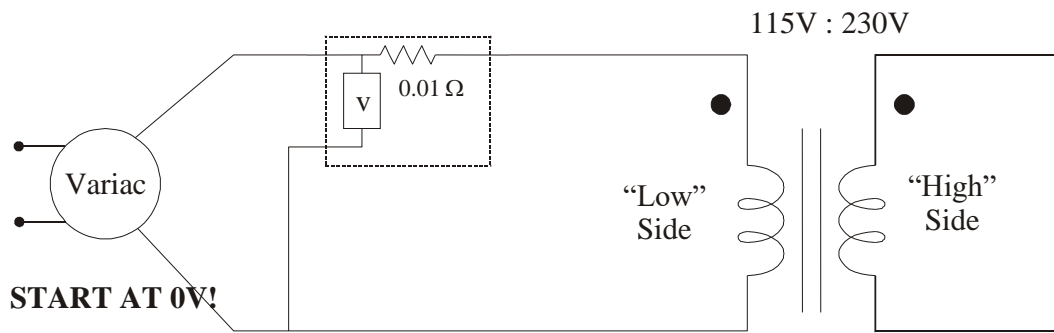


Figure 2.2: Wiring diagram for open-circuit test

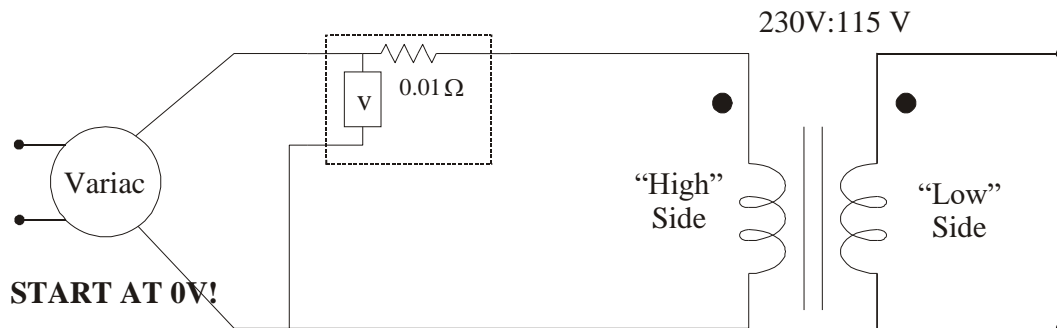
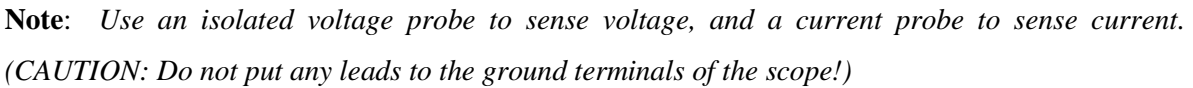


Figure 2.3: Wiring diagram for short-circuit test



Part E: Single-phase transformer saturation

1. Set up the circuit shown in Figure 2.4. Set the capacitor box for 48 μF .
2. Beginning with minimum voltage, increase the Variac output to obtain 50% rated voltage on the 115 V coil.
3. Record all measurements.
4. Increase the Variac output to obtain rated transformer voltage, and repeat step 3.
5. Use the oscilloscope in X-Y mode to observe v_c vs. i . Current is on Channel 1, and voltage is on Channel 2. Save a screenshot of the waveform. Record v_c and i peak-peak value with oscilloscope.
6. A sample transformer should be available for geometric measurements. Record as needed to find magnetic areas and path lengths.

Notes

1. Designate the high-voltage side as “1” side.
2. The open-circuit test will yield the excitation impedance referred to the “2” side.
3. The short-circuit test will yield the equivalent impedance referred to the “1” side.
4. The winding resistances and leakage reactances may be found from step 3 by assuming equal r and x per turn, i.e.,

$$r_1 = \left(\frac{N_1}{N_2} \right)^2 r_2 \quad x_1 = \left(\frac{N_1}{N_2} \right)^2 x_2$$

5. The values of r_1 and r_2 can also be obtained from the dc test.

Report

1. Explain the logic used in determining the relative polarity and number of turns of each coil.
2. What assumptions are required for $V_1/V_2 = N_1/N_2$?
3. Compute r_1 and r_2 from the dc test.
4. Calculate the parameters of the equivalent circuit shown in Figure 2.1. You may assume

$r_1 = \left(\frac{N_1}{N_2} \right)^2 r_2$ and $x_1 = \left(\frac{N_1}{N_2} \right)^2 x_2$. Compare r_1 and r_2 computed this way with the values found from the dc test.

5. Compute the transformer impedance percentage.
6. Calculate the regulation and full-load efficiency of the transformer from the load test.

NOTE: “Full-load” means the smallest resistance (50 Ω) here. (Larger load means higher current.)

7. Calculate the peak values of the magnetic flux density (B), magnetic flux (ϕ), and the magnetic field intensity (H). Use your data, or $A = 40 \text{ cm}^2$ for the cross-sectional area and $l_m = 27 \text{ cm}$ for the magnetic-field path length.
8. Determine the saturation flux density based on the hysteresis plot obtained in part E.

Final Comments

The transformer is a fundamental component in power systems and electronic circuits. Its ability to raise or lower ac voltages is one of the main reasons for the widespread use of ac systems. In large-scale system analysis, the transformer must be modeled in a simple but representative manner. Typical models are based on the impedance percentage as computed in this experiment. While magnetic devices require time-varying voltages to support transformer action, magnetic transformers can be combined with external power electronics and energy storage for more flexible operation. A dc transformer can, in effect, be built in this way.

In circuit applications, transformers are used heavily in power electronics and radio frequency (RF) circuits. In power electronics, the transformer operates in the 1-100 kHz range, typically, and is very small for the amount of power that flows through it. In RF circuits, transformers are used for impedance matching and filtering. There are other applications as well.

The *IEEE Transactions on Power Delivery* publishes papers on transformer design and performance. The modern power system routinely employs three-phase voltages in the range of 345 kV to 765 kV. These high voltages enable the economic transmission of bulk power over long distances. The trend towards higher voltages is made possible by the reliability of ferromagnetic-core transformers. For low power, there is research in low-loss, high-temperature transformers. High-quality (Q factor) transformers are essential to RF applications. Research in the area of transformer technology is being done by both industry and universities to accommodate these demands.

Appendix A2

Transformer Polarity Test

Given a four-terminal transformer:

1. Verify that terminals 1-2 and 3-4 are the two coils by observing that the resistance across these points is near zero.
2. Short 1 and 3, apply $v(t)$ to 1-2, meter voltage across 2-4. Call this V_{m1} .
3. Disconnect $v(t)$, short 1-4, apply $v(t)$ to 1-2, meter voltage across 3-2. Call this V_{m2} .
4. If $V_{m1} < V_{m2}$ then terminals 1 and 3 should be marked with a dot since they have the same “relative” polarity. Alternatively, terminals 2 and 4 could be marked instead.

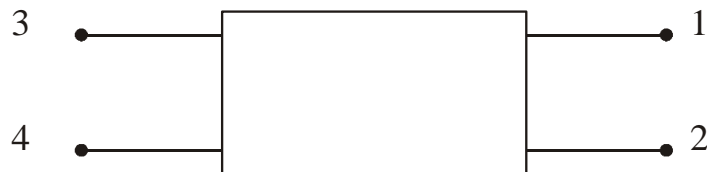


Figure A2.1: Four-terminal transformer

5. If $V_{m1} > V_{m2}$ then terminals 1 and 4 should be marked with a dot since they have the same “relative” polarity. Alternatively, terminals 2 and 3 could be marked.
6. When more than two windings are present, the above test should be run on all windings. Winding 1-2 could be used as the “reference” coil.

Appendix B2

Multiple-winding Transformer Connection

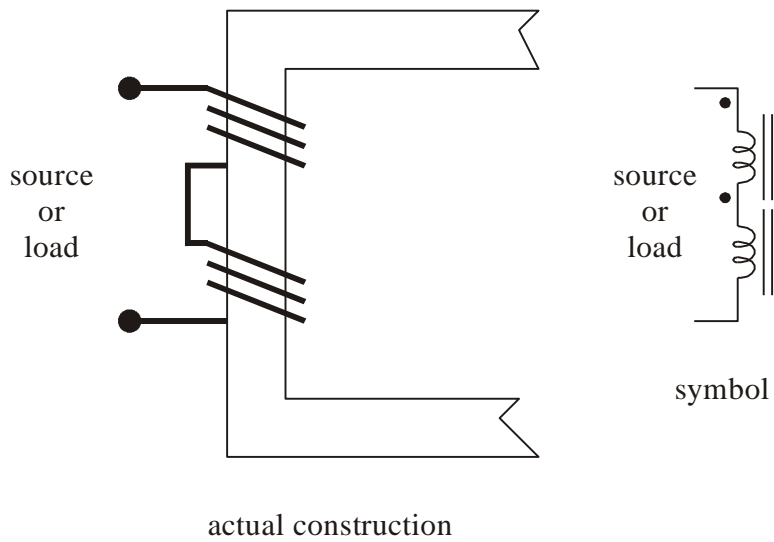


Figure B2.1: Series connection of two coils

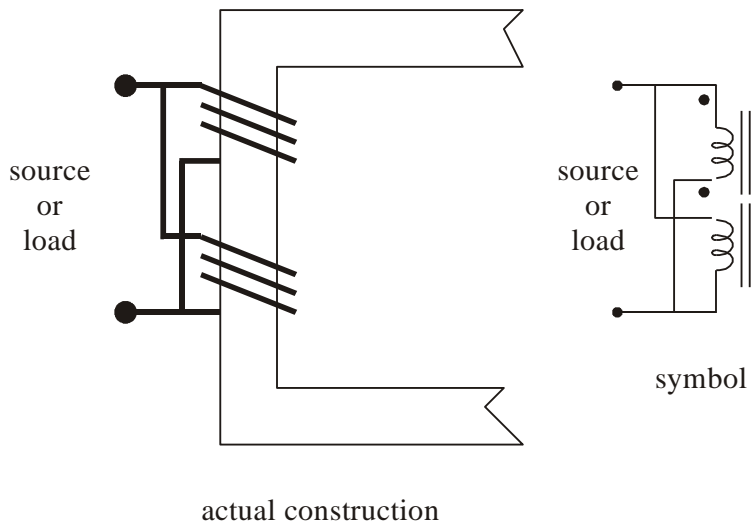


Figure B2.2: Parallel connection of two coils

(Caution: reversal of polarity results in a short circuit of source)

Experiment #3: Stepper Motors (Reluctance Machines)

Objective

The objective of this experiment is to become familiar with the operation theory of a stepper motor. Specifically, tests will be performed to characterize a small, high-torque stepper-motor drive system, program a control for a mock automation system, and observe the performance capabilities.

Introduction

Stepper motors have been used to provide accurate position control for electromechanical systems. The stepper motor we will explore is an example of the more general class of *reluctance machines*. In a reluctance machine, the basis for force generation is a change in inductance as a function of position, brought about by the geometric structure. The stepper motors we use are small reluctance machines. Their simple construction and control needs allow them to be used in a wide variety of applications, from printers and disk drives to torpedo systems and milling machines.

A qualitative examination of a simple three-phase variable reluctance machine provides a basic understanding of stepper machine operation. Figure 3.1 shows the machine geometry and winding. Note the salient (not round) construction with six teeth on the stator and four on the rotor. Each phase-winding on the stator is wound with series or parallel coils on opposite teeth as labeled. When a phase is energized, it creates a flux in the motor that essentially turns one of the teeth into a north

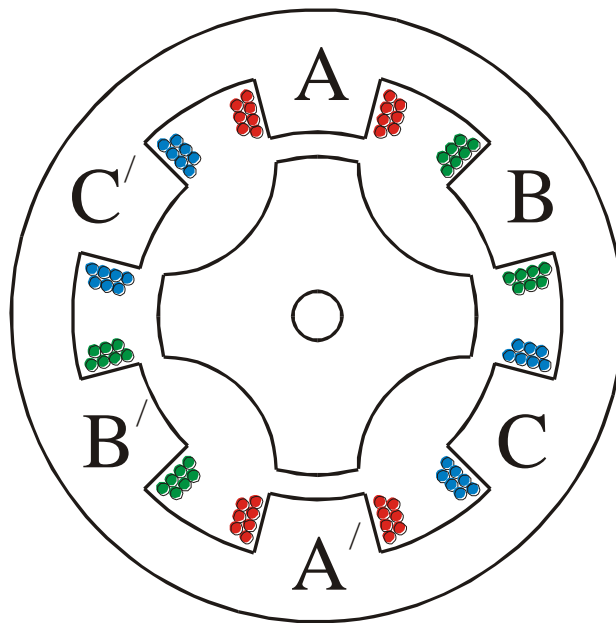


Figure 3.1. "Six-four" variable reluctance machine geometry

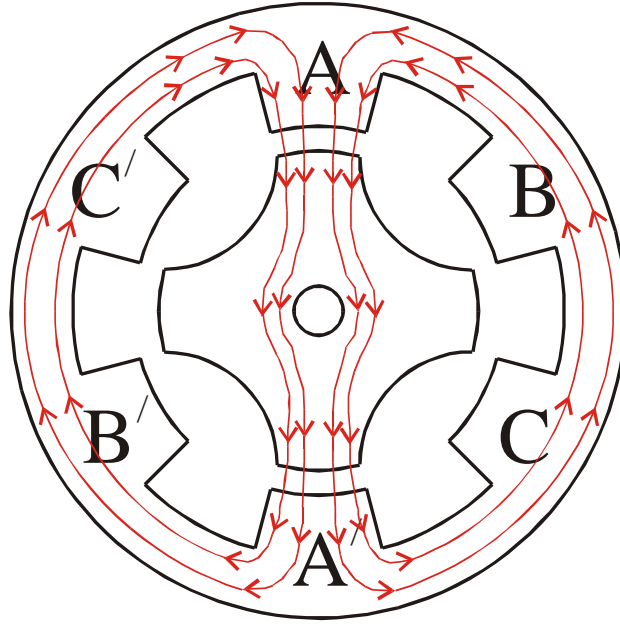
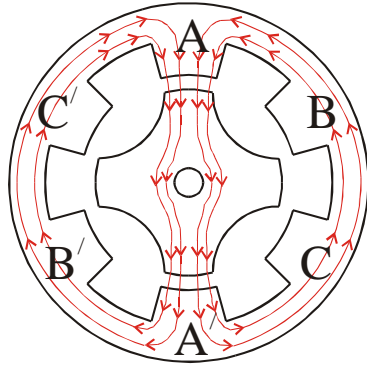


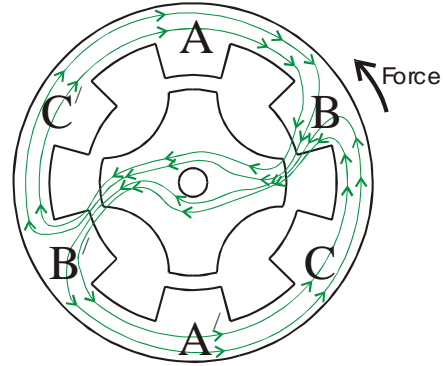
Figure 3.2. Energized variable reluctance motor

magnetic pole and the opposite tooth into a south magnetic pole as shown in Figure 3.2. As the rotor rotates, the minimum air gap seen by the flux will change. This gap will have an absolute minimum when the stator teeth of the energized phase are aligned with the rotor teeth. Here, the motor reluctance will be minimized, and thus the Maxwell stress created by the magnetic flux will try to align the rotor to this position.

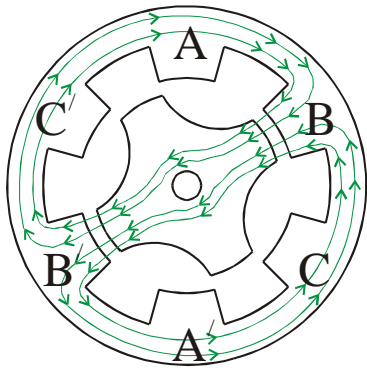
Figure 3.3 illustrates how, with appropriate polarization of the phases, this phenomenon can be used to create a useful stepping torque. In Figure 3.3A, the A phase is energized and the rotor is already in its equilibrium holding position. Next, the A phase is turned off and the B phase is turned on, which creates the flux shown in Figure 3.3B. The rotor is no longer in the minimum reluctance position as compared to the flux generated by the B phase. Thus, the magnetic fields of the B windings will pull the rotor to align the rotor teeth with the B phase stator teeth. This results in the geometry and fields shown in Figure 3.3C. Now, the C phase can be excited and the same phenomenon will pull the rotor into alignment with the C-phase stator teeth. Finally, the A phase is excited once more and a symmetrical geometry, as was depicted in Figure 3.3A, is obtained with the rotor having made a 90° rotation. Convince yourself that a reversal of the sequence of phase energizing would result in similar motion in the opposite direction.



