ELECTROMECHANICAL ENERGY CONVERSION

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EE-340 LABORATORY MANUAL

ELECTROMECHANICAL
ENERGY CONVERSION

Dr. H. Saadat
Version 1.0

MILWAUKEE SCHOOL OF ENGINEERING
Department of Electrical Engineering
And Computer Science

LABORATORY SAFETY RULES

When working in the Industrial Control laboratory, there are several rules, which must always be observed:

1. Do not close the power supply switch until the instructor has checked connections.

2. Be sure to inform all group members before power is switched on and after it is switched off.

3. Do not change the circuit components with the power on. Turn the power off. Beside the danger to yourself, you could damage the components if you change them with the power on.

4. Use only one hand for component adjustment with power on during the experiment. This minimizes the danger of electrical shock.

5. Avoid placing any part of your body across live terminals or from such terminals to ground.

6. Safety goggles must be worn when operating electric machines. Also, do not wear loose clothing, which could become entangled in moving parts.

7. Report any defective equipment or components to the instructor. Instructor will tag the equipment with date and a brief explanation of problem.

8. Know where the emergency stop palms buttons are located in the laboratory and use them when it is necessary to quickly remove all power.

9. In case of emergency:
   a. De-energize the circuit and depress any one of the emergency palm buttons.
   b. Notify the instructor as quickly as possible.
   c. In case of fire, use the extinguishers that can put out electrical fires. Call the Public Safety Department (7159) if necessary. Pull fire alarm, evacuate the building, and call from someplace outside if the fire is serious.

LABORATORY PROCEDURE

The students should always work in squads of two or more. Always have the lab instructor check the wiring before turning the bench power supply on and energizing the circuit. When disconnecting or modifying the circuit, first turn off the power.

There are four drawers in each bench containing power cords, AC and DC meters, AC series motor, a capacitor, and a 5Ω, 1000 W resistor. The cabinet behind each bench contains AC and DC starter boxes, two field rheostats and one DPST SW box. A resistive load on the bench consists of six 60 W resistors in parallel, providing six load steps. Students are not allowed to remove and/or replace equipment from anywhere but the bench drawers of the assigned bench without permission of the instructor.

When you have completed your experiment, have the instructor check and initial your notebook. Return all equipment to your drawers in their proper locations. Equipment taken from the cabinets and all leads must be returned to their original locations. Just before you leave the laboratory, put your stools back under your bench and clean up all paper and scraps.

LABORATORY REPORT

Students are expected to read the material for each experiment prior to attending the lab. Each student should keep a spiral science notebook. The notebook should contain a complete record of all laboratory work, including pre-laboratory analysis, circuit diagrams, lab data, computer results and graphs.

A formal report is required for some of the experiments. The formal report should have the name of the experiment in the middle of the page, and in the lower right hand corner the following:

COURSE/SECTION
DATE
STUDENT NAME
PARTNERS
INSTRUCTOR

The formal report (and to some degree the informal report) should include the following topics in the order presented below:

PURPOSE
This should clearly and concisely state the objectives for the experiment in suitable engineering terminology.

BACKGROUND AND THEORETICAL DISCUSSION

The background necessary to understand the main principles in the experiment. Integrate the pre-laboratory analysis in this section.

PROCEDURE

A brief description of what was done in the laboratory written in past tense. All circuit diagrams drawn neatly with template should be included here. Use third person in the passive voice. Don't use the pronouns I, we, us, etc. Thus in place of a statement "We measured the current ... ", use the statement "The current was measured ..."

RESULTS

This section contains data obtained in tabular form including derived data. This section should not contain any text other than table headings, column titles and units. A subsection for **sample calculations** must be included which shows a sample of each type of calculation made for the data. Place all graphs here. Include graph title, legend and label all axes. All curves must be drawn smooth and continuous. No computer programs or MATLAB statements should appear in this section. If you need to include any programs place them in the Appendix.

DISCUSSION OF RESULTS

Summary of results, answers to all questions and make sure all the report requirements are addressed. All statements should be supported by the data or by the theory. You must analyze your data and state why your graphs are shaped the way they are. Relate your results to the theory where appropriate.

CONCLUSION

Draw appropriate conclusions, and where possible, relate the results to engineering applications. What did you achieve and what recommendations do you make for further work, if appropriate.

The original manuscript was developed by Dr. Hadi Saadat in 1989 and was written using the Chi Writer word processor. After few revisions in 1993 and 1997, I have written this new version with several modifications in MS Word format. This Laboratory Manual is available on the Internet for download only for MSOE students and faculty.

Dr. Hadi Saadat
Winter 2000-01

LABORATORY SESSION 1

BASICS OF PROGRAMMABLE CONTROLLERS
PART I

Courtesy of Allen-Bradley

Purpose

1. To define what a programmable logic controller (PLC) is, and to identify the main parts of a PLC and describe their functions. To become familiar with the operation of the Allen-Bradley SLC-500 programmable controller.
2. To understand how the ladder diagram language is used to communicate information to the PLC.
3. To identify input and output devices including switches push-buttons, contactors and relays commonly used in PLCs.
4. To learn experimentally how a programmable controller is programmed. To describe the use of the RSLogix 500 software and to become familiar with some of its commands and capabilities for programming the Allen-Bradley SLC-500 Programmable Controller.
5. To program several simple ladder logic circuits, test them, download to SLC-500 and demonstrate their operation.

1. Introduction

A programmable controller, also known as programmable logic controller (PLC), is a device designed to perform sequential logic control in which one event follows another in a prescribed way to complete a task. An industrial machine may contain pushbuttons, limit switches, timers, interlocks, etc. In the past, these devices had to be hard-wired to perform a specific function, and they could not easily be modified to perform a different task. With a programmable controller, however, all that is required is to change the controller's program and possibly some of the connections to the inputs and/or output. Today, programmable controllers are used for the control and operation of almost any machine, process, or production line. The continued advancement of PLC technology and the partnership of PLCs with computers and other digital devices are providing industry with sophisticated control systems and advanced decision making processes.

A programmable controller is composed of three components as illustrated in Figure 1.1. These three components are the input/output (I/0) interface system, the central processing unit (CPU), and a programming device.

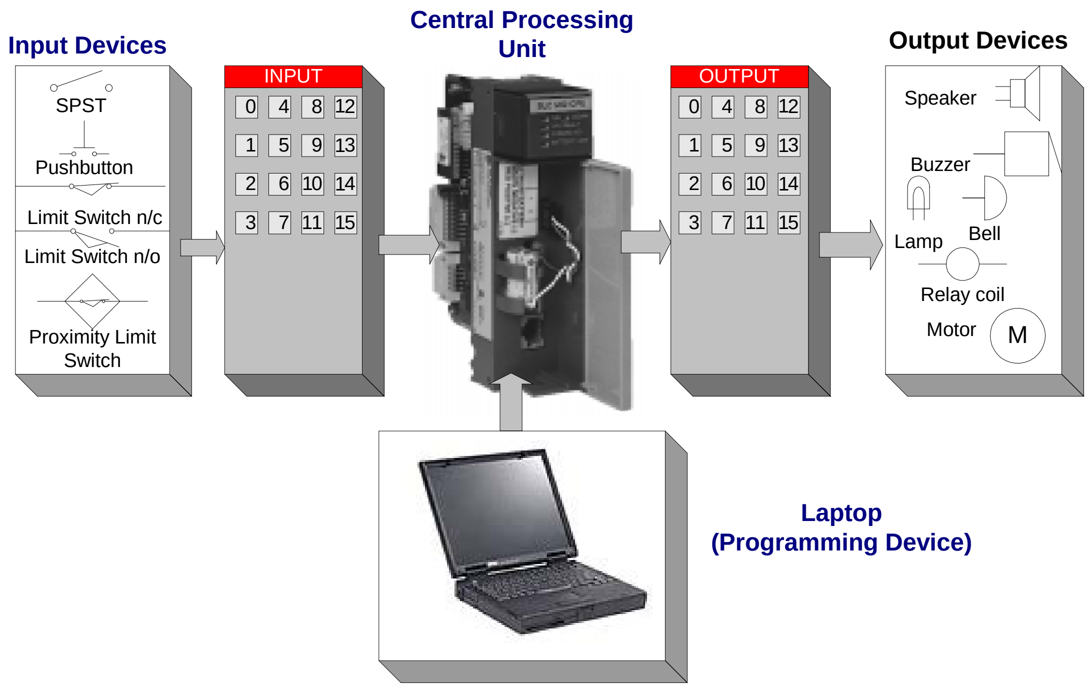


Figure 1.1 The Programmable Controller System.

The input/output system forms the interface by which field devices are connected to the controller. The main purpose of the interface is to condition the various signals received from or sent to external field devices. Incoming signals from sensors such as pushbuttons, limit switches, analog sensors, motor starters, etc. are wired to terminals of the input interfaces. Devices that will be controlled, like motor starters, solenoid valves, pilot lights, and position valves, are connected to the terminals of the output interfaces.

The CPU section of a PLC has three components: The memory system, the processor, and the system power supply. The memory system stores the program usually in the form of a ladder diagram. The processor executes the control program stored in the memory system. The system power supply provides all the necessary voltages required for the proper operation of the various CPU sections.

The programming device allows the user to enter, change, or monitor a PLC program. The programming device may be a CRT terminal, a hand-held unit with a display or a personal computer. Four major languages can be used in programming the modern PLC. These languages may use Boolean algebra equations, mnemonic commands, logic diagrams and ladder diagrams. Some PLCs also permit BASIC language statements or allow the programmer to use a special high-level control language. Ladder diagram logic, which is the same as that for relay control circuits, is a popular choice for programming most PLCs.

During the operation, the CPU reads or accepts the input data or status of the field devices via the input interfaces, executes the control program stored in the memory system, and writes or updates the output devices via the output interfaces. This process of sequentially reading the inputs, executing the program in memory, and updating the outputs is known as scanning.

Allen-Bradley's programmable controllers are efficient and effective in providing industrial control. Allen-Bradley was one of the first companies to manufacture PLCs for enhancing plant productivity. Allen- Bradley's PLC family of programmable controllers, are among the most advanced and versatile PLCs worldwide. In the Industrial Control Lab we have SLC-5/02 in the benches and PLC-5 and SLC-500 on the wall.

1.1 Input-Output Devices

Both discrete and analog Input/Output devices are provided. Discrete input devices are essentially a switch that is either open or closed, signifying a 1 (ON) or 0 (OFF). The input panel on the bench shown in Figure 1.2; consists of the following devices:

- 8 Toggle switches (S0 - S7).
- 8 NO and NC pushbuttons (PB0 - PB7).
- 4 Thumbwheel switches (TW0 - TW3). Rotating switch to input numeric information into the controller.

Discrete input devices operate from a 120 V AC supplied from the back plane of the rack enclosure. (L1 - L2).

Discrete output devices provide connections between the programmable controller and output field devices.

The output panel on the bench shown in Figure 1.3; consists of the following devices:

- 8 Signal lights.
- 4 5-A relays with both NO and NC contacts (R0 - R3).
- 2 18-A, Contactors (C0 - C1).

The panel also contains analog input and output devices, which provide control capability for field devices, which respond to continuous voltage or current level.

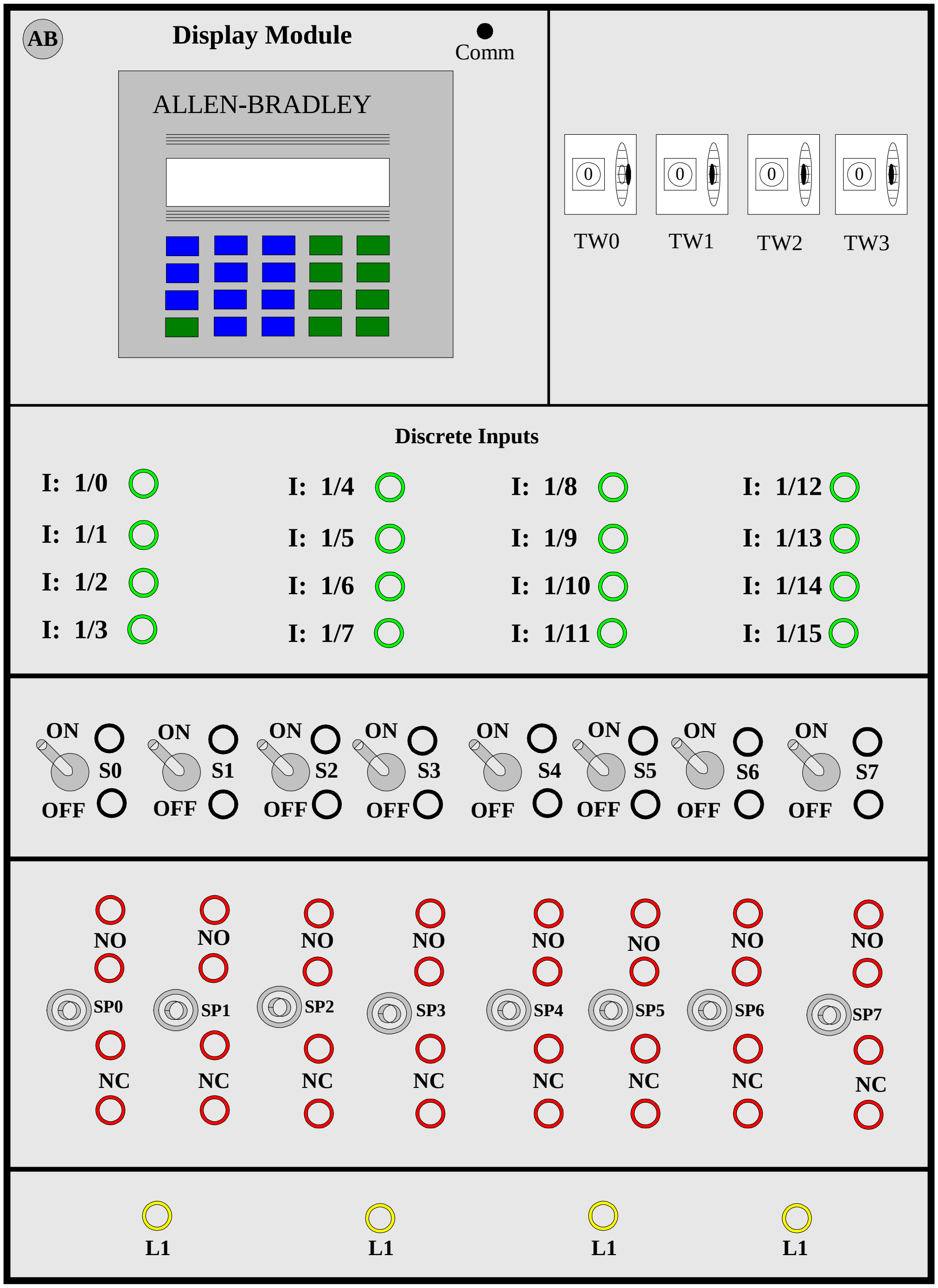


Figure 1.2 Bench Panel Input Devices

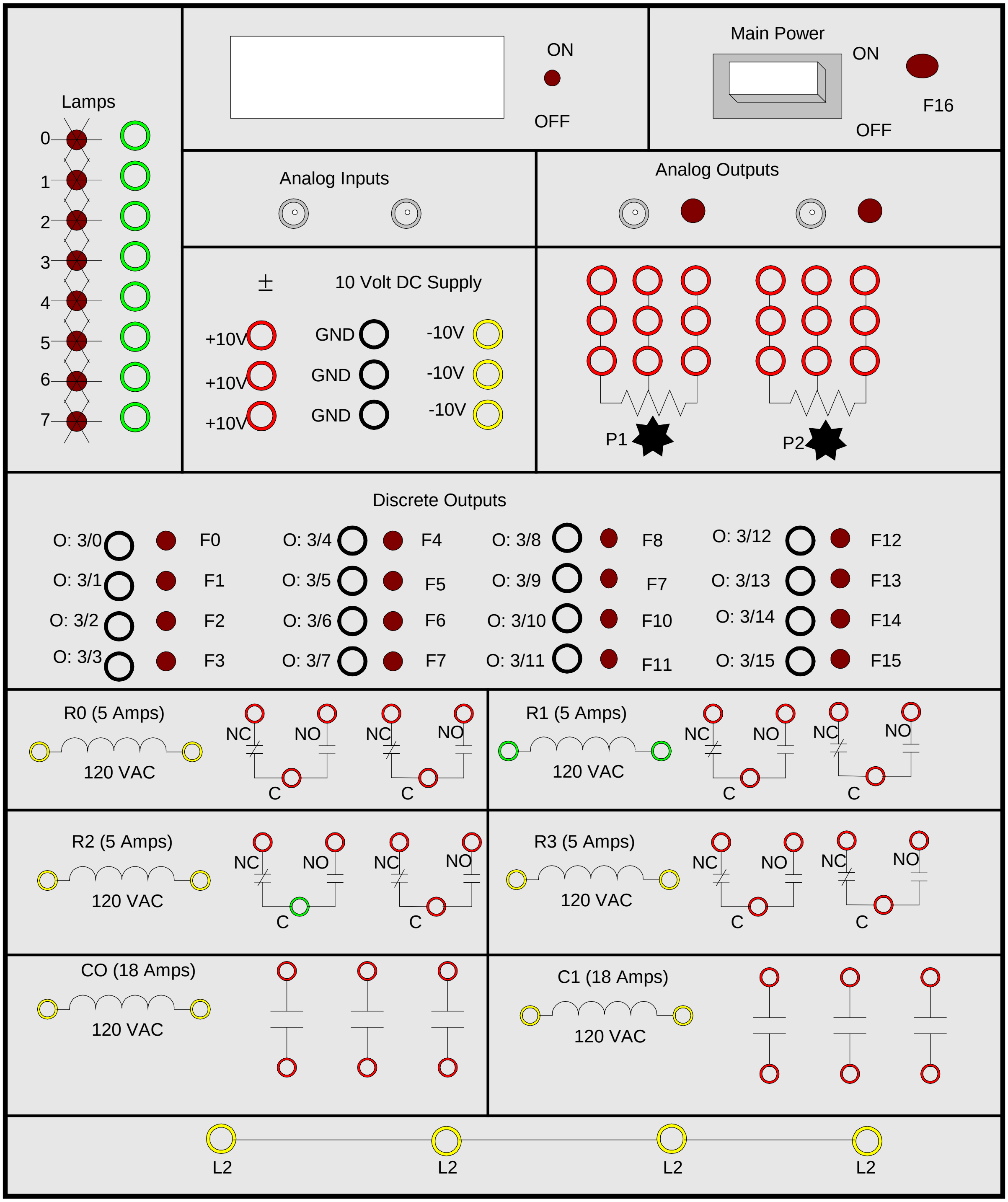


Figure 1.3 Bench Panel Output Devices

1.2 Ladder Diagrams

The logic implemented in PLCs is based on the three basic logic functions (AND, OR, NOT). These functions are used either singly or in combinations to form instructions that will determine if a device is to be switched ON or OFF. The most widely used languages for implementing ON/OFF control and sequencing are ladder diagrams. It is easy to understand, and most plant or industrial electricians are accustomed to working with elementary relay diagrams. Since this type of instruction set is composed of contact symbols, it is also referred to as contact symbology. The ladder circuit connections in the PLC are implemented via software instructions. All the logical wiring can be thought of as being inside the CPU (softwired as opposed to hardwired).