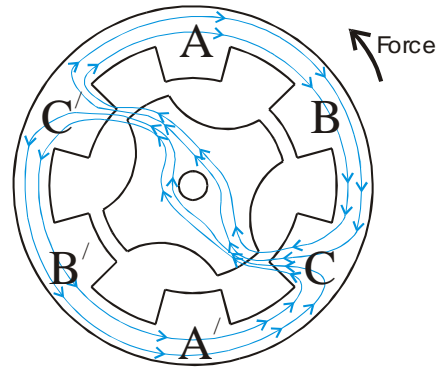
A) Phase A energized
Rotor at holding position



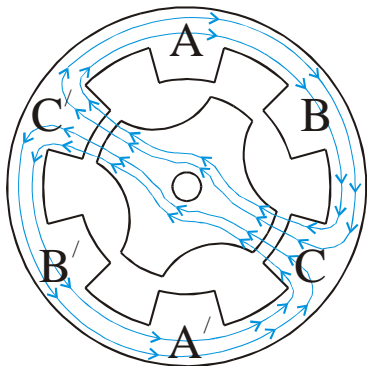
B) Phase B energized
Bent magnetic flux causes
the rotor to be pulled towards
B phase pole on stator



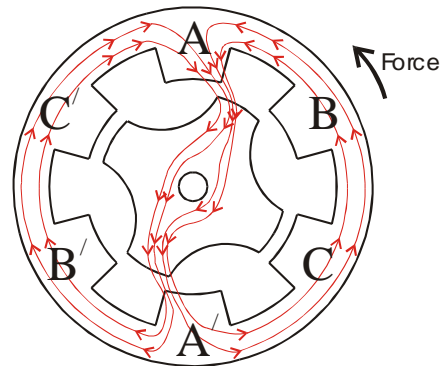
C) Phase B energized
Rotor at holding position



D) Phase C energized
Bent magnetic flux causes
the rotor to be pulled towards
C phase pole on stator



E) Phase C energized
Rotor at holding position



F) Phase A energized
Bent magnetic flux causes
the rotor to be pulled towards
A phase pole on stator

Figure 3.3. Stepping sequence

The process described above is known as *single-phase excitation* and one can see that each time a “step” is taken the rotor advances 30° . This angle is referred to as the *step angle* of the motor. A smaller step angle gives a motor more precise positional resolution. Equation (3.1) below describes the relationship between the number of steps per revolution and the step angle where θ_s is the step angle and S is the number of steps per revolution:

$$\theta_s = 360^\circ / S \quad (3.1)$$

Equation (3.2) shows a more interesting relationship that describes the number of steps per revolution for a given geometry where N_r is the number of teeth on the rotor and m is the number of phases. (This applies to motors without permanent magnets).

$$S = mN_r \quad (3.2)$$

Notice that the number of steps, and thus the step angle, does not depend on the number of teeth present on the stator. Typical configurations will have between 2-5 phases and as many as 100 teeth on the rotor, resulting in resolutions finer than one degree per step. Typically the speed of a stepping motor is referred to by its step rate (f_s) which has the units of steps per second. Often times, when dealing with rotating machinery, the speed is referred to in *revolutions per minute* which can easily be calculated in terms of step rate as

$$n = 60 \frac{f_s}{S} . \quad (3.3)$$

There are some practical limits involved in designing a small step angle. As N_r is increased, a manufacturing precision limit is approached. Also, each phase added increases the necessary drive hardware cost.

Although the single-phase excitation was presented for its simplicity, dual-phase excitation is typically used due to improved dynamic performance. In dual-phase excitation, two consecutive coils are energized simultaneously and the rotor will align with a new minimum reluctance position that is halfway between the two single-phase equilibrium positions. The motor step angle is the same whether operated in single- or dual-phase excitation; however, an interesting new control scheme known as *half stepping* emerges by applying the two in an alternating fashion. Essentially, each clock pulse will cause the drive to advance the motor a half step, which results in a doubling of the positional resolution. Appendix A3 includes charts indicating the control sequences for a three-phase variable reluctance (VR) stepper motor.

Other topologies of stepper motors exist. Most of these can be classified into three basic categories: *variable reluctance*, *permanent magnet (PM)*, and *hybrid*. The previously presented machine describes the basic theory governing the machines of the VR type. The PM motor is an extension of the basic principles of the VR motor. Instead of a salient rotor, a rare earth magnet is used for the rotor as depicted in Figure 3.4. Now, when a phase is energized, magnetic flux exists, originating from the coil and from the magnet. These two magnetic fields will generate a force drawing them to alignment. Since the permanent magnet generates a constant field, a small amount of force will be generated due to the stator iron salience, even in the absence of stator excitation. This torque is known as the *detent torque* and is usually relatively small. Finally, hybrid motors incorporate a combination of these two principles in a single rotor. The PM and hybrid motors offer an advantage over the VR motor in that the number of steps per revolution is doubled for a given number of rotor teeth as described in

$$S = 2mN_r. \quad (3.4)$$

Several other interesting points should be mentioned, although their derivation is beyond the scope of this discussion. First, the stepper motor is, in effect, a synchronous machine where the stator field is rotating in fixed steps as opposed to continuously. Thus the static torque equation reduces to the same form of a synchronous machine and is dependent upon the displacement of the rotor from its equilibrium position as shown in (3.5). K is a constant derived from the physical construction of the motor, I_ϕ is the magnitude of the exciting current, and δ is the displacement or “torque” angle.

$$T_e = KI_\phi N_r \sin(\delta) \quad (3.5)$$

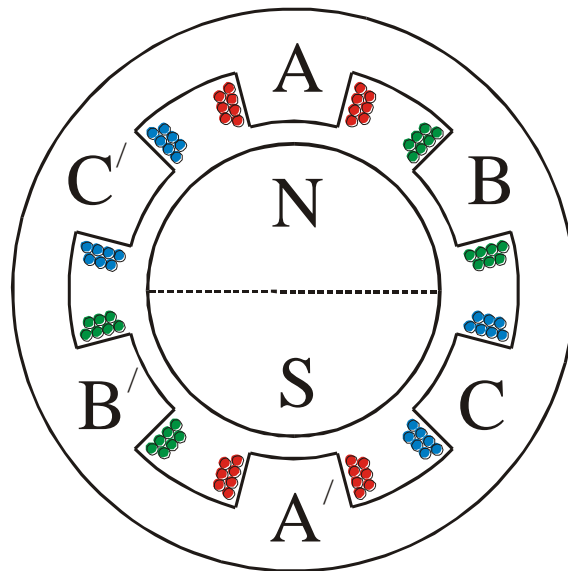


Figure 3.4. Permanent-magnet stepper motor

As a synchronous machine, a few implications arise regarding the ability of a stepper motor to be an effective open-loop positional actuator. First, there will be a limit on the maximum speed that can be maintained for a given load torque that is related to the stator time constant of the phase. Examination of (3.5) makes one reason apparent for why this problem occurs. The stator time constant limits the rate at which the current can rise in the next phase energized during operation. The maximum and average I_ϕ attainable begins to decrease as the switching frequency increases until the machine cannot provide the necessary torque without losing synchronism. Additionally, there is a maximum rate of acceleration or deceleration that can be obtained for a given load profile. This arises from the maximum torque limits attainable according to (3.5). Newton's second law for rotational systems dictates that the inertia (J) times the angular acceleration (α) equals the sum of the torque as

$$J\alpha = T_m. \quad (3.6)$$

This limits how quickly the load can be accelerated to match the increasing synchronous speed that the control is receiving.

The stepper motor analyzed in this experiment is a 4-phase motor with a uni-polar drive system. The front panel of the drive is shown in Figure 3.5. The AA2020A Motor Driver Controller is at the heart of the drive. In its current configuration, the controller accepts three inputs on connector D1 seen in Figure 3.5 and described in Table 3.1: clock, direction, and step size. At each rising edge of the clock signal, the chip reads the direction and step-size inputs and determines a "next state" for the gate signals. These gate signals are then used to switch on the appropriate phases for the motor to take a full or half step in the correct direction.

Stepper motors are widely used in open-loop robotic systems. *Open loop* means that no special sensors are used to try to guarantee there is no error. Since very small step angles are possible, only a small maximum percentage error results when a given position is desired. However, many applications require more accurate positioning than the open-loop control can provide, but that is beyond our scope.

Table 3.1
Stepper Motor Drive Pinout

Pin #	1	2	3	4	5	6	7	8	9
Description	Clock (Red)	Half/Full Step (Purple)	Direction (Green)	NC	+5 Volts	NC	NC	NC	Ground (Black)

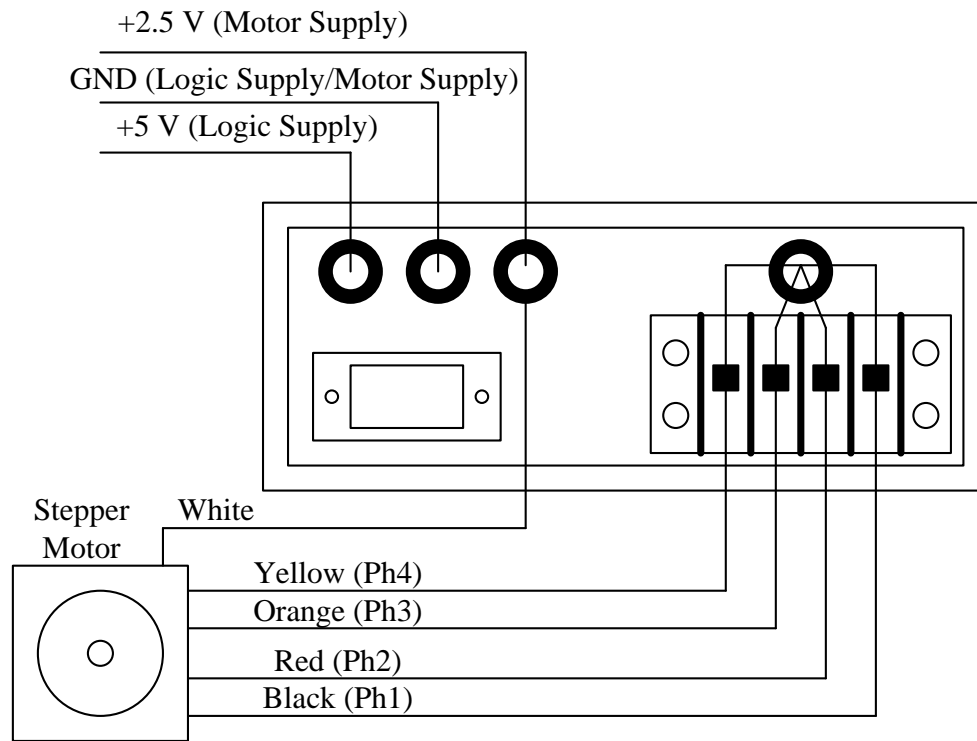


Figure 3.5. Stepper-drive panel layout

In this experiment, you will use the bench computer (equipped with a multifunction I/O board) to control the stepper drive. A driver program has been set up for you using *Labview* software. *Labview* programs are known as *V-I's*, or *virtual instruments*. A custom V-I has been set up such that you can command the digital outputs of the multifunction I/O board very easily through a graphical interface. You will supply the V-I with positioning command sequences and observe the motor operation. You will not be writing your own V-I's, although that is certainly possible. Industrial controllers would not normally use this high-level interface for such a simple task (writing a few pulses to some digital port), but for instructional purposes this will be preferred. Microcontrollers, FPGA's, etc., can be used for the control more economically.

The programming will involve listing the commands to change directions, switch from full- to half-step (or vice-versa), determine the number of steps to be taken in a burst, and set the step speed. Through several sequences of commands, the motor will rotate back and forth, stop, change directions, etc., to a prescribed pattern to simulate some hypothetical robotic function. You will have to determine the step lengths, numbers of steps, and step speeds. You will also have to determine direction changes and half/full step changes. The object is to make the motor complete the task faster with no errors. There can be no error in positioning in the task; since there is no sensing (open loop), the error cannot be corrected and will accumulate each time the task is performed.

Procedure

NOTE: Always power the logic circuit first before applying power to the motor.

Part A: Machine parameterization

1. Series resistance
 - a. With the motor disconnected from the drive system, measure the phase resistance of each of the phases using the Fluke multi-meter.
2. Inductance test
 - a. Connect the power and signal wires as shown in Figure 3.5. Do not connect the motor leads at this time. The 2.5V supply should be current-limited to 2A.
 - b. Connect Phase 1 to the drive and apply a slow step rate command. Recommended: 10 Hz and 5 steps on the LabVIEW command.
 - c. Use the cursors on the scope to measure the time constant for this phase. The time constant for a series RL load can be obtained by observing the current rise or fall due to a step change in the voltage applied.
 - d. Repeat this process for each of the motor phases.
 - e. Plot one of the phase currents for inclusion in the report.
3. Maximum step rate
 - a. Start the motor with a slow step rate (recommended 100 Hz) in full-step mode.
 - b. Slowly increase the frequency of stepping until the motor begins to miss steps. You may find it easier to feel or hear the motor missing the steps rather than seeing the missed steps.
 - c. Record this frequency.
 - d. Repeat steps a-c for half-step operation.
4. Repeat Step 3 for motor supply voltages of 3.5 V and 1.5 V. Observe any pattern and predict from it.

Part B: Control waveforms

1. Full-step operation
 - a. Connect the drive as shown in Figure 3.5.
 - b. Connect a standard voltage probe to observe the clock signal (Pin 1). Run the motor at 100 Hz. Save the clock signal as a reference signal by using the REF button.
 - c. Disconnect the voltage probe connected to the clock and connect four standard voltage probes to observe gating control signals from the FETS.

- d. Save an oscilloscope plot showing the clock signal and the four reference waveforms. This shows the switching patterns for this operation mode.
2. Half-step operation
 - a. Repeat the process from Step 1 to obtain the switching patterns for half-step operation.
3. Minimum phase number
 - a. Disconnect one of the four phases from the drive box.
 - b. Run the motor in full stepping mode at 100 Hz.
 - c. Does the motor spin? If yes, does it skip steps?
 - d. Disconnect more phases, one at a time, and record your observations.

Part C: Programming

1. Normal operation of a complex sequence. Based on the positional moves shown below in Table 3.2, determine a command sequence that will **result in the shortest possible execution time based on a fixed step rate of 100 Hz**. Run this sequence with the motor, and see if it behaves as expected. Use a motor supply voltage of 2.5 V. Note that the minimum execution time may involve switching between CW and CCW rotation. Assume that each row corresponds to a single command.

Table 3.2
Series of Positional Moves to be Programmed

Positional Move	Wait (s)
$0^\circ \rightarrow 360^\circ$ (1 full revolution)	0.1
$0^\circ \rightarrow 135^\circ$	0.5
$135^\circ \rightarrow 273.6^\circ$	0.3
$273.6^\circ \rightarrow 263.7^\circ$	0.0
$263.7^\circ \rightarrow 0^\circ$	0.5
$0^\circ \rightarrow 308.7^\circ$	0.1
$308.7^\circ \rightarrow 148.5^\circ$	0.1
$148.5^\circ \rightarrow 0^\circ$	-

Report

1. Calculate and report the time constant, phase inductance, and series resistance for each motor phase.
2. Compare the calculated time constant with the maximum step rate obtained in Part A.
3. Compare your plots of the switch patterns for full- and half-stepping to the expected sequences.
4. List the exact sequence of commands in a table that you used in Part C to achieve the fastest completion of the sequence given in Table 3.2. Determine the estimated execution time for this sequence based on the 100 Hz stepping rate.
5. Plot the maximum step rates vs. supply voltage obtained in Part A. Comment on the results (give a physical explanation). What are some of the drawbacks to running the motor at continuously higher voltages?

Final Comments

Due to the importance of a stepper motor's ability to maintain synchronism even with a very fine positional resolution, stepper motors are often seen in applications which do not have large load inertias. Typically, a design will have a stepper motor that drives an inertia of no more than 3-5 times that of the rotor. It can be important to ensure that the load inertia is not significantly less than the rotor, as this can lead to harmonic frequency imbalance problems. It should also be mentioned that, although the stepper motor was presented as a simple open-loop system in this lab, closed-loop control systems coupled with more advanced switching schemes such as micro-stepping significantly improve the overall performance of practical stepping motors.

The most typical stepper-motor controls emphasize position, but they can also be used for speed control. Speed control is simple to achieve on an average basis by controlling the step rate.

However, there is a lot of torque ripple caused by the “cogging” of the teeth. Position controls based on other motors, such as induction and brushless permanent magnet motors, have advanced greatly and have reduced the need for steppers in some cases—particularly for heavy loads. For small loads, however, steppers are nearly ideal.

More detailed information on stepper motors may be found in References 5 and 6.

Appendix A3

Control sequences for a three-phase VR stepper motor.