The complete ladder diagram can be thought of as being formed by individual circuits, each circuit having one output. Each of these circuits is known as a rung. Therefore, a rung is the contact symbology required to control an output in the PLC. A complete PLC ladder diagram program then consists of several rungs, each controlling an output interface which is connected to an output field device as shown in Figure 1.5. Each rung is a combination of input conditions (symbols) connected from left to right between two vertical lines, with the symbol that represents the output at the far right. The symbols that represent the inputs are connected in series, parallel or some combination to obtain the desired logic; these input symbols represent the input devices that are connected to the PLC's input interfaces. When activated, these devices either allow current to follow through the circuit or cause a break in current flow, thereby switching a device ON or OFF. The input symbols on a ladder rung can represent signals generated from connected input devices, connected output devices, or from outputs internal to the controller.

In general, PLC architecture is modular and flexible, allowing hardware and software elements to expand as the application requirements change. A PLC eliminates hardwired control in favor of programmable control. Once installed, the control plan can be manually or automatically altered to meet the day-to-day control requirements without changing the field wiring.

1.2 Contact Symbol

Programmable controller contacts and relay contacts operate in a very similar fashion. For example, the control relay CR shown in Fig. 1.4 has two sets of contacts, one normally open (CR1) and one normally closed (CR2).

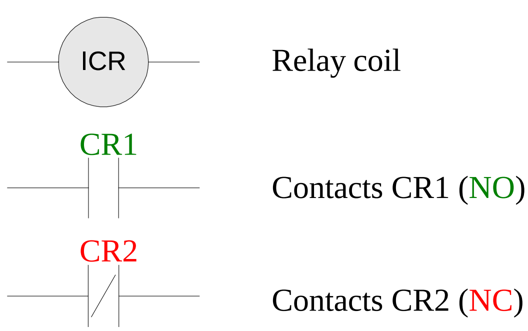


Figure 1.4 Relay Symbol with NO and NC contacts

If relay coil CR is not energized, contact CR1 will remain open and contact CR2 will remain closed. Conversely, if coil CR is energized, or turned ON, contact CR1 will close and contact CR2 will open. The following symbols are some of the basic bit instructions used to translate relay control logic to contact symbolic logic.

Symbol **Definition and symbol interpretation**

—] [— EXAMINE IF CLOSED INSTRUCTION:

XIC

Generally referred to as normally open (NO) instruction. Typically represents any input to the control logic. The input can be a real world input from a connected switch or pushbutton, a contact from a connected output, or a contact from an internal output. The status bit is examined for an ON condition. If the status bit is "1", then the instruction is TRUE. If the status bit is "0", then the instruction is FALSE.

—]/[— EXAMINE IF OPEN INSTRUCTION:

XIO

Generally referred to as normally closed (NC) instruction. Typically represents any input to the control logic. The input can be a connected switch or pushbutton etc., a contact from a connected output, or a contact from an internal output. The status bit is examined for an OFF condition. If the status bit is "0", then the instruction is TRUE. If the status bit is "1", then the instruction is FALSE.

—( )— OUTPUT ENERGIZED:

OTE

Typically represents any output that is controlled by some combination of input logic. An output can be a connected device or an internal output (internal relay). If the left-to-right path of input instructions in the rung is TRUE (all contacts closed), the output is energized (turned ON). If the rung is false, the output is reset to OFF.

—(L)— LATCH OUTPUT COII

OTL

An electromagnetic latching relay function can be programmed on a PLC to work like its real-world counterparts. This instruction is programmed if an output is to remain energized, even though the coil is energized only momentarily. The output is turned ON and remains ON until it is unlatched by an unlatch output instruction of the same reference address.

—(U)— UNLATCH OUTPUT COIL:

OTU

This instruction is programmed to reset a latched output having the same reference output. If any rung path has logic continuity, the reference address coil is turned off or unlatched to an off condition.

1.4 Address

Each symbol on the rung will have a reference number, which is the address in memory where the current status (1, 0) for the reference input is stored. When the field signal is connected to an input or an output interface, the address will also be related to the terminal where the signal wire is connected. The address for a given input/output can be used throughout the program as many times as required by the control logic.

The input addresses have the form I: e/b, where

I = Input data file
e = Slot number of the input module
b = Terminal number used with input device

Similarly, output addresses have the form O: e/b

O = Output data file
e = Slot number of the output module
b = Terminal number used with output device

It is important to remember that the program is not an electrical circuit but a logic circuit. In effect we are interested in logic continuity when establishing an output.

Example 1

Figure 1.5 illustrates an example of a simple ladder program with the NO and NC contacts driving an output rung.

With the limit switch LS0 open, when SP0 is pushed the reference input SP0 (I: 1/0) is closed, the output coil PL1 (O: 3/0) is energized closing all (O: 3/0) contacts and the pilot light PL1 will be lit. Control contact (O: 3/0) in parallel with contact I: 1/0 then closes sealing in the output coil PL1 even if the start button is released. Since output PL1 (O: 3/0) is ON, the normally open contact (O: 3/0) in the second rung will close, turning the internal output coil INT_OTE_1 (B3/1) ON. The NC contacts (O: 3/0) in the third rung will open because the examine for an OFF condition is not true (reference output is ON), therefore turning internal output INT_OTE_2 (B3/2) OFF. Note that outputs B3/1 and B3/2 will not turn a real output device ON because these internal bits are not mapped to the output device. When the limit switch LS0 is closed the NC contact LS0 (I: 1/1) in the first rung opens, the output O: 3/0 is de-energized, and the pilot light PL1 is turned off. The normally open contact (O :3/0) in the second rung will open, turning the internal output coil INT_OTE_1 (B3/1) OFF. The NC contact in the third rung is closed turning the internal output coil (INT_OTE_2), B3/2 ON.

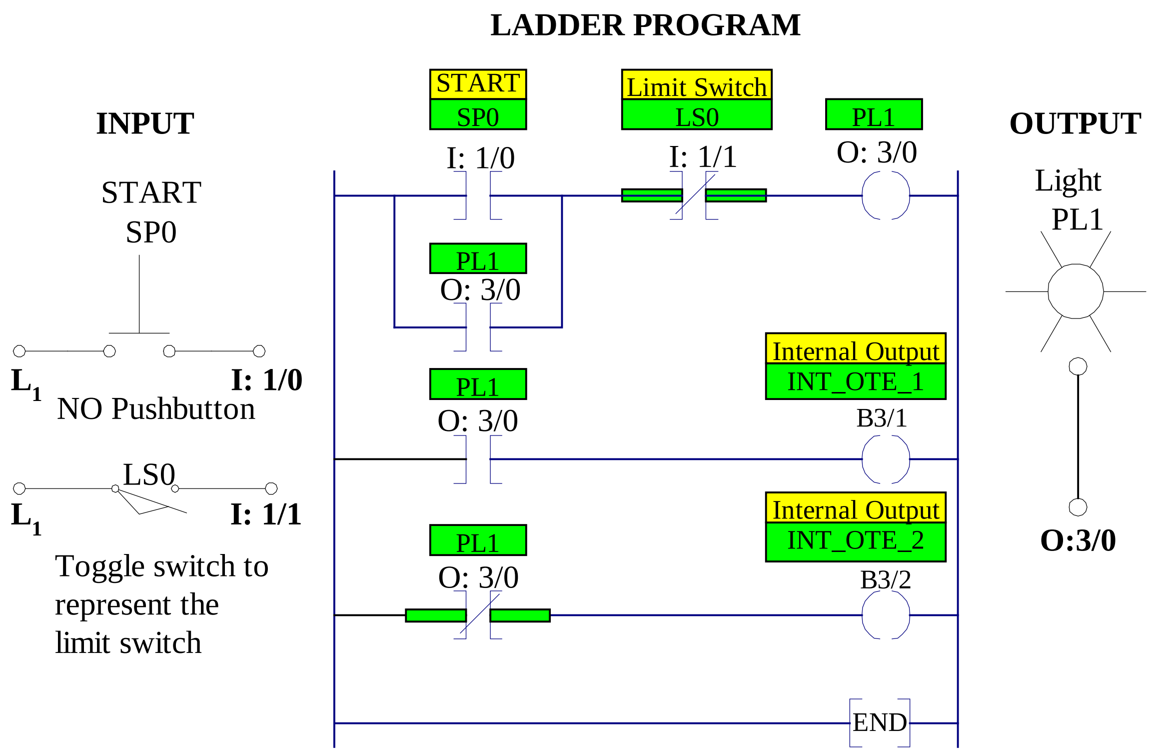


Figure 1.5 A simple ladder diagram with NO and NC contacts

2.1 Programming with RSLogix 500 Software

Creating a directory on your network drive

To work correctly, the software needs a directory for your RSLogix programs on your f drive. Using either Windows Explorer or the "My Computer" icon on your desktop, create the directory **f:\RSLogix** on your network drive.

Running RSLogix 500 and starting a new project

Double-click on the RSLogix 500 icon on the Windows™ desktop to start the software. With a new project, before you can edit a ladder program, you must configure the controller to reflect the actual hardware. The configuration procedure is outlined in section 2.2. Save this configuration in your F:\RSLogix directory with a file name say PLC500CONFIG.RSS. If you followed the configuration procedure the processor and I/O configuration has been completed, for your next project you can skip section 2.2 and copy the PLC500CONFIG file under a new file name, which you want to assign to your project.

2.2 Processor and Input/Output Configurations

The PLCs in S-340 have a 10-slot backplane with the following modules:

Slot #	Part #	Description
0	1747-L524	5/02 CPU – 4K Mem.
1	1746-IA16	16-Input 100/120 VAC
2	1746-IA16	16-Input 100/120 VAC
3	1746-OA16	16-Output (Triac) 100/240 VAC
4	1746-OA16	16-Output (Triac) 100/240 VAC
8	1746-NIO4V	Analog 2 Channel In/2 Channel Voltage Out

You can go through the configuration process as follow:

Double-click on the RSLogix 500 icon on the Windows™ desktop to start the software. To create a new project either click on the blank page icon or select “New...” from the “File” menu. A dialog box requesting processor information should appear, as shown

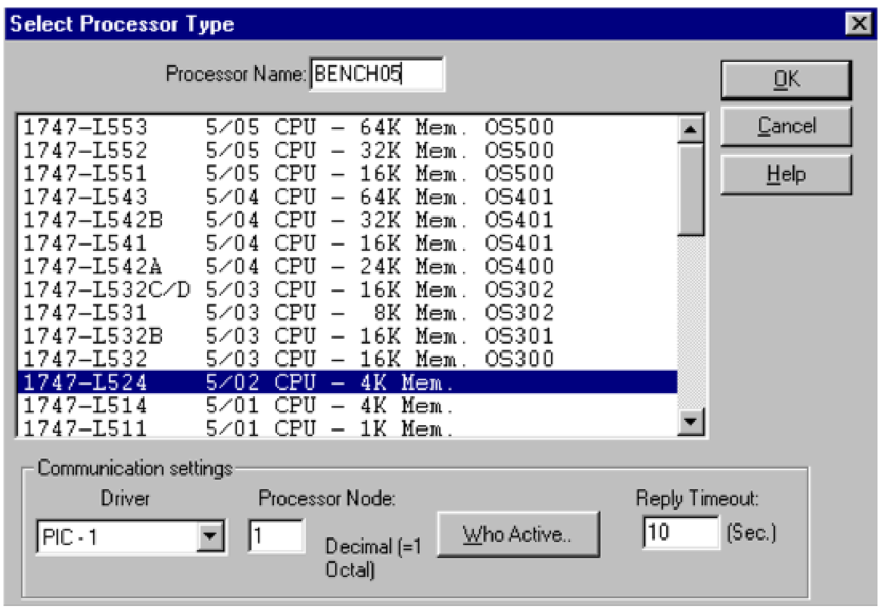


Figure 1.6 Selecting Processor type.

Select the **1747-L524 5/02 CPU** for the processor type and enter your bench number for the processor name.

You should now see a project tree window and a window to enter your ladder logic.

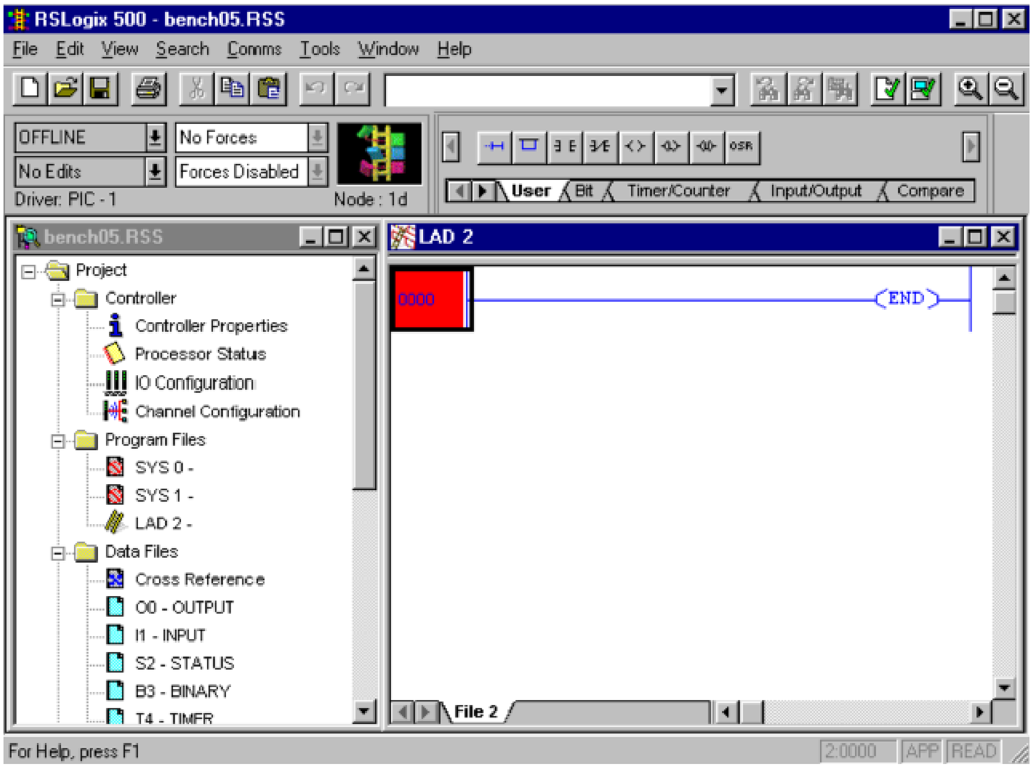


Figure 1.7 RSLogix 500 Project tree and Ladder Logic Windows.

Next, the chassis (the rack in which the modules are installed) and the individual modules must be defined. Double-click on the **IO Configuration** icon in the project tree window to access the I/O Configuration dialog box. In the Rack 1 pull-down menu select 1746-A10 10-Slot Rack chassis. In slot 0 under Part # and Description you should see the 1747-L524 5/02 CPU – 4K Mem. Next, the I/O modules are defined. To do this, highlight slot 1 and double-click on the 1746-IA16 input module. Place the same input module in slot 2. Use slot 3 and 4 to configure the 1746-OA16 output modules. Finally place 1746-NIO4V analog module in slot 8.

A completed I/O Configuration dialog box is shown below.

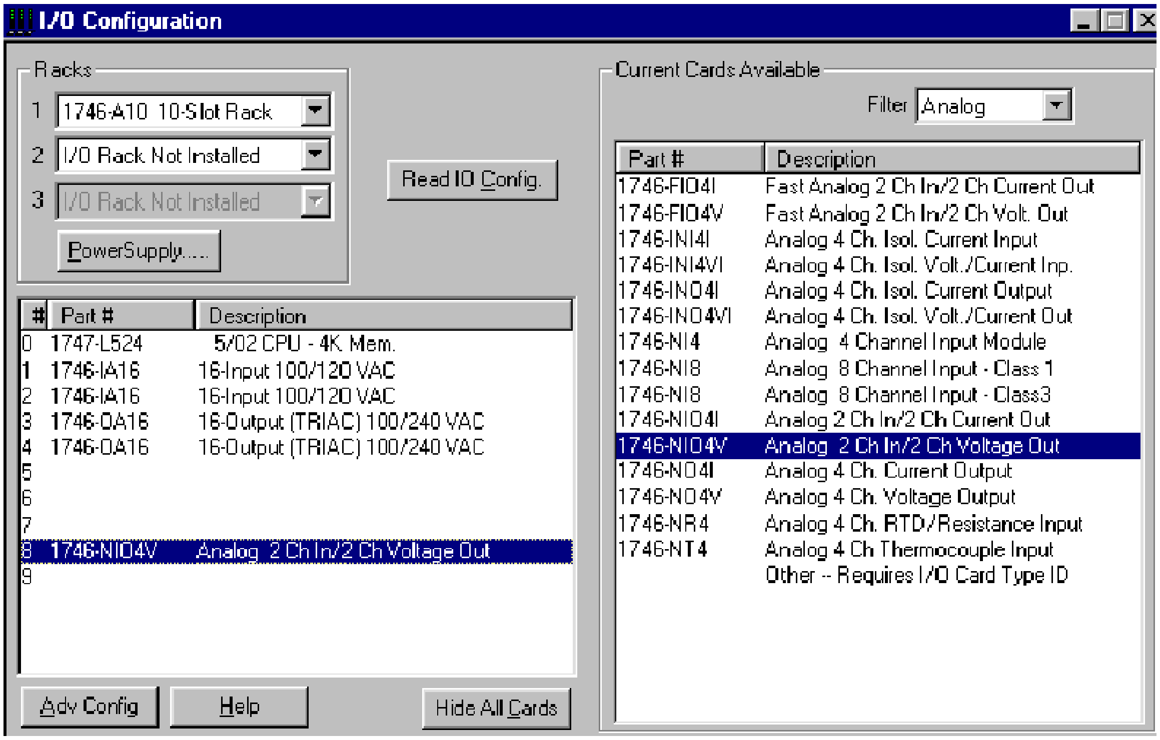


Figure 1.8 Completed I/O and Processor Configurations.