Table A3.1
Dual-Phase Excitation Full Stepping

	Phase A	Phase B	Phase C
CW	1	1	0
↕	0	1	1
CCW	1	0	1

Table A3.2
Single-Phase Excitation Full Stepping

	Phase A	Phase B	Phase C
CW	1	0	0
↕	0	1	0
CCW	0	0	1

Table A3.3
Half-Stepping Excitation

	Phase A	Phase B	Phase C
	1	0	0
CW	1	1	0
↕	0	1	0
CCW	0	1	1
	0	0	1
	1	0	1

Experiment #4: Induction Machine Characterization

Objective

The objectives of this experiment are to investigate basic induction machine principles and develop the steady-state equivalent circuit of a balanced three-phase induction motor. The equivalent circuit has the same volt/amp characteristics as the machine and is used to predict steady-state behavior.

Introduction

Note the following notations for this lab: ω_m is the machine mechanical speed in rad/sec, ω_r is the electrical frequency of the rotor currents, and ω_e is the electrical synchronous frequency. A balanced three-phase induction motor is essentially a three-phase transformer with an air gap and a movable winding. When a balanced set of three-phase voltages is applied to the stationary windings (stator), a revolving magnetic field is established in the air gap. The speed of this revolving magnetic field is termed *synchronous speed* and is found as

$$\omega_e = 2\pi f_e = \frac{p}{2} \omega_{m(synchronous)} \quad (4.1)$$

where f_e is the frequency of the stator voltages (and currents) in hertz and p is the number of magnetic poles of the stator. The mechanical rotor speed, ω_m , generally is not proportional to stator frequency. However, at synchronous speed, the two are proportional by the number of pole pairs. If the number of magnetic poles of the stator is equal to the number of magnetic poles of the rotor, then this revolving magnetic field induces a balanced set of three-phase voltages in the open-circuited movable (rotor) windings. When the rotor windings are shorted, a balanced set of currents will flow. If the rotor is held stationary by some mechanical means, the induction motor behaves similarly to a short-circuited transformer. This condition is termed *blocked rotor* or *locked rotor*. These rotor currents will have the same frequency as that of the induced rotor voltages, and are equal to

$$\omega_{r(blocked\ rotor)} = \omega_e .$$

In the blocked rotor case, ω_r equal to $\omega_m \frac{p}{2}$ and is equal to the synchronous speed, but at some other rotor speed

$$\omega_e - \omega_m \frac{p}{2} = \omega_r \quad (4.2)$$

thus

$$2\pi f_r = \omega_r \quad (4.3)$$

is the frequency of the rotor currents. When the electrical rotor speed and stator frequency are close, as they are in normal circumstances, the slip frequency is small and therefore the rotor currents are nearly dc. If we define a quantity called *slip* as

$$s = \frac{\omega_e - \frac{p}{2} \omega_m}{\omega_e} \quad (4.4)$$

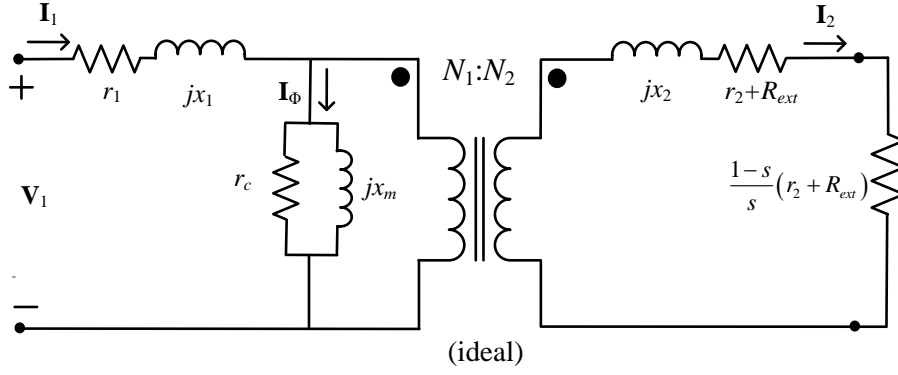
then

$$\omega_r = s\omega_e = \text{rotor current frequency} \quad (4.5)$$

The stator and rotor revolving magnetic fields both rotate at synchronous speed regardless of the rotor speed. This is essential for induction machine operation and is the source of the torque which initiates and maintains the rotation.

Continuing our progression of line startup—when the rotor is free to turn, the two revolving magnetic fields attempt to align (The rotor-field positive pole moves in the direction of the stator-field positive pole.). The rotor and stator currents are quite large during startup since the induced rotor voltages are large for large relative motion (large slip). The torque developed between the two fields must be greater than the shaft load torque to cause acceleration. As the machine accelerates, the relative motion decreases (smaller slip), and the resulting currents are smaller. Eventually, the torque of electrical origin and load torque will be equal, and the motor will achieve steady-state operation at some speed less than synchronous speed. Note that if the machine could reach synchronous speed, the relative motion would be zero, and thus no rotor current would flow, resulting in zero torque of electrical origin. Three-phase induction machines are designed such that the torque is maximized during normal operation, resulting in smaller current.

The standard single-phase equivalent circuit of a three-phase induction machine is shown in Figure 4.1. There are two basic types of induction motors. The squirrel-cage induction motor has only shorted bars for rotor windings and thus does not permit access to the rotor. The wound-rotor induction motor has actual windings, wound with the same number of magnetic poles as the stator. The terminals are brought out through slip rings to give access to the rotor. An external resistance is shown in the rotor portion of the equivalent circuit. This can only be included in a wound-rotor induction motor. Notice that for either type, when $s = 0$ (synchronous speed) the equivalent circuit acts as an open-circuited transformer. When $s = 1$ (zero speed) the equivalent circuit acts as a short-



V_1 = Stator line to neutral voltage phasor

I_1 = Stator line current phasor

r_1 = Stator single-phase winding resistance

x_1 = Stator single-phase leakage reactance

x_2 = Rotor single-phase leakage reactance

r_2 = Rotor single-phase winding resistance

s = Slip

N_1 = Equivalent turns of stator

N_2 = Equivalent turns of rotor

I_2 = A current phasor whose magnitude is the same as the actual slip frequency rotor currents

r_c = Core loss referred to stator

x_m = Magnetizing reactance referred to stator

R_{ext} = External resistance (wound-rotor machine only)

I_ϕ = Magnetizing branch current

circuited transformer. Thus we can apply the tests for the transformer to determine the induction motor equivalent circuit parameters.

Figure 4.1. Equivalent circuit of one phase of a three-phase induction machine

The rotor resistances are broken apart in the diagram to make the following analysis easier. By inspection, it is clear that the total real power into the machine rotor or across the air-gap is

$$P_{\text{gap}} = 3 |I_2|^2 \frac{r_2 + R_{\text{ext}}}{s} \quad (4.7)$$

and the real power lost in the rotor is

$$P_{\text{Cu,rotor}} = 3 |I_2|^2 (r_2 + R_{\text{ext}}) \quad (4.8)$$

Thus the electromagnetic power imparted to the shaft is represented by the fictitious speed-dependent resistance as

$$P_{\text{shaft}} = 3 |I_2|^2 \left(\frac{1-s}{s} \right) (r_2 + R_{\text{ext}}) \quad (4.9)$$

If I_2 can be calculated, then so can (4.9). The torque produced is then

$$T_e = \frac{P_{shaft}}{\omega_m} \quad (4.10)$$

Induction motor torque

The induction motor is by far the most common industrial motor. The simplicity and ruggedness of construction and absence of brushes generally make the squirrel-cage motor very attractive from an economic viewpoint. The wound-rotor induction motor has rotor coils which terminate in slip rings and are accessible. Insertion of external resistance in the rotor circuit (wound-rotor machines only) makes variations in the machine characteristics possible.

Consider the steady-state equivalent circuit shown in Figure 4.1. The real or average power to the shaft is

$$P_{shaft} = 3|\mathbf{I}_2|^2 (r_2 + R_{ext}) \left(\frac{1-s}{s} \right) \quad (4.11)$$

Also, the torque to the shaft is

$$T_e = \frac{P_{shaft}}{\omega_m} \quad (4.12)$$

where, if the power is in watts and the speed is in mechanical radians per second, then the torque is in newton·meters. This can be written as

$$T_e = \frac{P_{shaft}}{\frac{2}{p} \omega_e (1-s)} \quad (4.13)$$

where p is the number of poles, so that

$$T_e = \frac{3}{2} \frac{1}{\omega_e} p |\mathbf{I}_2|^2 \frac{(r_2 + R_{ext})}{s} \quad (4.14)$$

The rotor current will generally vary for different load levels. We would like to have an expression for torque which varies only with rotor speed (or slip). This can be done by finding the steady-state relationship between the applied stator voltage and the rotor current. By neglecting core losses and magnetizing inductance we obtain

$$|\mathbf{I}_2| = \frac{|\mathbf{V}_2|}{\left[\left(r_1 + \frac{r_2' + R_{ext}'}{s} \right)^2 + (x_1 + x_2')^2 \right]^{1/2}} \quad (4.15)$$

So in terms of the constant applied stator voltage,

$$T_e = 3 \frac{P}{2} \frac{|\mathbf{V}_1|^2 (r_2' + R_{ext}') s}{\omega_e \left[(s r_1 + r_2' + R_{ext}')^2 + s^2 (x_1 + x_2')^2 \right]} \quad (4.16)$$

where

$$r'_2 + R'_{ext} = \left(\frac{N_1}{N_2} \right)^2 (r_2 + R_{ext}) \quad (4.17)$$

and

$$x'_2 = \left(\frac{N_1}{N_2} \right)^2 x_2 \quad (4.18)$$

The maximum motor torque which can be obtained for fixed stator voltage and variable slip can be found to be

$$\max(T_e) = \frac{3|\mathbf{V}_1|^2}{2\omega_e \left[r_1 + \left(r_1^2 + (x_1 + x'_2)^2 \right)^{1/2} \right]} \left(\frac{P}{2} \right) \quad (4.19)$$

which occurs at a slip of

$$s(\text{for } \max T) = \frac{r'_2 + R'_{ext}}{\left(r_1^2 + (x_1 + x'_2)^2 \right)^{1/2}} \quad (4.20)$$

Note that the actual maximum value is independent of rotor resistance, but the slip at which it occurs is not. Also note that for slip values near zero (near synchronous speed), the torque slip curve is nearly linear. This can be verified by looking at (4.16) and noting that for small s ,

$$\left[(sr_1 + r'_2 + R'_{ext})^2 + s^2(x_1 + x'_2)^2 \right] \approx (r'_2 + R'_{ext})^2 \quad (4.21)$$

so that for small slip

$$T_e \approx \frac{3|\mathbf{V}_1|^2 s}{\omega_e (r'_2 + R'_{ext})} \left(\frac{P}{2} \right) \quad (4.22)$$

The dynamometer as a load

In this experiment, a portion of the torque-slip curve will be created by an induction motor load test. Since the motors should not be loaded past their rating, data can be taken only for values of slip between zero and full load. (However, with automated testing, the machine can be overloaded temporarily in order to get the whole torque-speed characteristic.) The load on the induction motor will be the electrical load of the dynamometer drive (the black machine coupled to the motor). This machine can operate in four quadrants—either direction in speed or torque—at our will. It is controlled electronically and is powered from a dc voltage even though the machine itself is ac. The torque provided by the dynamometer will then be seen as a load torque by the induction machine.

Procedure

Any time the dynamometer is used, a resistor box (250 Ω) must be used between ± 120 V dc (accessible at the DC Mains switch). This is done to ensure a place for regenerative energy flow when the dynamometer is running as a generator.

The software interface for the dynamometer control (see Figure 4.2) is divided into two sections, control (left panel) and information display (right panel). The control section consists of two operating modes: Velocity Mode and Torque Mode. In Velocity Mode, the machine tracks a speed command entered through the dial or in the numeric box just below the dial. Torque Mode works in an analogous way. You should ALWAYS use the numeric box to enter commands. Additionally, a switch is provided to change the dynamometer rotation direction. To operate the machine, the following sequence has to be followed:

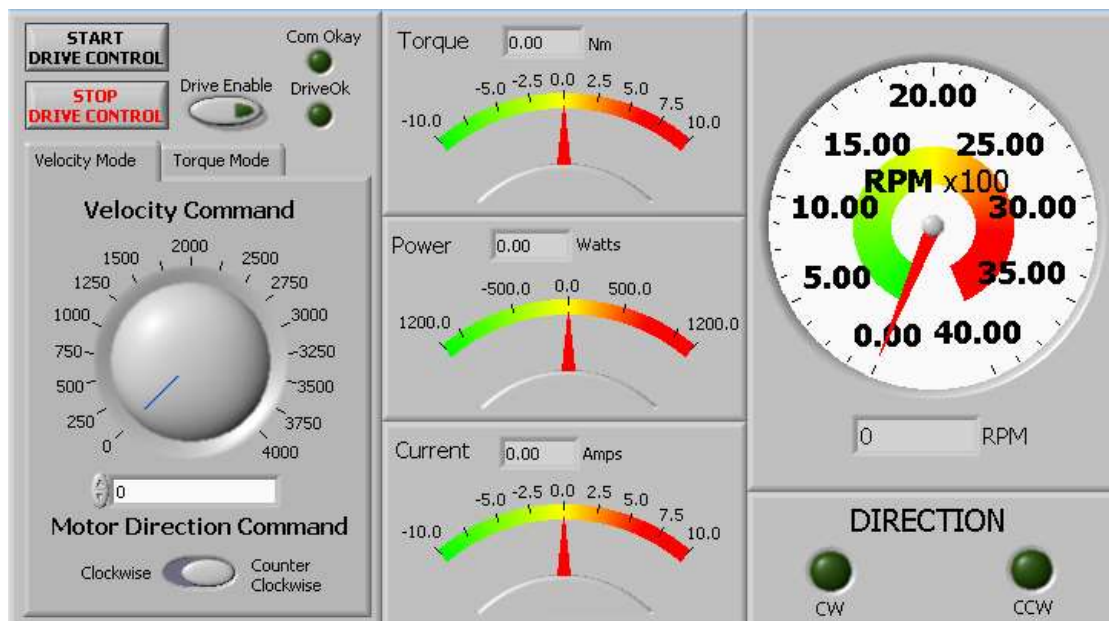


Figure 4.2. Dynamometer control software interface

1. Turn on the DC Mains.
2. Power up the dynamometer drive logic (Dyno Control switch in upward position).
3. Run the software interface and start the dynamometer by clicking the “START DRIVE CONTROL” button.
4. Select the operating mode (Velocity or Torque) and then click the “Drive Enable” switch.
5. Now commands can be entered. Remember to use only the numeric box in doing so.
6. To stop the machine, push the “Drive Enable” switch.
7. To close the drive control software, click the “STOP DRIVE CONTROL” button.

Part A: No-load test (open-circuit test)

1. Set up the circuit of Figure 4.3 (2-wattmeter method should be used).
2. Slowly turn the Variac until the induction motor is spinning. Note the direction of rotation. This direction can be observed in the LabVIEW program. Turn off the machine by bringing the Variac back to zero.

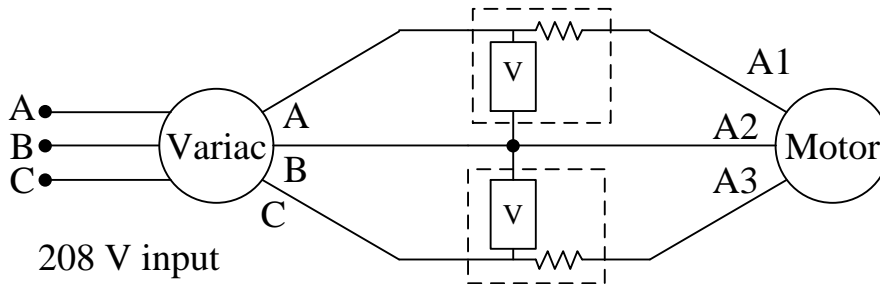


Figure 4.3. Wiring diagram for ac tests

3. Use the dynamometer to set the speed to synchronous ensuring that the direction matches that of Part A.2.
4. Slowly turn the Variac up from zero to rated voltage. Allow it to run for a three-minute warm-up period.
5. Record the measured line currents, line-to-line voltages, power input, and speed.
6. Return all voltages to zero.
7. Disable dynamometer.

Part B: Friction and windage

1. Start the dynamometer in Torque mode at 0 Nm.
2. Start the induction motor by turning the Variac from 0 to rated voltage in ~ 3 seconds.
3. Record all line currents, line-to-line voltages, input power, and speed at rated voltage.
4. Reduce the voltage to 90% of the rated value, and again record the line currents, line-to-line voltages, power input, and speed. Repeat for 80%, 70%, 60% voltage. Stop taking measurements when a rise in stator current is seen.
5. Return the voltage to zero and then disable the dynamometer.

Part C: Blocked-rotor test (short-circuit test)

CAUTION: Monitor the line current as power is applied. Do not exceed 120% of rated current.

1. Turn on the dynamometer in speed mode at zero speed. **Raise the voltage slowly until rated current flows in the stator.** If the motor begins to turn, lower the voltage. The Variac dial will only need to be turned to a few percent.