Click on the X in the upper right corner to close the configuration dialog box.

You should now save the file by selecting “Save As” from the “File” menu. Save with a file name say PLC500CONFIG. We will use this file as a starting point (the base project file) for the remaining projects. For example, to start a new project you can copy the PLC500CONFIG file under a file name, which you want to assign to your project say example Lab1a.

2.3 Editing Ladder Logic

With RSLogix 500 Window in the OFFLINE mode, select the PLC500CONFIG file (i.e., the base project file that you configured in section 2.2) and save it under a new name, for example, Lab1a. You should see icons for the instructions you need for editing a program at the top of the RSLogix 500 programming window. A detailed description of the instruction appears in a balloon and on the status bar when you move the cursor over one of the instructions. Click on the tabs below the icons if you don’t see an instruction you need. Use the following Step-by-step guide to edit the ladder diagram of Example 1 as shown in Figure 1.5.

1. Select the number of the first rung to begin entering instructions. The rung number should now be highlighted in red.
2. Click on the examine if closed (XIC) icon. An XIC instruction should now be on the rung.
3. Enter the instructions address. There are two ways to enter the instruction address:
   a. Click on the question mark and type in the address I: 1/0.
   b. Click on the I1-Input under project tree and drag the desired address (I: 1/0) to the instruction.

   You may add a symbolic address. A symbol, once it has been associated with an address, can be used for other instructions referencing its address. To add symbols, click on the instruction and with address highlighted type over the address SP0 as the symbol for this instruction. You may also add a description for the instruction. To add a description, right click on the instruction and select “Edit Description.” A dialog box then appears for entering the description. You may type START for the description of this instruction.

4. Click on the examine if open (XIO) icon. An XIO instruction should appear on the rung next the XIC instruction. Follow step 3 for entering the address (I: 1/1), symbol (LS0), and description Limit Switch.
5. Click on the output enable (OTE) icon. An OTE instruction should appear at the end of the rung. For the addresses enter O: 3/0 and for the symbol type PL1.
6. Click on the branch icon. A branch appears with one end highlighted. Drag each end of the branch to its proper location. A green box appears at each possible location when you drag the branch ends.
7. Select the bottom left corner of the branch and click on the XIC icon. An XIC instruction is added to the branch. For its address you can type the symbolic address PL1 defined in step 5.
8. Select and double click on the End rung to insert a new rung. Add an examine if closed (XIC) instruction and type PL1 for its address. Next add the output enable (OTE) instruction. B3/1 (you may use B3 Binary icon under project tree and drug the desired address to the instruction). Type INT_OTE_1 for the symbolic address, and Internal output for the description.
9. Repeat step 8 to add an XIO and an OTE instructions for the last rung.

After you have placed all the instructions, make certain they are all addressed. As a shortcut, you can drag addresses from one instruction to any other.

Verify the program logic

Click on the file verify or project verify icon, or select them from Edit menu, to verify the program logic. If there are any logic errors in your program, a window appears below the project tree and ladder logic windows. Correct any errors before proceeding on with the lab.2.4

Downloading Program To SLC-500

The *Upload/Download Program,* transfer programs between the computer and the SLC-500. By performing a download operation, you will be able to monitor your program when you enter the Online Programming mode. Turn on the processor Main Power and download the program of Example 1. The system displays a message stating:

> Downloading Program
> ……
> Are you sure you want to proceed with Download?

If this is the correct file to download press *Yes*. If the processor was in the Run or Test mode before you began downloading, the system asks if you want to switch the processor back to the

PROG mode? Press *yes* to switch to the program mode. During the download procedure, the system displays a status screen showing the ladder and data table files being downloaded to the processor. After the program is downloaded, you can switch back to the desired mode.

2.5 Testing and Running the Program

Connect the Input/Output circuits shown in Figure 1.5. After the program has been successfully downloaded to the processor, use the following step to test and run the program.

Testing mode

Select the `Test Continuous` mode. The system displays a message stating, Are you sure you want to change processor mode to Test? Press *Yes* to test the program.

In the test mode the ladder diagram executes, but outputs are not enabled.

To test the program press the start pushbutton SP0 the input address is forced, causing the output for that rung to be true and they will appear in reverse video. Control contact across pushbutton closes, sealing in the output coil PL1. On the second rung, since the condition is true, the NO contact and its output will appear in reverse video, and the internal bit B3/1 is turned on. On the third rung, the condition for an examine OFF is not true and the output for the rung is not energized and will not appear in reverse video.

Close the toggle switch LS0. On the first rung, the NC contact LS0 opens, and the output coil PL1 is turned off. On the second rung, the condition for an examine ON is not true and the output for the rung is de-energized and will not appear in the reverse video. On third rung, since the condition is true, the NC contact and its output will appear in reverse video, and the internal bit B3/2 is turned on.

Running mode

Select the `Remote Run` mode. In the running mode the output is enabled, performing the intended operations. Press the start pushbutton and later close the toggle switch and observe the events made during test procedure.

3. Timer and Counters

Timers and counters are internal instructions that provide the same functions as timing relays and counters. They are used to activate or de-activate a device after a preset interval of time. The timer is assigned an address as well as being identified as a timer. Also included, as part of the timer instruction is the *time base* of the timer, the timer's *preset value*, and the *accumulated value*. The timer instructions include:

3.1 Timer On-Delay (TON)

This instruction is programmed to provide time delay action. Once the rung has continuity, the timer begins counting time-based intervals and times until the accumulated value equals the preset value. When the accumulated time equals the preset time, the output is energized, and the timed output contact associated with the output is closed. The timed contact can be used throughout the program as an NO or NC contact. The accumulated value is reset when rung condition goes false.

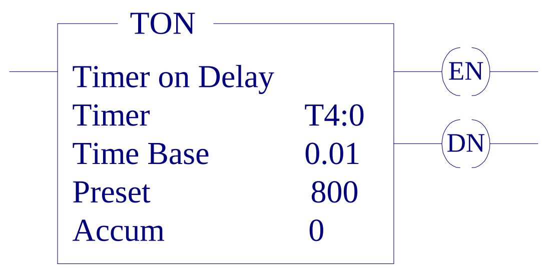


Figure 1.9 Timer On-Delay Instructions

For SLC-500 processor the time base can be selected as 0.01 sec or 1.0 sec.

The control word uses three control bits:

- **Enable (EN) bit** The enable bit (EN) is set when rung conditions are true; it is reset when the rung condition becomes false.
- **Done (DN) bit** The done bit (DN) is set when the accumulated value is equal to the preset value. It is reset when rung condition becomes false.
- **Timer-timing (TT) bit** The Timer-timing bit (TT) is true when the timer is timing. When the timer is not timing the TT bit is false.

3.2 Timer Off-Delay (TOF)

This instruction is programmed to provide time delay action. If the rung does not have continuity, the timer begins counting time-based intervals and times until the accumulated value equals the preset value. When the accumulated time equals the preset time, the output is energized, and the timed output contact associated with the output is closed. The timed contact can be used throughout the program as an NO or NC contact. The accumulated value is reset when rung condition goes true.

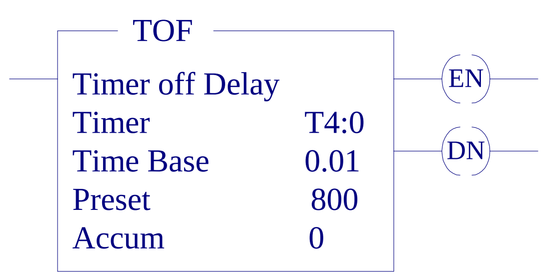


Figure 1.10 Timer Off-Delay Instruction

The done bit (DN) is set when the accumulated value is equal to the preset value. It is reset when rung condition becomes true. The enable bit (EN) is set when rung conditions are true; it is reset when the rung condition becomes false.

3.3 Counters

Counters are similar to timers, except that they do not operate on an internal clock, but are dependent upon external or program sources for counting. The counter is assigned an address as well as being identified as a counter. Also included, as part of the counter instruction is the counter's *preset value* as well as the current *accumulated count* for the counter. There are two basic types of counters, one that counts up and another one that can count down.

Count Up (CTU) and Count Down (CTD)

The up-counter output instruction will increment by one and the down-counter output instruction will decrement by one each time the counted event occurs. These events could be caused by the number parts traveling past a detector or a limit switch. When the accumulated counts equal the preset count, the output is energized, and the counter output is closed. The counter contact can be used throughout the program as an NO or NC contact

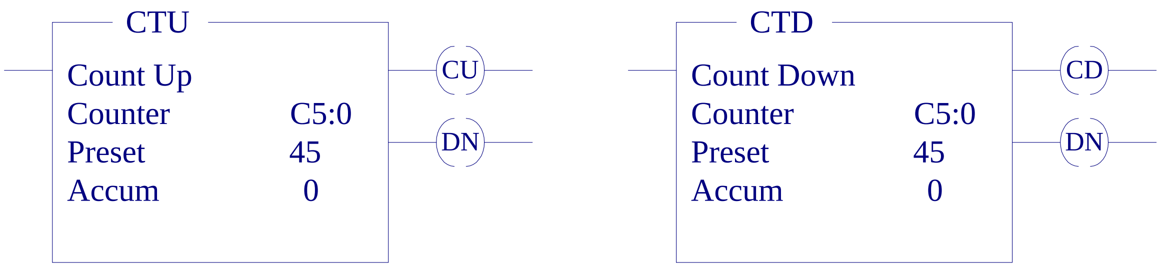


Figure 1.11 Count Down and Count Up Instruction

The done bit (DN) is set and remains set when the accumulated value is equal to the preset value. It is reset when rung condition becomes true. The count up enable bit (CU) or the count down enable is set when rung conditions are true; it is reset when the rung condition becomes false or the appropriate reset instruction is enabled.

Counter and Timer Reset (RES)

The [RES] instruction is used to reset the timing and counting instruction accumulated values. A rung containing an NO or an NC contact together with the [RES] instruction is used. The [RES] instruction must be given the same reference address as the related timer or counter. When the [RES] instruction is enabled, the counter accumulated value is reset.

Example 2

Figure 1.12, a logic ladder program, which can be used as a warning signal when moving equipment, such as a conveyor motor, is about to be started. The internal output INT_OTE is energized when the START pushbutton SP0 is momentarily actuated. As a result contact B3/0 across SP0 closes to seal in the output coil INT_OTE. Also, contact B3/0 on the second rung closes to energize timer coil, and contact B3/0 on the third rung closes to sound the horn. After a 10 second delay period, the NC timer contact (4:0.DN) opens to automatically switch the horn off. Pressing the REST Pushbutton SP1 will reset to the initial condition.

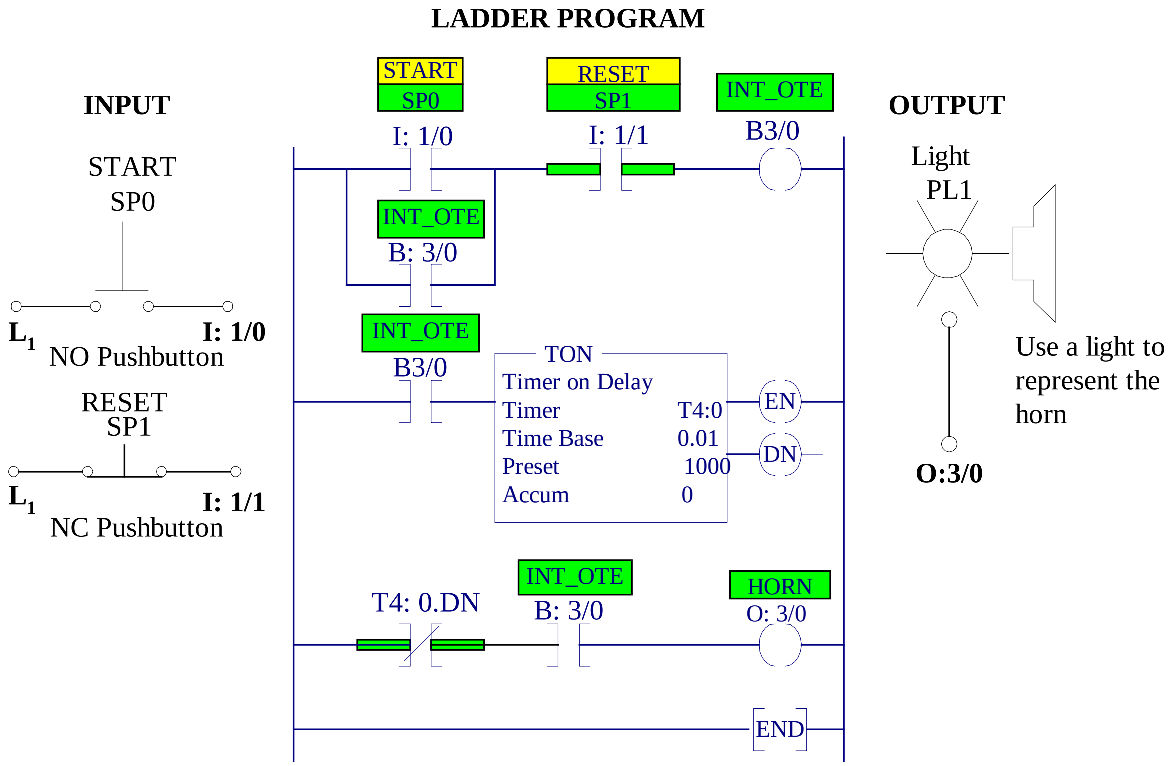


Figure 1.12 Starting-up warning signal circuit

Refer to section 2.3 to define a new file name and edit Figure 1.12 ladder diagram.

<u>Test and Run Example 2</u>

Connect the Input/Output circuits shown in Figure 1.12. Follow the procedure in parts 2.4 and 2.5 to download Example 2 to SLC-500, to test and run the project.

Press the start pushbutton SP0, the input address is forced, causing the output for that rung to be true and they will appear in reverse video. Control contact across pushbutton SP0 closes, sealing in the internal output INT_OTE. On the third rung, since the condition is true, the output at O: 3/0 is turned on and appears in reverse video. On the second rung, since the condition is true, the timer is energized. After 10 seconds timer is enabled opening the timer contact (T4: 0.DN) in the third rung. This will de-energize output coil and turn off the horn. The timer-accumulated value is reset to zero.

4. RSLogix 500 Program Reporting

To send a report of your project to the file server HP LaserJet, from the SLC-500 Main Menu, you can select which reports you want to print by accessing File > Report Options.
Select a check box on the Report Options dialog to print that report. If you'd like a step-by-step

procedure for selecting and printing a report, from the file menu select Report Options and refer to the help menu.

Pre-Lab for next session

Edit the ladder logic program for the following two exercises. For Exercise 2 study the timer operation and the ladder logic program for project 2 (Motor Starter Control) given in the LABORATORY SESSION 2. Your work will be checked in the next session.

Exercise 1

A motor control circuit has two start and two stop buttons. When either of the start buttons is depressed, the motor runs. It is required that the start buttons be latched so that, after it has been pressed, the output remains on until either stop buttons are pressed. Figure 1.13 shows the gate logic for this task. Use RSLogix 500 software to edit a ladder logic program. Note that the AND gate is converted to series contacts and the OR gate is converted to parallel contacts.

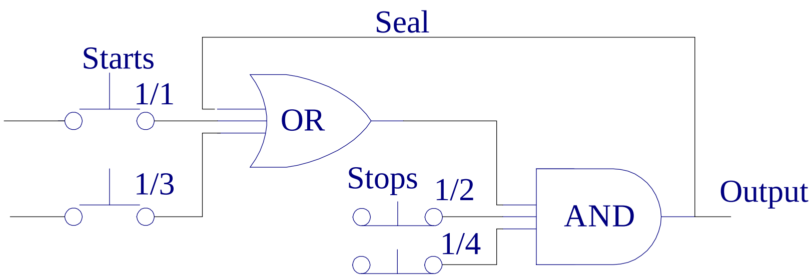


Figure 1.13 Gate Logic for Exercise 1

Connect the Input/Output circuits for this exercise. Download the ladder logic to SLC-500, test and run Exercise 1.

Exercise 2

Construct a ladder logic program for a washing machine to switch a pump for 30 second. It is then to be switched off and a heater switched on for 20 seconds. Then the heater is switched off and another pump is started for 30 seconds to empty the water. (Hint: use the DN and TT control bits).

Connect the Input/Output circuits for this exercise. Download the ladder logic to SLC-500, test and run Exercise 2.

5. Report Requirement

Include a printout of the ladder logic programs for examples 1 and 2, and exercises 1 and 2. Describe each control circuit. Outline the step-by-step sequence of operation and discuss the observations made during the operation for each example in this Lab.

LABORATORY SESSION 2

BASICS OF PROGRAMMABLE CONTROLLERS
PART II

Courtesy of Allen-Bradley

PURPOSE

Most industrial processes require the completion of several operations to produce the required output. Manufacturing, machining, assembling, packaging, finishing, or transporting of products requires the precise coordination of tasks. The majority of industrial control processors use *sequential* controls. Sequential controls are required for processes that demand certain operations be performed in a specific order.

The purpose of this session is to become familiar with a few simple typical industrial applications of the PLC, such as transporting of products, controlling motor starters and sequential control systems requiring timers and counters.

1. Stop/Start & Limit Switch Circuit

A simple process flow diagram for moving packages to a certain position is illustrated in Figure 2.1.

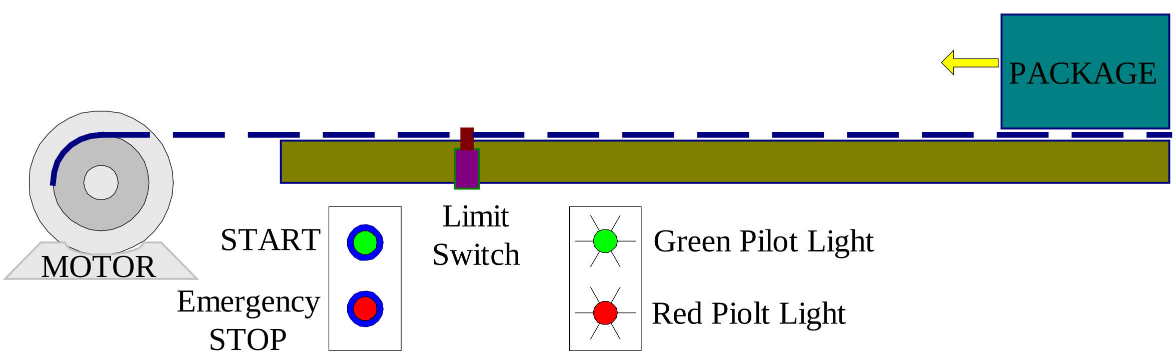


Figure 2.1 Process flow diagram.