2. Measure and record line currents, line-to-line voltages, and power input.
3. Drop I_a by about 20% (100%, 80%, ..., 20%), and again record current, voltage, and power.
4. Once the machine is off, turn off the dynamometer.

Part D: Dc tests

NOTE: Use a benchtop dc supply, NOT the mains.

1. Use your bench dc power supply to apply rated dc current into two motor phases (A-B). Be careful, only a few volts will be needed. Set current limits appropriately.
2. Measure I_a and V_{ab} .
3. Repeat for the other two phase combinations (A-C, B-C).

Part E: Load test

NOTE: Ensure that the torque direction is opposite of machine's rotation.

1. Power up the dynamometer in torque mode.
2. Start the induction motor from the line using the Variac.
3. Record the following quantities:
 - a. Dynamometer torque and speed.
 - b. Induction motor stator line currents, line-to-line voltages, power, and information for reactive power and power factor.
4. Increment the torque command (0, 0.5, ..., 3.0 Nm) on the dynamometer and repeat Step 4. Continue until reaching rated current for the induction motor. Double check the value entered in LABVIEW before entering the command.
5. Set the dynamometer torque to 0 N-m, turn off the motor, and then turn off the dynamometer.

NOTE: The test results yield per-phase values, except the dc test.

Report

1. Estimate the equivalent circuit parameters from your data.
2. To obtain the estimate of friction and windage loss, subtract the stator conduction losses from the input power at each of the test voltage points. For your Part B data, plot the resulting power vs. voltage squared, and extend the curve to zero voltage. The intercept with the zero voltage axis is an estimate of the no-load friction and windage loss. Obtain an estimate of this loss component.

3. Plot phase A I_l vs. V_{in} for your Part C data. Estimate, by extrapolation, the starting current which would appear if the rated voltage were suddenly applied to your motor. Comment on the starting current.
4. Now do an iteration: Given your estimates of circuit parameters, correct for the various drops and create a more refined set of circuit parameter values (Refer to IEEE Standard 112.).
5. Based on your refined parameters, plot the expected torque-speed curve for this motor from zero speed to synchronous speed.
6. Compare the torque as commanded by the dynamometer with the torque you expect from the induction motor (based on the machine parameters). Plot them both on the same graph versus the mechanical speed.
7. Compute the reactive power (and power factor) into the motor for Part E data.
8. Compute the slope of the curve near zero slip and compare this with the expected values using equivalent-circuit parameters and Equation 4.22.
9. Compute the induction motor efficiency from each data point. Plot the efficiency versus output power.

Final Comments

The induction motor is the workhorse for virtually all jobs requiring an ac motor. The squirrel-cage motor is most common because of its ruggedness and durability. The wound-rotor induction motor has applications when special speed-torque characteristics are required at high power levels (like wind power). The equivalent circuit developed in this experiment is that of a balanced three-phase induction machine in steady state. The equivalent circuit is also valid for a two-phase machine. A single-phase machine is quite different and has a similar but more complicated equivalent circuit. As a generator, the induction machine has found application in the excitation systems of synchronous generators, wind generation, and variable-speed generators.

The squirrel-cage motor is durable and almost maintenance-free. Induction motors are normally designed for full-load operation very close to synchronous speed when the rotor circuit has no external resistance. It can be very efficient under full-load conditions. The modern trend is to use electronic control as much as possible to enhance flexibility. It is easy to see, however, that if the appropriate external rotor resistance could be added, the maximum torque could be moved virtually anywhere, including zero speed.

Experiment #5: Advanced Induction Machine Topics

Objective

The objectives of this experiment are to examine additional aspects of induction machine operation and applications. The experiment requires special-purpose instrumentation and care. Parts A and B will be run as a demonstration.

Introduction

Induction motor speed control:

The induction motor equivalent circuit measurements were based on operation at 60 Hz. We saw that the induction motor will run at speeds close to the synchronous speed in most applications. We also saw that the induction motor is a simple, rugged machine providing years of reliable service in many harsh applications. For example, fans, pumps, and compressors have made the induction motor the dominant electric machine. Although these applications are not very sensitive to speed and can be operated with little or no speed control, they can sometimes benefit from speed control.

Induction motor speed control has been an objective of many designers. The idea is to combine the ruggedness and low cost of an induction motor with the easy control of a dc machine. This has been achieved in recent years through using power electronics control circuitry. One such controller is outlined in class. This circuit converts a dc source (often produced through rectification, but many dc sources, including batteries, fuel cells, and solar cells, exist) into an adjustable ac source. The adjustment involves both voltage and frequency. Since induction motor operation is determined by its slip, a change in the input frequency would be expected to change the shaft speed. Frequency adjustment alone is not sufficient. At any frequency below the rated value, the machine magnetic circuits will saturate. This increases losses without contributing to torque. Modern control circuits change the stator voltage in step with the stator frequency to avoid saturation.

In Experiment 5, a commercial device which implements a pulse-width modulated inverter will be used to operate an induction motor. This device demonstrates the major features of simple inverter control:

1. Inverter output adjusts voltage and frequency such that V/f is approximately constant.
2. Frequency adjustment is the basic method used for speed control.
3. Motor starting is controlled by ramping up the frequency slowly from zero.
4. The motor can even run beyond rated speed simply by applying a frequency greater than 60 Hz.

Data which address many of these features will be taken.

The induction generator

When an induction motor is driven beyond its synchronous speed by some external prime mover, energy flows from the shaft to the electrical terminals. The induction machine can be used as a generator by this method. It is an unusual generator—an ac source must be applied to the stator for proper operation. Induction generators are difficult to use in isolation because of the need for an ac source. They are appropriate only as small parts of a large ac power system.

The most common modern application of the induction generator is conversion of wind energy. The ruggedness of an induction machine, along with its ability to convert energy over a wide speed range, makes it appropriate in this application. A difficulty is the reactive power required by the machine. This can detract from generator output by reducing the available current. In most cases, capacitors are connected near the motor terminals to avoid these problems.

The dynamometer can be used to drive an induction motor beyond synchronous speed. This technique will be used to study generator operation.

Exploring the torque-speed curve

Experiment #4 allowed us to probe the induction motor torque-speed curve for small values of slip. The induction generator results of this experiment probe small slips just below zero. How can we study the rest of the curve?

Consider an augmented version of the torque characteristic from Experiment #4 where core resistance is ignored (by use of Thevenin's Theorem):

$$T_e = \left(\frac{p}{2} \right) \frac{3 |\bar{\mathbf{V}}_{1,eq}|^2 (r_2' / s)}{\omega_e \left[(r_{1,eq} + (r_2' / s))^2 + (x_{1,eq} + x_2')^2 \right]}. \quad (5.1)$$

Here,

$$\mathbf{V}_{1,eq} = \mathbf{V}_1 \frac{jx_m}{r_1 + j(x_1 + x_m)} \quad (5.2)$$

and

$$Z_{1,eq} = \frac{jx_m(r_1 + jx_1)}{r_1 + j(x_1 + x_m)} = r_{1,eq} + jx_{1,eq} \quad (5.3)$$

From here, if voltage is altered, torque varies as V^2 . This will be true of peak torque as well. For example, at 50% of rated voltage, the machine's torque should be 25% of the normal value at any given speed. This reduced torque can be used to explore speeds not close to synchronous.

Linear Induction Motors

If the induction motor is “unrolled,” it can be used as a linear (not rotary) actuator. Of course, the unrolling is conceptual. Linear, unlike rotary, motors have limited movement in their axis of motion but are convenient for many actuation systems. They have been used to replace some hydraulics in roller coasters, electromagnetic guns, aircraft launchers, sliding doors, and other applications. In the laboratory exercise, we will demonstrate a linear motor under operation. The motor has an open frame so that the windings and rotor construction can be easily observed.

Procedure

Be sure to use a resistor box (250 Ω) between ± 120 V dc as described in Experiment #4.

Part A: Linear induction motor demo (done by TA)

1. Sketch out all key features of the linear induction motor as compared to an ordinary rotary motor.
2. Apply a controlled ac voltage to the machine to observe force generated in each direction.

Part B: Speed control

1. Set up an induction motor, powered by an inverter.
2. Start the motor, and set the frequency to 60 Hz.
3. Record voltage, current, frequency, and speed at no load. Care must be taken when measuring voltage due to the switching nature of the drive. For voltage, use the oscilloscope in either “Average Mode” or “HiRes Mode.”
4. Save a screenshot of oscilloscope for voltage and current PWM waveforms.
5. Repeat steps 2–3 for frequencies 40 Hz, 50 Hz and 70 Hz. Keep observing the waveforms.

Part C: Exploring the torque-speed curve - I

1. Set up the dynamometer to drive the induction machine. Pay close attention to the rotation direction; it must be the same as the normal rotation direction of the induction motor.
2. Start the dynamometer with no power applied to the induction motor. Adjust the speed to be within about 10 RPM of synchronous speed.
3. Use the Variac to gradually increase the induction machine voltage toward 95% of rated value. Monitor current, voltage, power, torque, and speed, and be sure they are well within rated values.
4. Record all data at five operating points below synchronous speed (3500 RPM to 3600 RPM in steps of 20 RPM). While the speed changes, keep the input voltage constant when needed.
5. Adjust the dynamometer for speed just beyond synchronous speed. Record all data for at least five data points above synchronous speed (20 RPM steps are suggested, 3600 RPM to 3700 RPM).

Part D: Exploring the torque-speed curve - II

1. Continuing from Part C, adjust the speed to synchronous speed.
2. Drop the induction motor voltage to 33% of its rated value.
3. Use the dynamometer to adjust speed to various values from 3000 to 3900 RPM. Stop whenever the rated current is reached. Change the speed in 50 RPM increments for generator operation, and 100 RPM increments for motor operation. Record line current, line-to-line voltage, power, torque, and speed. Measurements should be made quickly at high currents. Look for torque maxima for motor operation and for generator operation. Make sure to keep the voltage constant as it may vary.

Report

1. Comment on the linear induction machine demo. Attach a photo or a diagram with basic descriptions.
2. Comment on the shape of current waveform from Part B. From Part B, plot the measured synchronous speed vs. frequency. Does 60 Hz correspond to the expected speed? Does 40 Hz correspond to 2/3 of this speed? Comment on the shape of the plot.
4. Plot torque vs. slip for Part C. Calculate the expected slope for small slip from the theory of Experiment #4. Compare this to the measured value.
5. Plot torque vs. speed for Part D data. Compare the maximum torque with values predicted from the theory of Experiment #4.
6. Given your data at reduced voltage, use equation 4.19 to estimate the breakdown (max) torque at the rated voltage.

Experiment #6: Synchronous Machine Tests and Synchronization

Objective

The objectives of this experiment are to obtain the equivalent circuit parameters of a synchronous machine from the open and short-circuit tests and to examine synchronized operation.

Introduction

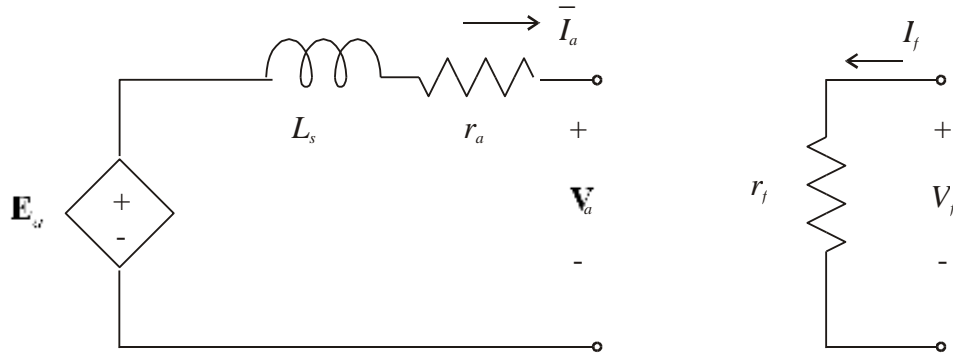
A synchronous machine consists of a rotor and a stator, the rotor normally being a dc circuit called the *field*, and the stator normally being a polyphase ac circuit called the *armature*. In motor operation, the application of ac to the armature causes a rotating magnetomotive force (MMF) wave in the machine air gap, as in the case of the induction motor. The application of dc to the field produces a magnetic field which is stationary with respect to the field winding. If the field is rotating at any speed different from that of the revolving MMF of the armature, a pulsating torque will result. A synchronous motor is thus a useful device, provided it is first brought to a speed equal to synchronous speed

$$n_s = \frac{120 f_e}{p} \quad (6.1)$$

where f_e = frequency of armature supply and p = the number of magnetic poles per phase of the armature, where the speed, n_s , is in revolutions per minute (RPM).

In generator operation, dc is supplied to the field coil and the shaft is rotated by a *prime mover*. Voltage is induced in the armature in synchronism with the rotor motion, with an electrical frequency determined by equation (6.1). A synchronous generator is also known as an *alternator*—the common name used for the device as used in gas-engine automobiles. Hybrid electric vehicles (HEVs) use generators as well, but in a much different way. Virtually all electric power is generated by such synchronous machines.

For a round rotor machine (non-salient poles) the steady-state equivalent circuit of a synchronous machine can be expressed as an internal voltage source proportional to net air-gap flux in series with a reactance and resistance. The *field circuit* is simply a dc voltage across a resistor and inductor. When saturation is neglected, the *internal voltage* can be expressed as a linear function of the field current (or field flux, in the case of permanent-magnet excitation). Such an equivalent circuit is shown for generator operation in Figure 6.1. This experiment will determine the equivalent circuit parameters and examine the operation of a synchronous generator when it is synchronized to an infinite bus. An



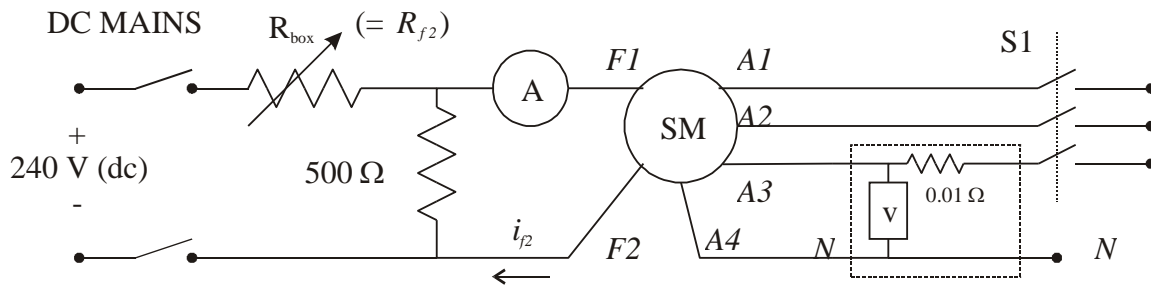
- r_a = Armature resistance per phase
- x_s = Synchronous reactance per phase
- E_a = Internal machine voltage $|E_a| = K_f \omega_s I_f$
- I_a = Armature current per phase
- V_a = Terminal line-to-neutral voltage
- R_f = Field resistance
- I_f = Field current
- K_f = Field constant with units of henries
- V_f = Field voltage
- $\omega_s = 2\pi f_e$

Figure 6.1. Round-rotor steady-state synchronous machine equivalent circuit (generator notation)

infinite bus is a terminal which has constant voltage magnitude and frequency. The main power supplies in the laboratory can be considered such terminals.

In order to synchronize a generator to an existing “hard” source, three things must agree: voltage magnitude, frequency, and phase. The voltage magnitude can be adjusted by the generator field, the prime mover frequency, and the phase using appropriate switch-time selection. Once the generator is synchronized, the speed cannot change since this would require changing the frequency, which is virtually constant for a “hard” source. If the prime mover attempts to speed up the generator, this will cause power to flow into the source. If the prime mover attempts to slow down the generator, this will cause power to flow out of the source. Thus the machine can act as a generator or motor, respectively.

Similarly, the voltage magnitude cannot be changed on the “hard” source. Attempts to increase or decrease this magnitude by adjusting the field current will cause reactive power to flow into or out of the source. These phenomena will be analyzed in a later experiment. Reference [2] discusses synchronous machines in detail.



Procedure Figure 6.2. Wiring diagram, Part A

Remember to use a resistor box (250 Ω) across the 240 V dc supply as described in Experiment #4.

Notes

1. Do not open any connections while power is connected. **You will get shocked if you do.**
2. Be sure to record the nameplate data of the synchronous machine.

Part A: Open-circuit characteristics (OCC)

1. Measure the synchronous machine field and armature resistances with an ohmmeter.
2. Wire the circuit of Figure 6.2. The dynamometer, not shown, will act as the prime mover.
3. Set all resistors on the R_{box} open.
4. Switch on the DC Mains, start the dynamometer in Velocity Mode, and set the speed command to 1800 rpm. **Remember to use the numeric entry box in doing so.**
5. Record all voltages and currents.
6. Switch R_{f2} to 500 Ω . Take all readings.
7. Switch in other resistors on R_{f2} , one at a time, and record the synchronous machine stator voltage and field current. Take data only for increasing i_{f2} to avoid hysteresis problems.