The ladder program shown in Figure 2.2(a) is designed for the following sequential task:

1. Start pushbutton is pressed.
2. Table motor is started.
3. Package moves to the position of the limit switch and stops.
4. An emergency stop pushbutton is included to stop the table for any reason, before the package reaches the limit switch.
5. A red pilot light indicates the table is stopped.
6. A green pilot light indicates the table is running.

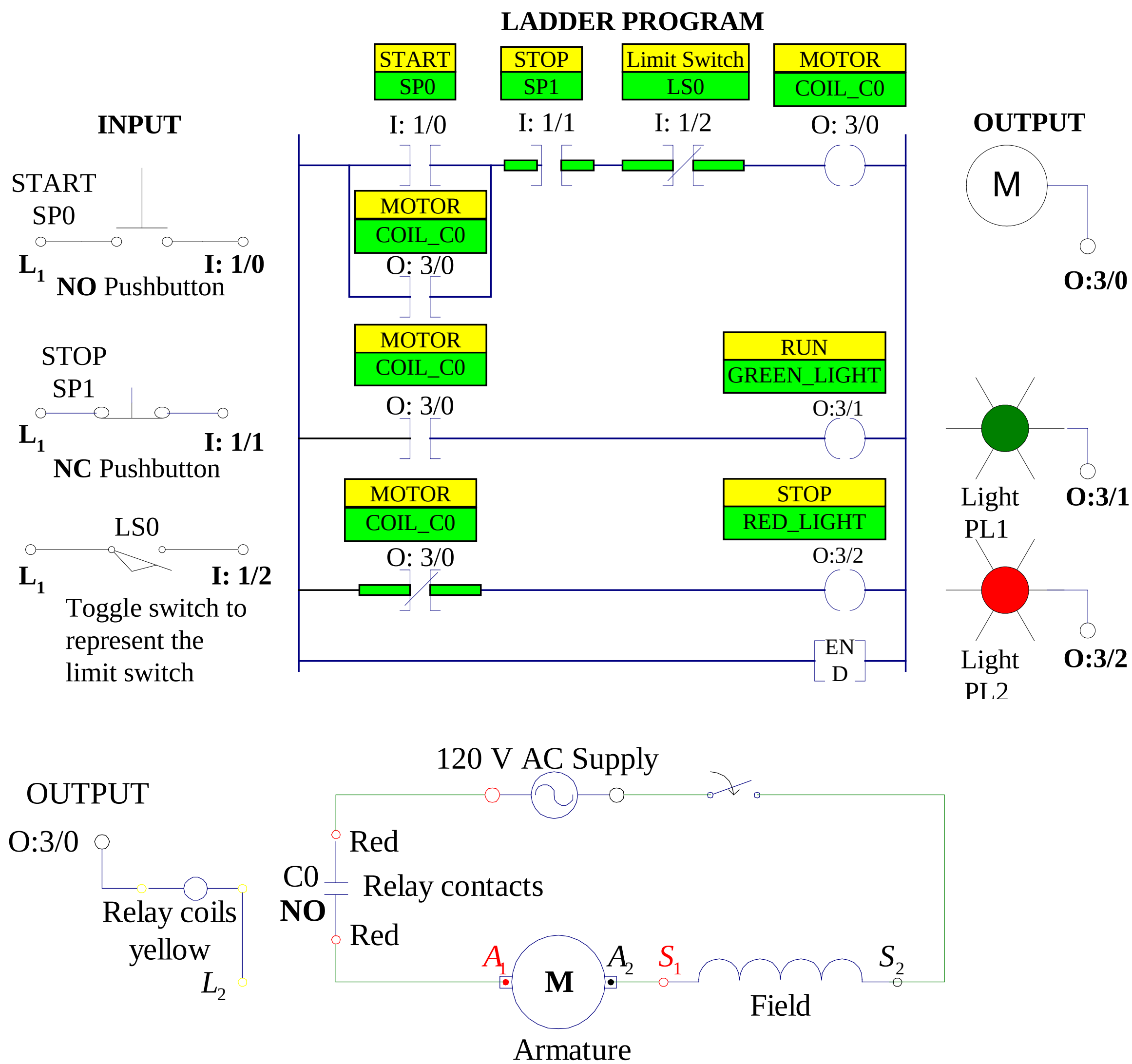


Figure 2.2(a) Ladder program for the process flow diagram
Figure 2.2(b) Electric circuit for the table motor

PROCEDURE

Program the ladder diagram shown in Figure 2.2(a) using the RSLogix 500 software and connect the input/output circuits. Use the contactor C0 (18 Amps) to energize the armature of the motor. Connect the motor armature in series with its field winding via the contactor red terminals to a separate 120 V AC source as shown in Figure 2.2(b). Connect its yellow coil terminals to the related output address and the return supply L_2.

After your I/O circuits and ladder logic program have been checked by the instructor turn on the Processor Main Power and the 120 V supply to the motor. Follow the procedure in Laboratory Session to download the program to the SLC-500 and demonstrate its operation in Test and Run modes.

TURN OFF THE MAIN POWER.

2. Motor Starter Control

In most industrial applications we generally find the PLC controlling motor starters. Starters are required for dc motors and induction motors to limit the starting current and protect the armature winging. A universal motor (ac series motor) is used in this experiment. Although the above motor may be started directly from the rated voltage, it is required to start the motor with a resistor (□ 60-125W) as shown in Figure 2.3(b). The starter resistor is to be shorted out after 8 seconds.

The ladder program shown in Figure 2.3(a) is designed for the following sequential task:

1. Start pushbutton is pressed. Reference input SP0 (I:1/0) is closed, the output Coil_C0 (O:3/0) is energized. Contactor C0 closed and the motor starts with the resistance in the circuit.

2. Contact (O:3/0) across pushbutton closes sealing in the output Coil C0.

3. Contact (O:3/0) in the second rung closes and the timer is energized.

4. After 8 seconds TMR is enabled closing the timer contact (T4:0.DN) in the third rung. This will energize output Coil_C1 at (O:3/1). The contactor C1 across the resistor is closed, shorting out the resistor.