Part B: Short-circuit characteristics (SCC)

1. Stop the dynamometer.
2. Open all resistors on R_{f2} .
3. Apply a short circuit across the ac machine terminals at S1.
4. Close S1. Start the dynamometer at synchronous speed. Add resistors on R_{f2} , one at a time, recording synchronous machine stator and field current at each step. *Be sure to stay within all ratings.* Stop when you reach a rated current value on either machine.
5. Open all resistors on R_{f2} . Open S1 and remove the short circuit..
6. Stop the dynamometer.

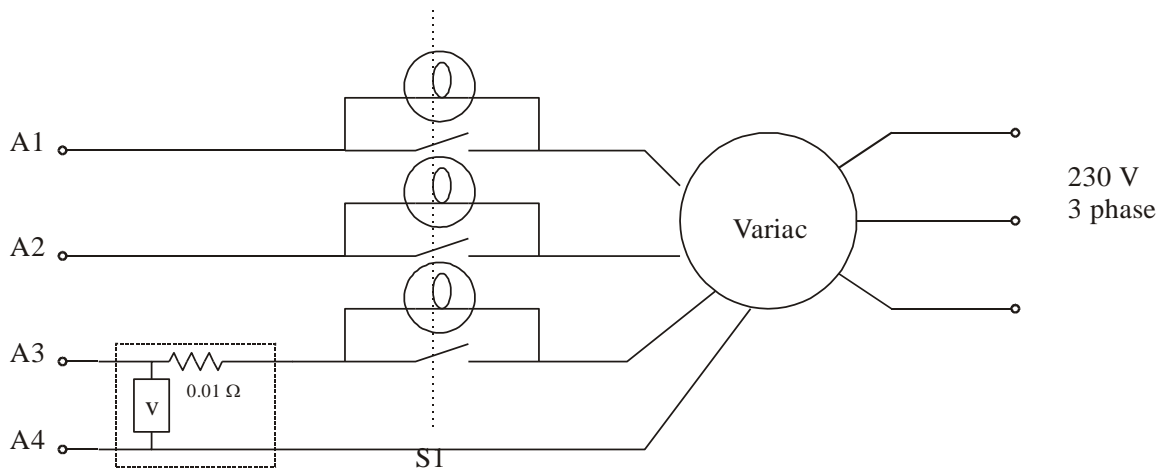


Figure 6.3. Wiring diagram, Part C

Part C: Synchronized operation

1. Be sure S1 and all resistors on R_{box} are open and that your short circuit has been removed.
2. Wire the Variac output (set at 100%) to the right side of switch S1, as shown in Figure 6.3. Connect a lamp set across S1, as shown.
3. Enable the dynamometer in Torque Mode.

Perform the following steps with your instructor supervising.

4. Bring up the speed of the machines to synchronous speed by first applying a small torque (~ 0.4 Nm). **Remember to use the numeric entry box.**
5. Keep switch S1 off. Turn on some resistors on R_{f2} . The lamps should glow periodically as a unit. If they cycle, instead set $R_{\text{box}} = \infty$ and switch the wires A2 and A3.
6. Adjust torque (small steps 0.1 Nm at first, and 0.01-0.02 Nm near synchronization) until the speed is close to synchronous (± 10 RPM). Adjust the ac machine voltage to about $138 V_{\text{in}}$, by changing the value of the resistor box R_{f2} .
7. Adjust the torque slowly (0.01-0.02 Nm steps) until the speed is very close to synchronous speed and the lamps cycle on and off very slowly, staying dark for 2-3 seconds each cycle. Wait a few cycles to be sure proper adjustments have been made.
8. When all three lights are fully dark, turn on S1. The ac machine is now synchronized.
9. Slowly adjust the torque control value in an attempt to change speed. Notice that power flow is affected. Stay within all ratings, and record your observations. Gently adjust R_{f2} in an attempt to change voltage. Notice that current to/from the network is affected.
10. Set the torque command to zero. Shut down the dynamometer. Turn off S1, then S2. Shut off ac and dc power.

Report

1. Plot the OCC and SCC on the same graph (I_f on the x-axis, $|\mathbf{V}_a|$ on the left axis, and $|\mathbf{I}_a|$ on the right axis).
2. Compute the unsaturated K_f in henries and x_s in ohms.
3. Compute the saturated K_f and x_s .
4. Comment on the observations of Part C.
5. Draw the two synchronous machine equivalent circuits (saturated and unsaturated), showing the parameter values.

Final Comments

The synchronous machine is essentially a constant-speed device. In applications where tightly controlled speed is critical, such as clocks or CD players, synchronous machines are used (although the *wound-field* type is not always used—permanent magnet machines will be studied later). As a large-power-system generator, the synchronous machine is normally operated as a source as part of a network with many other synchronous machines connected. In smaller, *finite-inertia* power systems, synchronous machines may be present in quantities of one or two (such as in ships, planes, cars, etc.). In the following experiment, the real and reactive power characteristics will be analyzed in detail.

Experiment #7: Synchronous Machine Power Characteristics

Objective

The objectives of this experiment are to become more familiar with the synchronous machine and, in particular, to investigate the real and reactive power-flow characteristics. The synchronous machine will be run as a motor with dynamometer to provide shaft loading. The machine V curves and power-angle curve will be obtained.

Introduction

A synchronous machine supplies or takes real power from a fixed-voltage bus, depending on the sign of the torque (power) angle. In motor action, with stator resistance (r_a) neglected, the power angle is always negative and becomes more negative as load is added. A synchronous machine supplies or takes reactive power from a fixed-voltage bus depending on the field excitation. Consider the steady-state equivalent circuit of a round-rotor synchronous machine with a magnetically linear core and lossless stator windings (Figure 7.1).

Our machines have round rotor construction. The total power into the machine stator (and thus the air gap since $r_a \approx 0$ is

$$\mathbf{S}_{IN} = 3\mathbf{V}_a \mathbf{I}_a^* \quad (7.1)$$

and substituting for \mathbf{I}_a , from KVL

$$\mathbf{S}_{IN} = 3\mathbf{V}_a \left(\frac{\mathbf{V}_a - \mathbf{E}_a}{jx_s} \right)^* \quad (7.2)$$

so that

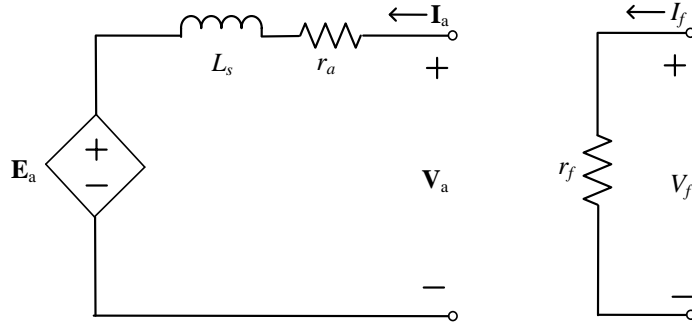
$$\mathbf{S}_{IN} = \frac{3|\mathbf{V}_a|^2 \angle 90^\circ}{x_s} - \frac{3|\mathbf{V}_a||\mathbf{E}_a| \angle (90 - \delta)}{x_s} \quad (7.3)$$

or, since $\mathbf{S}_{IN} = P_{IN} + jQ_{IN}$

$$P_{IN} = \frac{3|\mathbf{V}_a||\mathbf{E}_a|}{x_s} \sin(-\delta) \quad (7.4)$$

$$Q_{IN} = \frac{3|\mathbf{V}_a|^2}{x_s} - \frac{3|\mathbf{V}_a||\mathbf{E}_a|}{x_s} \cos(\delta) \quad (7.5)$$

Note: δ is in electrical degrees



- r_a = Armature resistance per phase $\delta = \angle \mathbf{E}_a - \angle \mathbf{V}_a$
 x_s = Synchronous reactance per phase $\phi = \angle \mathbf{V}_a - \angle \mathbf{I}_a$
 \mathbf{E}_a = Internal machine voltage
 \mathbf{I}_a = Armature phase current
 \mathbf{V}_a = Terminal line-to-neutral voltage
 R_f = Field resistance
 I_f = Field current
 K_f = Field constant with units of henries
 V_f = Field voltage
 $\omega_s = 2\pi f_e$

Figure 7.1. Synchronous machine equivalent circuit, motor notation

Reactive Power Characteristics

Notice that the magnitude of the stator line current is

$$|\mathbf{I}_a| = \frac{|\mathbf{V}_a - \mathbf{E}_a|}{x_s} \quad (7.6)$$

where $\mathbf{V}_a = V_a \angle 0$, $\mathbf{E}_a = \omega_s K_f I_f \angle \delta$. In general, the phasor diagram for motor operation is as shown in Figure 7.2.

To visualize the V curve phenomenon, consider \mathbf{V}_a and δ fixed as shown. Allow $|\mathbf{E}_a|$ to vary (equivalent to varying I_f). Observe how \mathbf{I}_a will shift in position and change in magnitude as $|\mathbf{E}_a|$ varies. (Remember, x_s is constant, so that the voltage $-jx_s \mathbf{I}_a$ must always be 90° behind \mathbf{I}_a in phase). Observe also the sign on Q_{IN} from (7.5). With δ fixed, the sign will change depending on $|\mathbf{E}_a|$ (or I_f). If P_{IN} rather than δ is fixed, it can be shown that as I_f varies, the magnitude of \mathbf{I}_a goes through a minimum when $Q_{IN} = 0$.

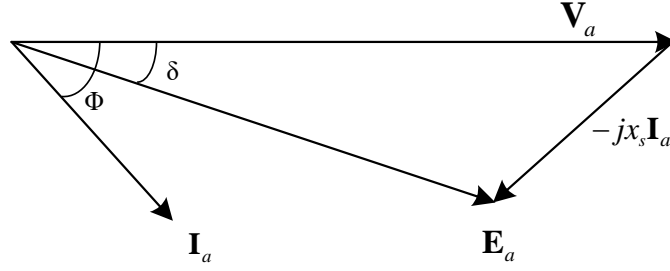


Figure 7.2. Underexcited ($Q_{IN} > 0$), ($\phi > 0$), motor ($P_{IN} > 0$), ($\delta > 0$)

Real Power Characteristics

For fixed values of $|\mathbf{V}_a|$ and I_f , the total power into the motor is proportional to the $\sin(-\delta)$ term of (7.4). Since this term must be less than one, the maximum power which the motor can take in shaft load is fixed by $|\mathbf{V}_a|$ and I_f . Note that at maximum load ($\delta = -90^\circ$), the machine is always absorbing reactive power (refer to (7.5)). Consider the plot of steady-state input power versus δ in Figure 7.3. For some initial load P_0 , the torque angle is δ_0 . This angle cannot be measured directly. However, if a new load P_1 is put on the shaft ($\delta P = P_1 - P_0$), an angle change can be observed ($\Delta\delta = \delta_1 - \delta_0$). The angles δ_0 and δ_1 can be computed from measurements of P_0 , P_1 and $\Delta\delta$. The power-angle curve can be obtained by repeating this procedure until the angle is close to 90° .

A note on starting the synchronous motor

A synchronous motor can be started in three ways. The machine can be driven by an auxiliary drive motor and brought to synchronous speed. Then the field is excited with a direct current source and the 3ϕ stator is synchronized to the 3ϕ supply bus. After synchronization, the stator is placed on the 3ϕ bus and the drive motor may be de-energized. A second method is to use an adjustable frequency supply and slowly ramp up the frequency from zero to rated frequency.

Alternatively, the synchronous motor field can be shorted and the stator connected through starting resistors (or an ac starting box) to the 3ϕ ac bus. The machine is started as an induction motor. This method works quite well when the machine is equipped with amortisseur (or damping) windings in addition to the field circuit. These internally-short-circuited windings are used to damp oscillations during transients and offer induction rotor current during startup. If the motor is unloaded, it will come up to nearly synchronous speed. Direct current is slowly introduced to the field circuit, and the machine will pull into synchronism.

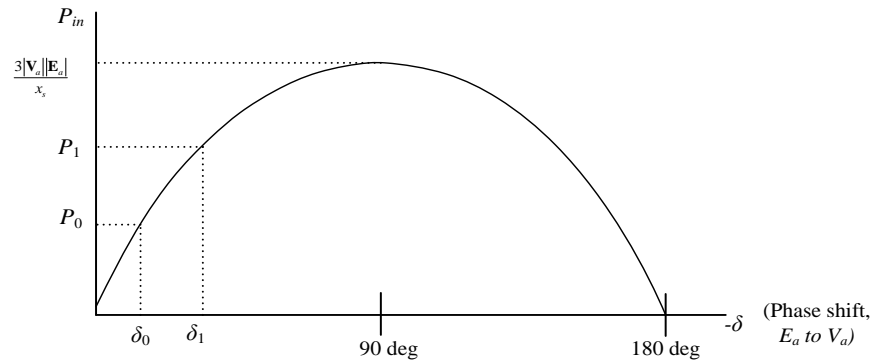


Figure 7.3. Round-rotor synchronous machine power-angle curve
(3 ϕ input power in versus \mathbf{E}_a to \mathbf{V}_a phase shift)

Procedure

Remember to use a resistor box (250 Ω) between ± 120 V DC as described in Experiment #4.

For these experiments, make sure that the **synchronous machine operates as a motor**.

NOTE: If synchronism is lost, use the following procedures:

- 1) Disable drive.
- 2) Short S1 (field windings)
- 3) Power down the Variac
- 4) Repeat Part A.3: Steps (d) through (g)

Part A: Reactive power characteristics

1. Set up the synchronous machine as a motor, and the dynamometer as a load, as shown in Figure 7. 4. Use a 3-pole switch for S1.
2. Set the dynamometer in Torque Mode.
3. Start the synchronous motor as follows: (perform all these steps quickly one by one)
 - (a) Set the torque command to zero.
 - (b) Set $R_f = 500 \Omega$.
 - (c) $S_1 = \text{CLOSED}$ (rotor shorted).
 - (d) Start the motor through the Variac.
 - (e) OPEN S_1 (remove the rotor short).
 - (f) At this point the synchronous machine should lock into synchronism.
 - (g) Adjust the Variac to set the machine voltage as specified by your TA.
4. Vary the field current to obtain data for the no-load V curve. That is, measure stator input armature current, voltage, and power, and the field current. Use the 2-wattmeter method. Take measurements at all field points.
5. Adjust R_f for rated field current.

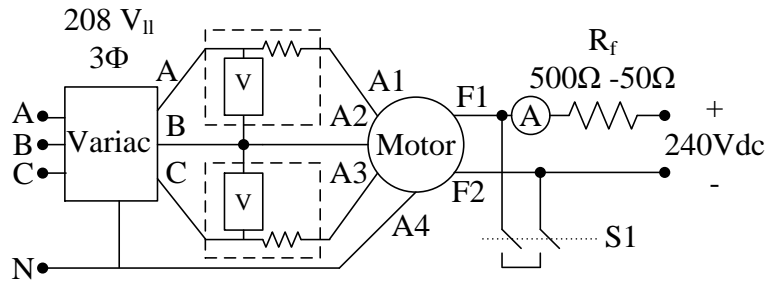


Figure 7.4. Wiring diagram for synchronous machine power tests

6. Obtain a V curve (as in Step 4) for different torque values from 0 to 5 Nm in 1 Nm increments. You should get a whole set of data for each torque value. Only increase torque at minimum armature current.
7. To turn off, remove the torque load, short S1, shut the ac power, and shut the dc power.

Part B: Motor real power characteristics

NOTE: Use stroboscope in “Line” mode.

1. Start the synchronous motor as described in Part A.3.
2. Adjust the synchronous machine field current (use $R_f = 500 \Omega$).
3. Set the Variac to 60% of the rated value. Read the no-load armature current, voltage and power. The no-load value of δ is unknown.
4. Increase torque in 0.5 N_m increments and record the following at each point:
 - a) Change in rotor angle using stroboscope
 - b) Armature current, voltage, and power

NOTE: The stroboscope measures $\delta_{\text{mechanical}}$ where $\delta_{\text{electrical}} = (p/2)\delta_{\text{mechanical}}$.

5. Investigate maximum sudden loading. Apply a sudden torque load to do so (from 0 to 1 Nm, 0 to 2 Nm). When the machine loses synchronism, follow the necessary procedure.
6. Set the torque slightly below the maximum sudden loading you found in Step 5. Now go further by “sneaking up” the curve. This means to fine-tune (in 0.2 Nm increments) until you find the maximum torque.
7. Set the torque to zero and power down the machine.

Part C: Generator characteristics

1. Start the machine. Adjust the field current to what it was when you began Part B, and set the torque command to zero.
2. Again, record no-load armature current, voltage, and power. Record the rotor angle change.

- Reverse the torque if necessary and record change in angle, current, voltage, and power for 4 to 5 torque values.

NOTE: **Remember to set torque to zero before powering down the machine.**

Notes

Remember, record only what was read in the lab. The Recorder should not do calculations but label everything well, e.g., shaft angle, line-to-line or line-to-neutral voltage, wattmeter reading, etc.

Report

- Plot the “V” curves ($|I_a|$ vs I_f) on one sheet from Part A data.
- Compute Q_{IN} and plot the Q_{IN} vs I_f curves on one sheet from Part A data.
- From each data point taken in Step 6 in Parts B and C, compute the initial δ_0 . To do that, first calculate the $\Delta\delta$ relative to no-load case for each of the data points. Recall $P_0 + \Delta P = P_{\max} \sin(-\delta_0 - \Delta\delta)$. This power curve can be used to obtain an expression for δ_0 as shown in equation (7.7). Next use equation (7.7) to estimate δ_0 for each measurement.

$$\tan(+\delta_0) = \frac{\sin(\Delta\delta)}{\frac{P_1}{P_0} - \cos(\Delta\delta)}, \text{ if } \Delta\delta \triangleq \delta_1 - \delta_0 \quad (7.7)$$

Take the average value of δ_0 for your plot in the next step. Calculate P_{\max} for each measurement, where $P_{IN} = P_{\max} \sin(-\delta)$. Take average P_{\max} for the plot in next step.

- Plot the $P_{IN_{3\phi}}$ vs δ on one sheet, and compare them to the theoretical curve obtained from P_{\max} and δ_0 (plot this theoretical curve in the same graph as the measured results).
- Comment on the results.
- What is the maximum sudden loading? Compare to estimate obtained from equal area criterion.

Final Comment

The synchronous machine is the most common form of power generator. As a dynamic component in a power system, it has a significant effect on the overall operation. Stability is a prime factor in successful power system operation. Loss of stability means that at least one machine has lost synchronism with the rest of the system. Research is being done in many areas of synchronous machine stability and in the control of power systems. The real power characteristics examined in this experiment are a basic part of this research and form the groundwork for analysis of multi-machine systems.

As a synchronous condenser, the synchronous machine offers versatile operation as a capacitive or inductive load. Such devices are often used when continuous variation of capacitive compensation is required rather than discrete capacitor switching. Thus the synchronous machine has very desirable power characteristics, which accounts for its wide use in high-power situations.

Experiment #8: Synchronous Machine Dynamic Simulation

Objective

The objectives of this experiment are to further understand machine dynamics through the mathematical simulation of synchronous machine step loading.

Introduction

The instantaneous rotor position of a synchronous machine may be written in electrical radians as

$$\theta = \int_0^t \omega(\tau) d\tau + \theta(0) \quad (8.1)$$

where $\omega(t)$ is the instantaneous rotor speed in electrical radians per second. Note that in steady state, a 6-pole 60 Hz machine running at 1200 RPM has

$$\theta_{ss} = 2\pi 60t + \theta_{ss}(0) \quad (8.2)$$

For a fixed voltage source, an electrical angular displacement may be written as

$$\theta_s = \omega_s t + \theta_{vs} \quad (8.3)$$

where for a 60 Hz source, $\omega_s = 2\pi 60$ electrical radians per second. Define the quantity delta

$$\delta_t \equiv \theta - \theta_s + 90^\circ \quad (8.4)$$

where θ , θ_s and thus δ_t are all in electrical radians. Newton's second law for rotating bodies requires

$$J \frac{d^2 \theta'}{dt^2} = \sum \text{torques} \quad (8.5)$$

where

$$\theta' = \frac{2}{p} \theta \quad (8.6)$$

so that

$$\frac{d^2 \theta'}{dt^2} = \frac{2}{p} \frac{d^2 \theta}{dt^2} \quad (8.7)$$

Also note that, using equations (8.1)–(8.4),

$$\frac{d^2\theta}{dt^2} = \frac{d}{dt} \left(\frac{d\theta}{dt} \right) = \frac{d}{dt} \left(\frac{d\delta_t}{dt} = \omega_s \right) = \frac{d^2\delta_t}{dt^2} \quad (8.8)$$

or

$$\frac{d^2\theta}{dt^2} = \frac{d}{dt} \left(\frac{d\theta}{dt} \right) = \frac{d\omega}{dt} \quad (8.9)$$

It can be shown that the steady-state electrical torque into a balanced three-phase round rotor P pole synchronous motor may be expressed as

$$T_e = \frac{P_{in}}{\omega_s \frac{2}{p}} = \frac{3 |\mathbf{V}_e| |\mathbf{E}_f|}{\frac{2}{p} \omega_s x_s} \sin(-\delta_t) \quad (8.10)$$

where $|\mathbf{V}_t|$ is the line to neutral RMS stator phase A voltage, x_s is the synchronous reactance, and

$$|\mathbf{E}_f| = \frac{\omega_s L_{asf} I_f}{\sqrt{2}} \quad (8.11)$$

where ω_s is in electrical radians per second, and δ_t is in electrical radians. The damper (amortisseur) windings of a synchronous machine provide an asynchronous torque through induction which contributes only when $\omega \neq \omega_s$, so that

$$T_D = -D \left(\frac{2}{p} \right) (\omega - \omega_s) \quad (8.12)$$

The steady-state shaft torque is

$$T_m = -\frac{P_m}{\frac{2}{p} \omega_s} \quad (8.13)$$

where P_m is the shaft load in watts.

Assuming that the steady-state electrical and mechanical torque expressions are valid for the relatively slow mechanical dynamics being investigated in this experiment, the equations which describe the synchronous machine dynamics are as follows:

$$\frac{d\delta_t}{dt} = \omega - \omega_s \quad (D.E.1)$$

$$\frac{d\omega}{dt} = \frac{1}{J} \frac{P}{2} (T_e + T_D + T_m) \quad (D.E.2)$$

Solution Method

Consider the Taylor series expansion of some function $f(x)$ about the point $x = x^0$

$$f(x) = f(x^0) + \left. \frac{df(x)}{dx} \right|_{x=x^0} (x - x^0) + \text{higher order terms} \quad (8.14)$$

To a first-order approximation, consider attempting to solve (D.E. 1) for $\delta_t(t)$,

$$\delta_t(t^0 + h) \approx \delta_t(t^0) + \left. \frac{d\delta_t}{dt} \right|_{t=t^0} h \quad (8.15)$$

Similarly, attempting to solve (D.E.2) for $\omega(t)$,

$$\omega(t^0 + h) \approx \omega(t^0) + \left. \frac{d\omega}{dt} \right|_{t=t^0} h \quad (8.16)$$

The solution method is clearly visible: To find the dynamic response of a synchronous motor running at no load when a load of P_m is suddenly added at $t = h$ seconds,

- Step 1. Set the initial values to the steady-state operating point.
- Step 2. Find the electrical torque, damping torque, and mechanical torque from (8.10)-(8.12).
- Step 3. Find the derivatives of angle and speed at time $t=0$ from the two differential equations.
- Step 4. Find estimates for $\delta_t(0+h)$ and $\omega(0+h)$ from (8.15) and (8.16).
- Step 5. Repeat steps 2 through 4 to obtain $\delta_t(h)$, $\delta_t(2h)$, $\delta_t(3h)$, ... and $\omega(h)$, $\omega(2h)$, $\omega(3h)$, ...

This solution method is termed *Euler's method of numerical integration* and works reasonably well when h is sufficiently small.

The Problem

Consider a balanced three-phase 6-pole 60 Hz round motor with

$$\begin{array}{ll} r_a = 0 & |V_t| = 230 / \sqrt{3} \text{ V} \\ x_s = 9\Omega & D = 0.3 \text{ N} \cdot \text{m} \cdot \text{s} \\ L_{asf} = 0.4 \text{ H} & P = 6 \text{ poles} \\ I_f = 1.2 \text{ A} & J = 0.4 \text{ kg} \cdot \text{m}^2 \end{array}$$

Start with no applied shaft power at $t = 0$ and $\delta_t(0) = 0$, in steady state such that $\omega(0) = \omega_s$.

- Find the motor's dynamic response to sudden shaft loads of 2500, 3500, 4500 W applied at $t = 0.01$ s. Using Euler's method or a Runge-Kutta algorithm with a (recommended) step size of $500 \mu\text{s}$, simulate the response from $t = 0$ to $t = 20$ s.
- Use your program to find the maximum P_m (within 10 W) which can be added suddenly from no-load. Use equal area criteria to predict this maximum.

Report

Submit results from MATLAB (or similar program) for all cases of P_m .

1. For each load condition, plot:
 - a. Speed vs. time
 - b. δ_t (electrical degrees) vs. time
 - c. δ_t (electrical degrees) vs. speed
 - d. Armature current vs. time.
2. Compare the actual maximum load, which can be added from no-load, with that predicted by equal area criteria.
3. Plot the curves for this maximum load and also the curves for 1 W more than this maximum load.
4. Attach your computer program code to Appendix.

Experiment #9: Brushless DC Motor Equivalent Circuit and Performance

Objective

The objectives of this experiment are to become familiar with the permanent magnet synchronous machine and understand its function as a brushless dc machine when coupled to an inverter-based drive.

Introduction

The brushless dc machine (BLDCM) has recently evolved as a replacement for the standard brush-type dc machine in many servo applications. In spite of the name, the BLDCM comprises a permanent magnet synchronous machine (PMSM) and an inverter-based drive that provides electronic commutation of the stator windings. Both machines, at a basic level, are ac machines since the magnetic fields fluctuate within the machine. In the brush-type machine, dc voltage is applied to the rotor circuit and the ac field is generated on the rotor by mechanical commutation of the rotor windings as the rotor rotates. A dc field is created on the stator by exciting the field winding with a dc voltage. In the BLDCM, a dc field is created on the rotor by the permanent magnet and the ac field is created on the stator by commutation action of the drive. The brush-type motor has several connection possibilities, but shunt-connected and permanent-magnet dc machines prevail in servo applications. The BLDCM, through various electrical commutation strategies, can be made to have the same characteristics of the shunt (with fixed field current) or PM dc motor. The main advantages of the BLDCM are higher power density, quieter operation, low maintenance, absence of arcing that causes severe interference, and increased flexibility through electronic control.

In order to understand the operation of the BLDCM, it is useful to first develop the PMSM model and then discuss how the electronic controls are applied to create a behavior similar to the dc machine. The PMSM is the same as a wound-field synchronous machine except with the field winding replaced by permanent magnets and the removal of damper windings. It is still a synchronous machine in the sense that in steady state it turns at synchronous speed. As such, the steady-state equivalent of the PMSM is nearly identical to the wound-field synchronous machine and is shown in Figure 9.1. The important difference to note is that the internal back emf is no longer a function of the field current (Figure. 6.1) but rather a constant flux multiplied by the rotor speed. Also, we no longer have a field-winding circuit. In this model, the power delivered to the voltage source e_a represents the power delivered to the shaft.

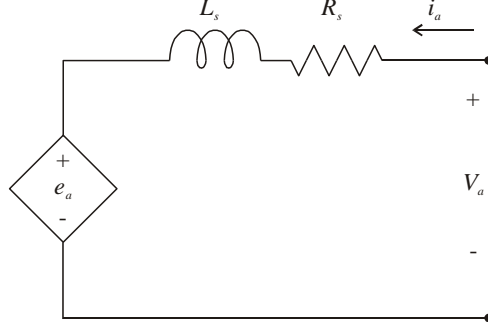


Figure 9.1. PMSM steady-state equivalent circuit model.

A straightforward dynamic model is obtainable since there are no rotor circuits. Equation 9.1 describes the terminal voltage characteristics for each phase where x represents either phase a , b , or c . For a phase x , the stator resistance is r_s and the flux linkage is λ_x :

$$v_x = r_s i_x + \frac{d}{dt} \lambda_x \quad (9.1)$$

The flux linkage depends on machine inductance and the permanent magnet flux, which varies with rotor position. Equation 9.2 shows this relationship for the a -phase, where L_s is the self inductance, L_m is the mutual inductance, λ_m denotes the magnet flux linkage, and θ_r is the electrical rotor position ($p/2$ times the mechanical rotor position, where p is the number poles).

$$\lambda_a = L_s i_a - L_m i_b - L_m i_c + \lambda_m \sin(\theta_r) \quad (9.2)$$

The rotor angle is arbitrarily chosen relative to the a -axis. Similar expressions exist for b and c phases and can be obtained by changing the subscripts and shifting θ_r by $\pm 2\pi/3$. Note that the magnets on the rotor, in effect, extend the effective air gap of the machine (since the relative permeability is near 1). This generally causes the mutual coupling between phases to be small. Thus we can neglect the effects of L_m .

The machine back emf is the stator voltage component induced by the changing magnet flux linkage, where ω_r is the electrical rotor speed:

$$e_a = \omega_r \lambda_m \sin(\theta_r) \quad (9.3)$$

Again, shifting θ_r by $\pm 2\pi/3$ yields expressions for phases b and c .

Once the PMSM machine is understood, the controls necessary for a BLDCM can be developed. The BLDCM consists of a PMSM, a power electronic inverter, and sensor feedback for position. The drive control logic interprets positional information and turns on the appropriate inverter phase. Essentially, the positional information allows the drive to determine in which direction the rotor flux is pointing. Next, the drive determines which phases to excite so as to

produce positive torque. The net effect of this process is very similar to the mechanical commutation of the brush-type dc machine where the brushes continually switch which rotor winding is excited, such that rotor flux is always nearly 90 degrees out of phase with the constant stator flux. In the PMSM, rotor position feedback will ensure that the stator electrical frequency is matched to the rotor speed, thereby ensuring stability. A simple cost-effective method of implementing the positional sensing is to fit the motor with several *Hall Effect* sensors. *Hall sensors are binary output devices that sense whether a north or south magnet pole is present under the sensor.* The binary outputs of the sensors are then used to determine roughly where the rotor flux is pointing. Based on the output of three sensors, a power converter can be used to convert a dc supply to a three-phase ac supply of the appropriate frequency. Ultimately, an ac voltage is applied to each stator winding through the switching action, even though only a dc voltage is used.

The torque of the BLDCM can be derived by first equating the power out to the power in, minus the losses:

$$P_{out} = T_e \omega_{rm} = P_{in} - P_{losses} = v_a i_a + v_b i_b + v_c i_c - r_s (i_a^2 + i_b^2 + i_c^2) \quad (9.4)$$

where ω_{rm} is the mechanical speed and T_e is the airgap torque. Ignoring mutual inductance between phases, (9.1 – (9.3) may be used to formulate the torque of electrical origin as

$$T_e = \frac{p}{2} \frac{1}{\omega_r} (e_a i_a + e_b i_b + e_c i_c) \quad (9.5)$$

This is straightforward to remember and intuitively elegant, because despite the complexity of the machine itself, the torque is just the sum of the products of back emf and current for each phase, divided by the rotor speed. In the form of (9.5), it first appears the torque is dependent on speed and has a singularity at zero speed, but note the speed cancels when (9.3) is substituted.

The synchronous speed of the excitation voltage is determined by the machine rotation speed; thus the BLDCM has a speed vs. voltage relationship similar to that of the constant-field-current shunt DC or PM DC machine. If the input voltage is increased, the current flowing into e_a is increased and thus power delivered to the shaft increases. This increase of power at the shaft will speed up the machine, thereby increasing e_a until the new equilibrium is reached (assuming a constant load on the shaft). An opposite effect occurs if the dc input voltage is decreased. Thus, varying the dc voltage supplied to the BLDCM allows for simple speed control similar to that of the brush-type dc motor.

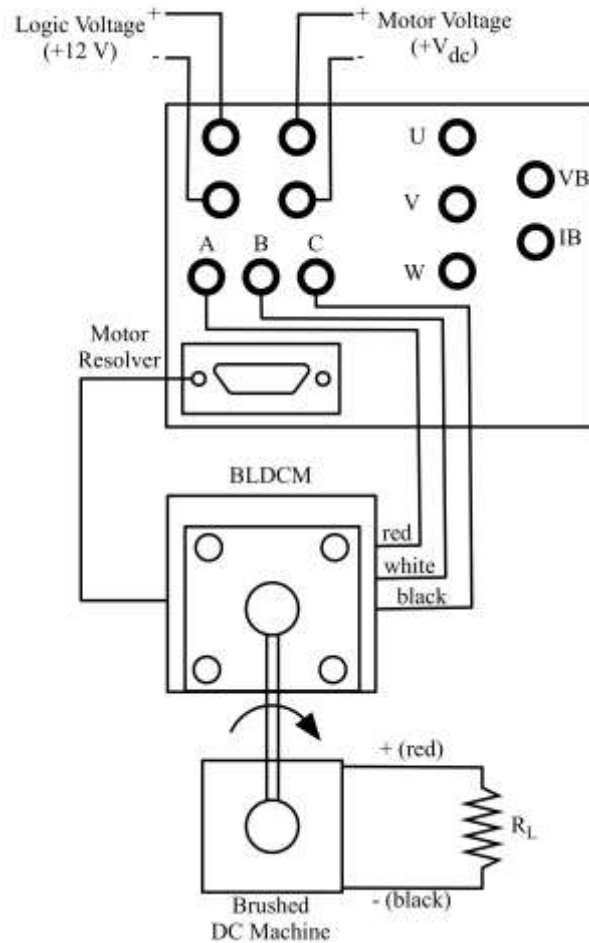


Figure 9.2. BLDCM drive connection.

Details about the Laboratory Equipment

The lab motor is a Shinano Kenshi Corp. LA052 PM ac motor with four poles rated at 40 W, 3000 RPM, 24 V, and 2.5 A. It has three delta-connected phases and is fitted with a position feedback system. While Hall Effect sensing as described earlier can provide sufficient information for simple switching, in other control schemes more precise angular position is required. Thus, in addition to the Hall sensors, these machines also have a 500 pulse-per-revolution position resolver. The increased positional accuracy can be useful in designing more sophisticated speed control, positional control, or other complex control strategies; however, this information will not be used directly in this experiment.

The control drive for this lab contains a 6-MOSFET inverter (IRF520), the inverter driver (the IRF2130), and some protection logic. Several terminals are brought out such that measurements of internal signals can be observed.

Procedure

Part A: Motor characterization

NOTE: Use the Agilent power supply for 12 V logic power, and the Keithley power supply for the main dc power. The current limit should be 2.5 A. All grounds need to be connected.

NOTE: For the machine, the ratings are: 4 poles, 40 W, 3000 RPM, 24 V, 2.5 A, delta-connected. Red color is phase A, Blue is phase B, and Black is phase C.

1. Measure the stator resistance, r_s , of the BLDCM. Do this by connecting the ohmmeter line-to-line across two phases and leaving the third phase open. Record the resistance for each of the three line-to-line combinations.
2. Measure the total stator self inductance, L_s .
 - a. Short one phase of the motor by connecting any two phase leads.
 - b. Connect a small 60 Hz voltage between the two remaining terminals (use the Variac). Be certain to start the Variac at 0 voltage.
 - c. Very slowly adjust the voltage from the Variac to obtain roughly 3 A of line current (should be at roughly 5 V).
 - d. Record the power, voltage, and current into the machine.
 - e. Repeat this for each line-to-line combination.
3. Measure the magnet strength, λ_m .
 - a. With the motor terminals open-circuited, connect an oscilloscope probe across two phases. Make sure none of the phase wire ends are touching.
 - b. Monitor the U Hall Effect signal.
 - c. Connect a dc voltage (5 V) to the brush-type dc motor to drive the machine at constant speed.
 - d. Measure the electrical frequency of the pulses from the Hall Effect sensor, and record the peak magnitude of the motor voltage waveform. This requires 12 V logic power.
 - e. Save a plot of these voltages to the computer.
 - f. Repeat this for each line-to-line combination.

Part B: Motor performance

1. Loaded performance
 - a. Probe a -phase current, a - b voltage (use an isolated probe), and the a -phase Hall Effect sensor output (U).
 - b. Monitor the voltage and polarity of the open-circuit armature terminal of the brush-type dc machine.
 - c. Apply 12 V to the drive to start the machine. Trigger the scope off of the positive rising edge of the U signal. Save all waveforms and associated measurements.

- d. Power off the machine, connect the electronic load to the armature terminals of the brush-type dc machine (ensure proper polarities!), and configure the load to $16\ \Omega$.
 - e. Repeat Step c.
2. No-load speed control
 - a. Remove the load resistance from the brush-type dc machine.
 - b. With the motor running, adjust the motor-input voltage to 12 V (dc input voltage).
 - c. Again measure the frequency of the pulses from the Hall Sensor to determine the speed of the machine.
 - d. Drop the input voltage by 1 V increments and record the speed at each data point until the motor stops rotating.
 - e. Stop the drive and power down.
3. Loaded operation
 - a. With the drive disabled, measure the armature resistance (r_a) of the brush-type dc machine. Take an average of many values while rotating the shaft.
 - b. Connect the electronic load to the brush-type dc machine. Set to constant-current operation at 0 A. Measure Pin to BLDC using the two-wattmeter method.
 - c. Apply 12 V to the drive, probe a -phase current, a - b voltage, and the frequency of the a -phase Hall Effect sensor (U). In addition, record the output power and output current using the electronic load display.
 - d. Increase the load to 0.1 A, and repeat Step c.
 - e. Repeat Step d. in 0.1 A increments until you reach 1.0 A.
4. Encoder feedback.
 - a. Turn off the logic and motor power supplies.
 - b. Disconnect the encoder feedback.
 - c. Turn the supplies on. Will the motor spin?

Report

1. Determine r_Δ by taking an average of your line-to-line resistance values and dividing by two-thirds. Show why the scaling factor is two-thirds for a delta-connected motor. r_Δ is different from r_s in single-phase equivalent circuit!
2. Using your power, voltage and current data from Part A. Step 2, determine the inductance, L_s . Recall that by shorting one phase of the delta-connected motor, we are exciting two

phases in parallel with a single input voltage. We can also estimate the stator resistance from this data. How does this compare to our direct line measurements?

3. Use the peak magnitude that you obtained in Part A Step 3 and the speed the motor was rotating to obtain an estimate of λ_m . Repeat for each phase and use the average value calculated for your final estimate of λ_m .
4. Plot the speed vs. voltage curve from the data obtained in Part B Step 2. Comment on this curve. Does the input voltage magnitude provide a useful control of the machine speed?
5. For Step 3, the load torque at each data point can be calculated as

$$T_L = \frac{P_{out} + i_a^2 r_a}{\omega_{rm}} = \frac{P_{in} - 3 \left(\frac{I_a}{\sqrt{3}} \right)^2 r_\Delta}{\omega_{rm}}. \quad (9.6)$$

Plot T_L vs. ω_{rm} . (Tip: Due to the nature of the BLDC switching waveform, the first equation for T_L works better than the second for analyzing the results).

6. For each data point in Step 3, calculate the machine efficiency. Assume that conduction loss is the only loss component in each machine. Plot efficiency vs. speed for both machines on the same set of axes.
7. Comment on the need for position feedback in BLDC drives.

Experiment #10: DC Machine Equivalent Circuit

Objective

The objectives of this experiment are to become familiar with dc machine characteristics and obtain the equivalent-circuit parameters.

Introduction

The dc machine has many applications as both a motor and a generator. This is primarily because of the versatile torque, speed and voltage characteristics of the machine and the simplicity of its equivalent circuit. The dc machine is essentially a rotating coil (armature) in the air gap of a stationary field. As a generator, the principle of operation is as follows: A stationary magnetic field is established by the flow of direct current in the stator windings. As the rotor is turned, a voltage is induced in the interconnected rotor windings. This voltage is maximum when the conductors pass through the stationary field at 90°. If the rotor windings are passed through slip rings to the external machine terminals, an alternating voltage would appear (this would be a synchronous generator with the field on the stator). In order to produce a constant voltage, the external terminals cannot maintain contact with only one rotating coil. The rotor of a dc machine consists of many interconnected coils which are sequentially connected to the external terminals through a split-ring commutator to complete the armature circuit. The commutator acts as a mechanical rectifier. It is constructed so that the coil which is connected at any instant has maximum induced voltage.

When current is allowed to flow in the armature by the connection of an external load, the armature current will establish a magnetic field with an axis perpendicular to that of the main field. The magnetic field produced by the armature current will tend to distort the magnetic field of the main winding in the air gap. The dc machine has salient poles on the stator upon which the main field is wound. Most dc machines also contain interpole windings between the poles and compensation windings under the poles to offset this armature reaction. Thus the voltage induced in the armature circuit can be attributed only to the magnetic field produced by the main field winding. If nonlinear magnetic effects such as saturation and core losses are neglected, the voltage which is induced in the armature in steady state is

$$E_a = K_f \omega_m I_f \quad (10.1)$$

where ω_m is the mechanical speed of the shaft. Initial reactions to this statement might include a question regarding the requirement of relative motion between a winding and a field for the production of a voltage. The relative motion occurs in the small time during commutation when the flux linking the armature coil is changing rapidly. As a motor, a stationary magnetic field is

established in both the field and armature windings. The commutator in this case acts to keep the two magnetic fields 90° apart to produce a maximum torque.

The approximate expression of Eq. (10.1) does not give good predictions in some cases. For example, a generator connection such as the one in this experiment is not modeled properly. A better model must consider that the voltage E_a is proportional to a magnetic flux linkage λ_f . This flux linkage is a nonlinear function of I_f . In addition, there is some remnant flux linkage λ_R , and we can write

$$E_a = \lambda_f \omega \approx (K_f I_f + \lambda_R) \omega \quad (10.2)$$

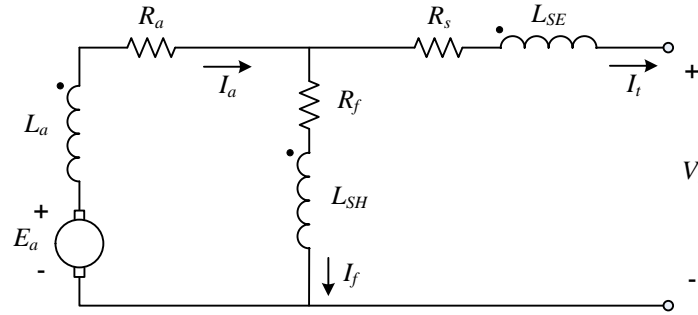
The main field produced in the air gap is obtained from the current flow in the stator windings. Many dc machines have two field windings. The shunt-field winding is constructed of small wire with many turns so that it can be excited by either an external source or rated armature voltage. That is, the shunt field has a relatively high (100-200 Ω) resistance. The series-field winding is constructed of large wire suitable for excitation by rated armature current. That is, the series field has a relatively low (0.2-1.0 Ω) resistance. The net voltage induced in the armature coil due to both field windings in a cumulative connection (acting to aid each other) is

$$E_a \approx K_f^{SH} \omega I_f + K_f^{SE} \omega I_s + \lambda_R \omega. \quad (10.3)$$

When the machine is modeled with all resistances and inductances, the machine equations are as shown with the equivalent circuit of Figure 10.1. Modifications to this circuit and resulting equations can be made according to Table 10.1.

Table 10.1
Dc Machine Modification of Figure 10.1

TO MAKE:	CHANGE:
Shunt dc generator	Omit series field ($R_s = K_f^{SE} = 0$)
Series dc generator	Omit shunt field ($R_f = \infty, K_f^{SH} = 0$)
Differential dc generator	Reverse polarity of series field (change sign on K_f^{SE}) OR Reverse polarity of shunt field (change sign on K_f^{SH})
Long-shunt dc generator	Move shunt field to other side of series field ($i_{SE} = i_a$)



R_a = Armature coil resistance
 R_s = Series field-coil resistance
 R_f = Shunt field-coil resistance
 L_a = Armature coil self inductance
 L_{SE} = Series field-coil self inductance
 L_{SH} = Shunt field-coil self inductance
 E_a = Armature voltage induced by fields

Figure 10.1. Self-excited short-shunt cumulative-compound dc machine
(Linear magnetic core)

Machine equations (generator notation, steady state):

$$V_t = -I_t R_s - I_a R_a + K_f^{SH} \omega I_f + \lambda_R \omega + K_f^{SE} \omega I_t$$

$$V_t = I_f R_f - I_t R_s$$

$$\omega = \frac{V_t + I_a R_a + I_t R_s}{K_f^{SH} I_f + K_f^{SE} I_t + \lambda_R}$$

$$P_{FROM\ SHAFT} = + (K_f^{SH} \omega I_f + K_f^{SE} \omega I_t + \lambda_R \omega) I_a$$

Notes

1. In steady state, all current derivatives are zero.
2. For purposes of metering, let the polarity mark be positive (the machine shown will have “positive” speed).

In this experiment, a dc machine will be driven by the dynamometer. If the dc machine is connected properly as a self-excited shunt generator, the residual flux will excite the shunt field so that a small increase in flux will be obtained in the air gap. If the polarity of the armature, shunt field, and direction of rotation are not additive, the flux will oppose the residual flux, and no voltage will build up. If proper polarity is achieved, eventually the $L \cdot di/dt$ induced voltages will reduce to zero, and the iron saturation will stop the voltage buildup at steady-state conditions.

The field constants of the equivalent circuit can be obtained through tests. If the machine is unloaded, a plot of terminal voltage versus shunt field current will determine K_f^{SH} and λ_R . Similarly, once K_f^{SH} is known, a load test can be used to determine K_f^{SE} .

Procedure

Remember to use a resistor box ($250\ \Omega$) between $\pm 120\text{ V}_{\text{dc}}$ as described in Experiment 4.

Notes

1. Be sure to make a note of all polarities as connected in the lab.
2. The units of the shunt field constants are henries.

Part A: Determining R_a , R_s , R_f , K_f^{SH} , λ_R

NOTE: Check dial position of $300\ \Omega$ potentiometer.

1. Measure the dc machine shunt field resistance with an ohmmeter. The shunt field is connected between terminals F1 and F2. Measure the resistance of the armature winding (A1 and A2) and the series field winding (F3 and F4).
2. Set up the circuit in Figure 10.2. This is a cumulative compound short-shunt dc generator driven by the dynamometer.

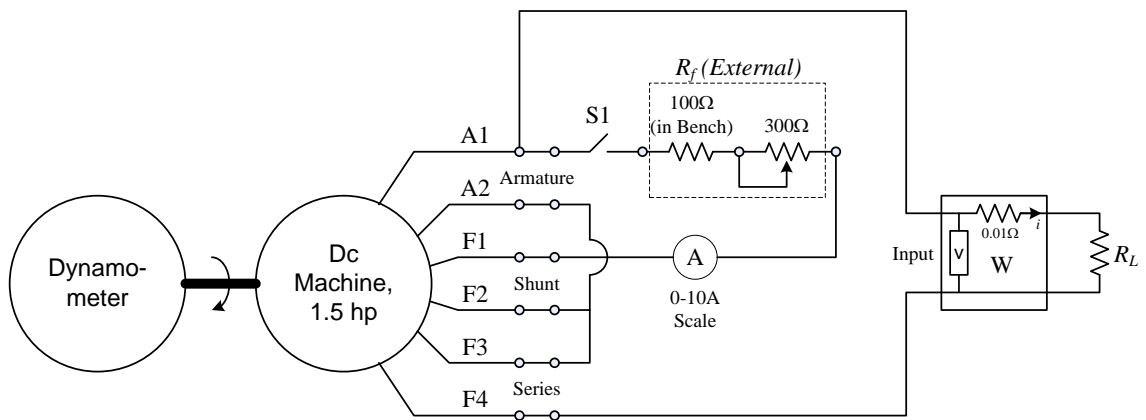


Figure 10.2. Field test connections for dc generator

3. With S_1 open and $R_L = \infty$ (open circuit), start the dynamometer in Velocity Mode at the dc generator rated speed. Measure the dc generator RPM and residual voltage.
4. Set the potentiometer for maximum resistance in the shunt field and close S_1 . Be sure to know which direction (clockwise or counter-clockwise) is to increase or decrease the resistance. If the voltage does not build up as R_f is decreased, turn off the machines, and reverse the armature polarity.
5. Slowly increase the shunt field current from zero to about 1.0 A in 0.1 A. steps. Measure V_t and I_f at each step once they are stable. Do not exceed about 280 volts on the terminals. Always increase the field current (or decrease R_f), not vice versa.
6. Power down the machine.

Part B: Determining K_f^{SE}

1. Follow Step 3 of Part A with switch S_1 closed, and start the dynamometer in Velocity Mode at the rated speed.
2. Adjust the shunt field potentiometer to obtain rated voltage at the dc generator.
3. Load the machine by decreasing R_L (1 “R” at a time, up to 6 “R” in parallel for torque less than 6.5 Nm. Take several measurements of V_t , I_a , I_f , RPM and torque as R_L is reduced.
4. Power down the machines, reverse the series field terminals, and repeat steps 1-3. This allows you to determine which series field connection results in a cumulative-compound machine (connection that provides largest terminal voltage).

Report

1. Plot the constant-speed no-load terminal voltage versus shunt field current of Part A. Comment on the shape of the curve.
2. Calculate λ_R .
3. Determine a value for the shunt field constant, K_f^{SH} , at rated terminal voltage.
4. Use the data from Part B to determine the series field constant K_f^{SE} (evaluate the terminal voltage equation at each data point, solving each time for K_f^{SE} and then compute the average value).
5. Tabulate the equivalent-circuit parameters R_a , R_s , R_f , K_f^{SH} , K_f^{SE} , λ_R .
6. Plot the following on one set of axes (in the same graph):
 - (a) measured torque as a function of I_a .
 - (b) the quantity $\lambda_R I_a + K_f^{SH} I_f I_a + K_f^{SE} I_a I_t$ as a function of I_a .Compare the two curves. What is the significance of the quantity plotted in (b)?
7. Plot no-load speed vs. armature voltage for Part C. Comment on the relationship. Is this expected?

Experiment #11: DC Machine Torque-Speed Characteristics

Objective

The objectives of this experiment are to examine the torque-speed characteristics of a dc motor. These characteristics reflect the possible motor applications.

Introduction

The dc machine has the major disadvantage of requiring a mechanical commutator that requires periodic maintenance. This drawback is often tolerated in order to take advantage of the versatile torque characteristics. As a motor, the commutator sequentially switches the direction of current flow in the armature coils to maintain constant maximum torque. This is done by the same mechanism by which maximum induced voltage was obtained in the generator mode.

When the armature of a dc motor is rotating at a speed of ω , a voltage is generated across the armature coils. This is called the *back emf* (or *counter emf*), and is given by

$$E_a = K\omega\phi \quad (11.1)$$

where ϕ is the net flux in the air gap linking the armature coils. With the use of compensation windings and interpole coils, this flux is due almost entirely to the field windings. If saturation is neglected, this flux is directly proportional to the field currents, and

$$E_a \approx \lambda_R \omega + K_f^{SH} \omega I_f + K_f^{SE} \omega I_a \quad (11.2)$$

Equation (11.2) implies cumulative compound windings so that the series and shunt fields aid each other. Under these assumptions, the equivalent circuit shown in Figure 11.1 may be used. Note that as a long-shunt self-excited motor, the speed required to satisfy a torque of

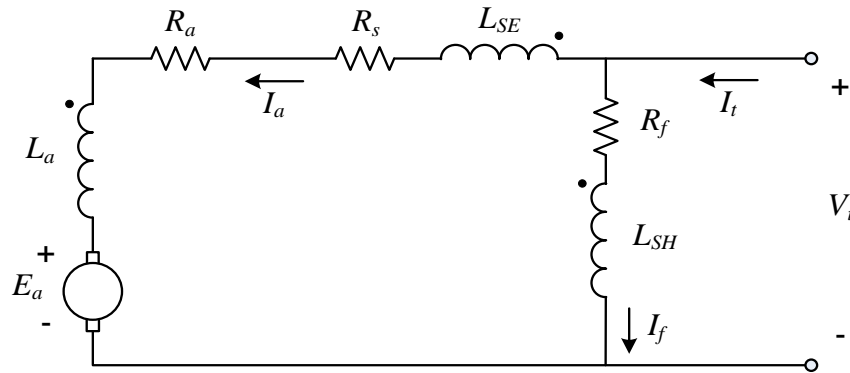
$$T_{Load} = T_{\omega_{SHAFT}} = \lambda_R I_a \pm K_f^{SH} I_f I_a + K_f^{SE} I_a^2 \quad (11.3)$$

is

$$\omega = \frac{V_t - I_a R_a - I_a R_s}{\lambda_R + K_f^{SH} I_f + K_f^{SE} I_a} \quad (11.4)$$

In normal operation, $V_t \gg I_a R_a + I_a R_s$, so that steady-state speed may be controlled by the adjustment of I_f . That is, for a constant V_t , a decrease in I_f will lower the net flux in the air gap, creating an increased difference between the back emf and V_t . This increases the armature current, causing an accelerating torque and thus higher speed. The variation of shunt field resistance thus offers a method of speed control. Notice that if the shunt field of a dc motor is open-circuited, I_f

drops to zero, resulting in a drastic speed increase. ***This will cause damage to both the machine and anyone near it and should be strictly avoided!***



- R_a = Armature coil resistance
- R_s = Series field-coil resistance
- R_f = Shunt field-coil resistance
- L_a = Armature coil self inductance
- L_{SE} = Series field-coil self inductance
- L_{SH} = Shunt field-coil self inductance
- E_a = Armature voltage induced by fields

Figure 11.1. Self-excited long-shunt cumulative-compound dc machine

Machine equations (motor notation, steady-state operation):

$$V_t = I_a R_s + I_a R_a + \lambda_R \omega + K_f^{SH} \omega I_f + K_f^{SE} \omega I_a$$

$$V_t = I_f R_f$$

$$\omega = \frac{V_t - I_a R_a - I_a R_s}{\lambda_R + K_f^{SH} I_f + K_f^{SE} I_a}$$

$$P_{IO_{SHAFT}} = +(\lambda_R \omega + K_f^{SH} \omega I_f + K_f^{SE} \omega I_a) I_a$$

When starting a dc motor, the back emf is zero initially, so the armature current is essentially equal to the impressed voltage divided by the armature resistance. As the impressed voltage may be 240 V across a one-ohm armature resistance, this would result in hundreds of amps of starting current. The current would surely damage the winding if it were not protected by a fuse or breaker. As in ac machines, a starting scheme is required to limit the inrush current. This could be done with power electronics switches arranged in an H-bridge configuration. In this lab, however, the inrush current is limited with a 50 Ω resistor in series with the armature circuit (Figure 11.2). The resistor can be shorted out once the machine reaches steady state.

In this experiment, the dynamometer machine will serve as a load on the dc motor. The dynamometer will be operated in Torque Mode to simulate a constant torque load. Torque versus speed for constant applied voltage will be analyzed.

Procedure

Remember to use a resistor box ($250\ \Omega$) connected to the 240 V_{dc} supply as described in Experiment 4. **Also, never place a series ammeter within the shunt field in order to avoid a risk of open-circuit field circuit.**

Notes

1. Do not open the motor shunt field circuit with the supply connected.
2. Be sure to observe correct polarity when connecting the compound motor

Part A: Shunt dc motor characteristics

1. Set up the $1\frac{1}{2}$ HP dc machine as a drive motor as shown in Figure 11.2, with the shunt field rheostat set at 150 ohms (half position).
2. With S2 open, turn on 240 V dc power.
3. Set up the dynamometer to operate in Torque Mode, and start it with a zero-torque command.
4. Close switch S2. Wait ten seconds for acceleration, then close S1 to remove the starting resistor.
5. Adjust the field resistors to bring the speed to 1200 rpm. Allow the system to warm up for two minutes.
6. Load the dynamometer to 0.5 N·m.
7. Measure the motor torque, armature currents, voltages, powers and RPM.
8. Observe all meters to keep both machines within their ratings.

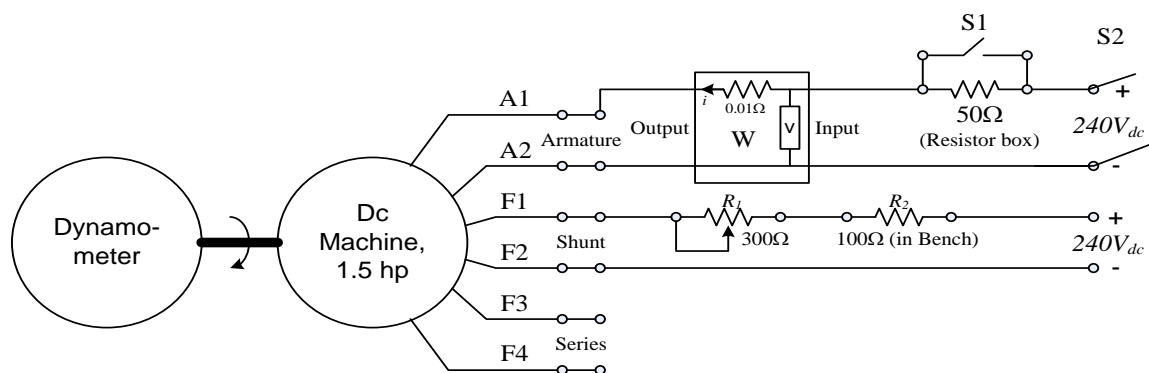


Figure 11.2. Dc motor torque-speed test

9. Repeat Steps 6 and 7 for torque values which give 0-100% of the smallest machine current rating (determine the dc machine rated torque from its nameplate for a good estimate of the maximum torque allowed. 0–6 Nm in steps of 0.5 Nm should be adequate).
10. Turn off the dynamometer and then the dc supply. Measure the value of the drive motor shunt field rheostat resistance with an ohmmeter. Be sure all the switches are off.

Part B: Compound dc motor characteristics

1. Turn off your bench dc supply. Reconnect the drive motor shunt field rheostat from Part A.
2. Insert the series field winding into the motor armature circuit for long-shunt cumulative compound operation. Take the polarity marks to be at F1 and F3 for this purpose.
3. Repeat Steps 2-10 of Part A.
4. Change the configuration to differential compound (reverse F3 and F4 to achieve this) and repeat the steps of Part A.

Report

1. Plot torque (vertical) versus speed (horizontal) curves for Parts A and B in N·m versus RPM.
2. Using your dc machine parameters determined in Experiment 10, calculate the torque vs. speed characteristics for both machine configurations in Parts A and B, using the model given in Figure 11.1.
3. Plot the predicted torque-speed characteristic together with the measured torque-speed values of the shunt dc machine in the same graph.
4. Repeat Step 3 for the compound dc machine.
5. Comment on all the curves. Do they agree with curves predicted by the model? What is the difference between the two different machine configurations in terms of their torque-speed characteristics?

Final Comments

Small dc motors are popular, especially as power electronics has made control of dc voltage straightforward. Industrial dc machines are less common but have advantages in terms of simple control and can be found in many legacy systems. Their use emphasizes applications such as those listed below in Table 11.1.

Table 11.1
Dc Machine Applications

Motor Type	Characteristic	Typical Applications
Shunt	Nearly constant speed medium-start torque	Machine tools, blowers, pumps, presses
Series	Very high-start torque	Electric hoists, conveyors, dc traction in trains, locomotives, and large ships
Diff. compound	Constant speed low-start torque	Sometimes used for generators
Cum. compound	High-start torque	Elevators, rolling mills, presses

Experiment #12: A Model Power System

Objective

The purpose of this experiment is to construct a small model power system using equipment in the lab. This experiment draws on knowledge obtained in previous experiments and attempts to tie all the pieces together into one system that is electrically independent from outside sources.

Introduction

A power system can be modeled and analyzed using equivalent circuits for all elements of the system. The machines can be modeled as previously seen. Transmission lines can be represented as series impedances. Load-flow analysis and other studies can be done using the equivalent-circuit information.

The prime movers used in this system are the permanent magnet synchronous machines (PMSM) that are controlled from power electronics drives and powered by the dc voltage in the lab. The synchronous machines can be regulated at a nearly constant speed—and hence system frequency—at various power levels. The PMSM replaces the steam turbine in our miniature system. The dc power into the motors is the only power source, and this power is delivered mechanically into generators.

Much of the switching in a typical system is accomplished with relays. A relay is a coil of wire around an iron plunger-type core. When a voltage is applied to the coil, a force is induced in the plunger causing it to move and close (or open) a set of contacts. In this way one switch in the coil circuit can effectively switch many circuits at once. This reduces the number of control cables required for switching and allows for complicated control schemes.

The control power for the relay circuits is obtained through transformers from the system buses. The control power plays an important role in any system, and complicated schemes are devised to provide reliable backup-control power sources. This system has a simple two-relay scheme that switches from the system transformers to an outside source almost instantly when the system goes down. When the system is back up again, the control power can be reinstated to normal by depressing both control-power push buttons on the control panel.

A small power system using three generators and various loads, both 1 ϕ and 3 ϕ , are shown in Figure 12.1. The system is in a ring configuration. This ring ideally allows power to flow to a load from two directions allowing better load sharing and higher reliability.

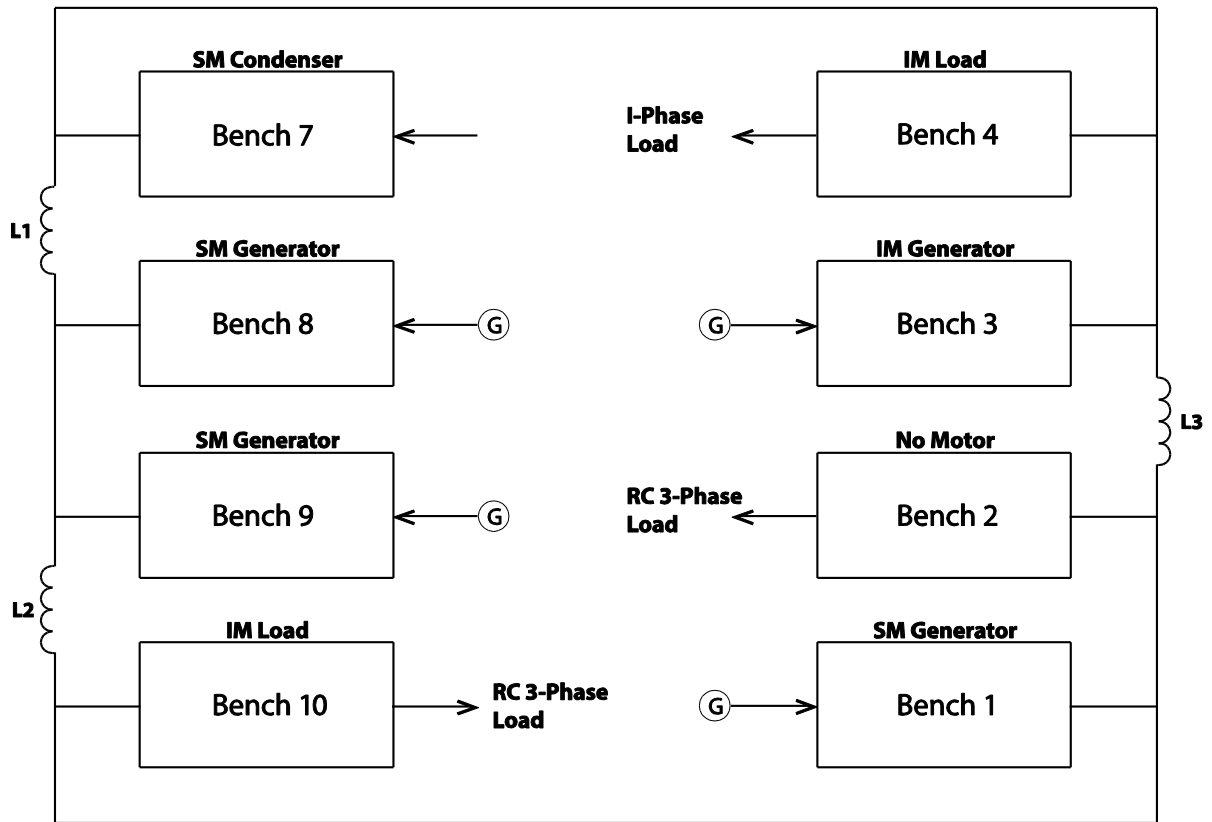


Figure 12.1 Power System Setup

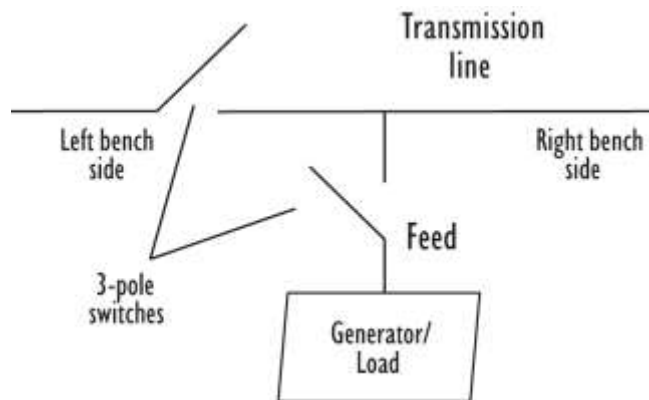


Figure 12.2 Switch configuration on the benches

The system is also described in Table 12.1. It is assumed to be a 3 ϕ , 10 kW system, with 208 V line-to-line 60 Hz voltage. The system has several switches and relays, which allow the configuration to be changed from a ring to a so-called *radial system*, in which power flows in only one direction. They should only be used when all the generators are on-line and the ring bus is closed. Care must be taken to assure that synchronism is not lost when using these switches. A quick check of the synchronism across the switch is advisable.

Bench 9 is treated as the *swing bus* generator in the system, as it is set for speed control and provides frequency stabilization. Other generators can be used to control the ac voltage and real power, and are set for torque control. This makes them *PV* buses in the sense of conventional power systems practice. The induction machines, as well as resistive and capacitive loads in the system, are large in a per-unit sense and thus represent a heavy industrial load. Capacitors can serve as power-factor correction devices within the network to support reactive power requirements. If desired, one of the induction machines can operate as a generator, as is common in many wind turbine systems.

Table 12.1.
Station Assignments

Bench #	Bench Arrangement	Notes
1	Synchronous Machine	Generator
2	R-C Delta Connection	Load
3	Induction Machine	Generator
4	Induction Machine, Single-Phase Load	Load
7	Synchronous Machine	Condenser
8	Synchronous Machine	Generator (Slack Bus)
9	Synchronous Machine	Generator
10	Induction Machine, R-C Delta Connection	Load

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