5. The stop pushbutton SP1 stops the motor releasing the holding contact across the START contact.

LADDER PROGRAM

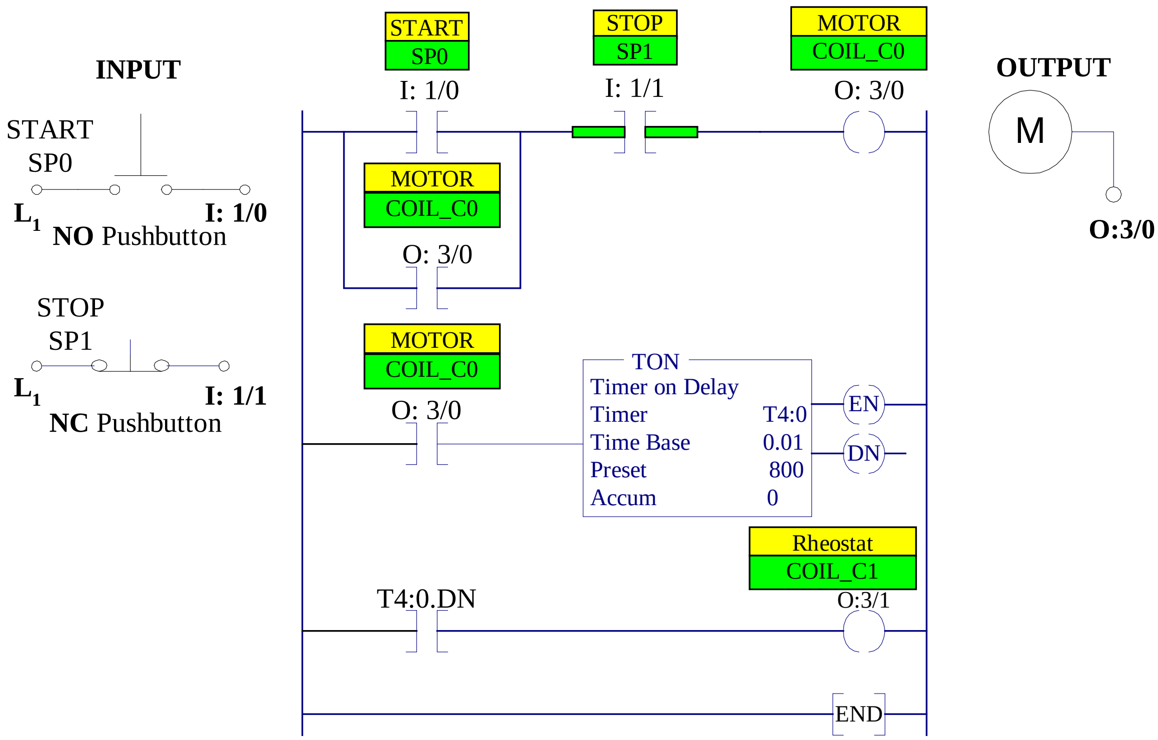


Figure 2.3(a) Ladder program for the motor starter control

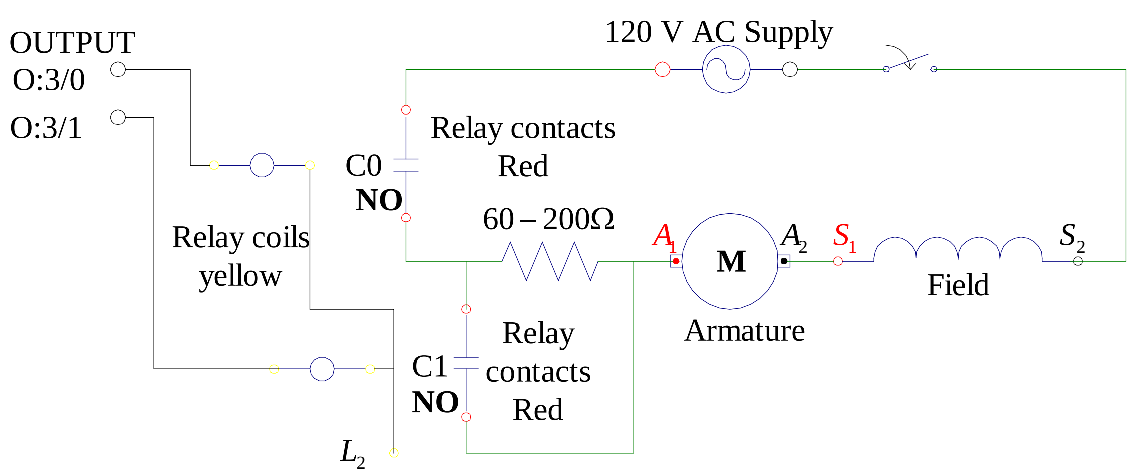


Figure 2.3(b) Electric circuit for the motor starter control

PROCEDURE

Program the ladder diagram shown in Figure 2.3(a) using the RSLogix 500 software and connect the input circuits. Use the contactor C0 (18 Amps) for the motor circuit. Connect the motor armature in series with its field winding via the contactor C0 red terminals to a separate 120 V AC source as shown in Figure 2.3(b). Connect its yellow coil terminals to the appropriate output address and the return supply L_2. Connect contactor C1 red terminals across the starter resistor and its yellow coil terminals to the related output address and the return supply L_2.

After your I/O circuits and ladder logic program have been checked by the instructor turn on the Processor Main Power and the 120 V supply to the motor. Follow the procedure in part 2.5 and 2.6 to download the program to the SLC-500 and demonstrate its operation in Test and Run modes.

TURN OFF THE MAIN POWER.

3. A simple counter application

The programmable controller includes both down counters and up counters. The up counter counts from zero up to the preset count where some action takes place. The down counter goes from a preset number down to zero where the action occurs. A conveyor motor diagram is shown Figure 2.4, illustrating the application of an up-counter. The counter counts the number of cases coming off the conveyor. When the total number of cases reaches 10, the conveyor motor stops automatically. A proximity switch is used to sense the passage of cases.

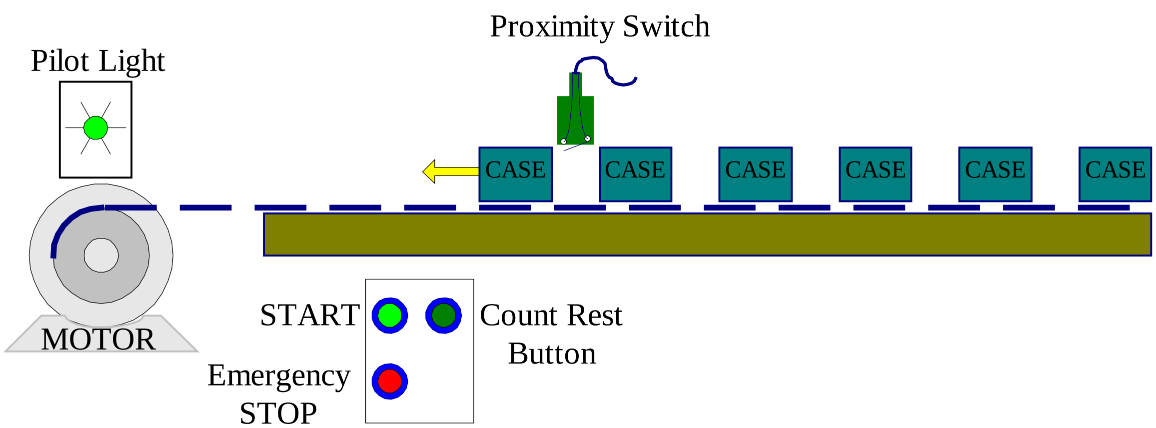


Figure 2.4 Processor flow diagram

The sequential task is as follows:

1. START button is pressed to start the conveyor motor.
2. Cases move past proximity switch and increment the counter's accumulated value.
3. After a count of 10 the conveyor motor stops automatically and the counter's accumulated value is reset to zero with SP2.
4. The conveyor motor can be stopped manually without loss of the accumulated count.
5. The accumulated count of the counter can be reset by means of the COUNTER RESET button.

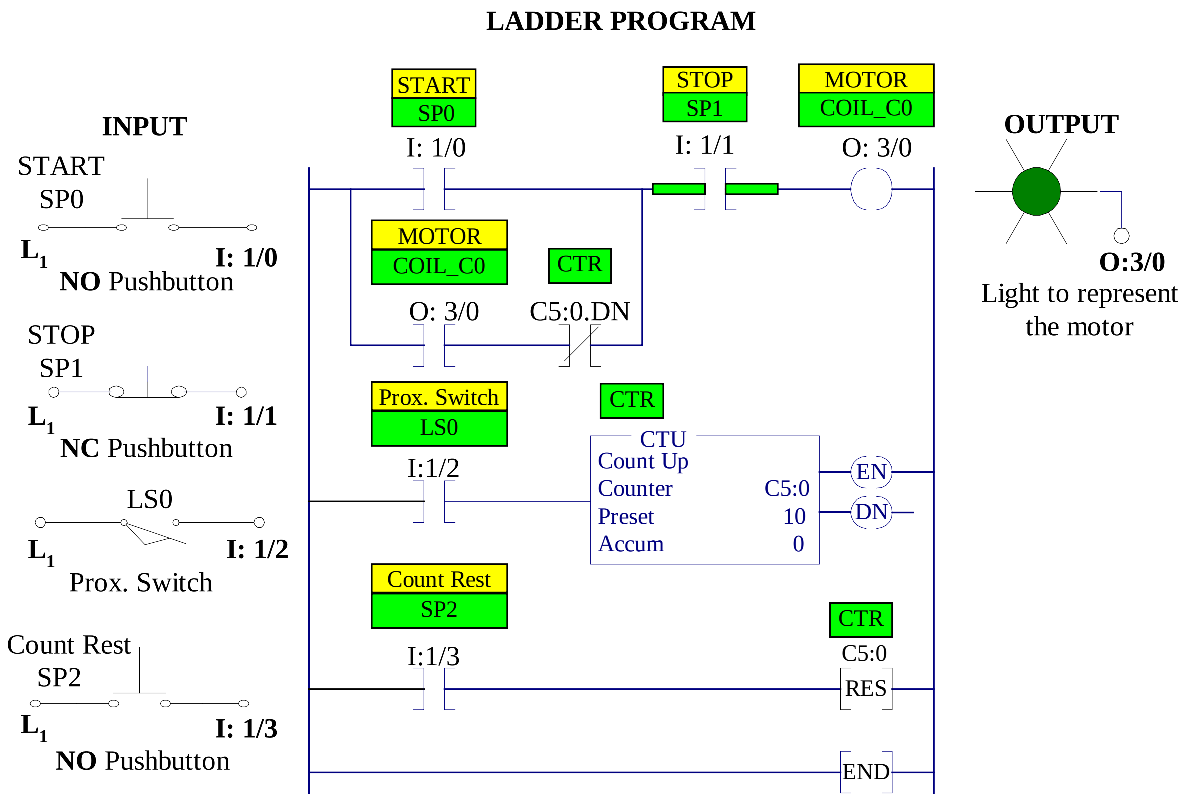


Figure 2.5 Ladder program for the process flow diagram

PROCEDURE

Program the ladder diagram shown in Figure 2.5 using the RSLogix 500 software. Connect the input/output circuits. Use a light to represent the conveyor motor.

After your I/O circuits and ladder logic program have been checked by the instructor turn on the Processor Main Power. Follow the procedure in part 2.5 and 2.6 to download the program to the SLC-500 and demonstrate its operation in Test and Run modes.

TURN OFF THE MAIN POWER

4. Exercises 1 and 2 (from Laboratory Session 1)

Connect the Input/Output circuits for exercise 1 described in Laboratory Session 1. Download the ladder logic that you have prepared to SLC-500, test and run Exercise 1. Repeat the procedure for Exercise 2.

TURN OFF THE MAIN POWER

REPORT REQUIREMENT

Obtain a hardcopy of your ladder logic diagram for each case study including Exercises 1 and 2. Include them in the report (refer to section 2.9). Outline the step-by-step sequence of operation and discuss the observations made during the operation for each case study.

LABORATORY SESSION 3
SINGLE-PHASE TRANSFORMERS

CAUTION:
High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power should be turned off before the circuit is modified

PURPOSE

- To determine the transformer polarity.
- To study the voltage ratio of a transformer.
- To perform the open-circuit and short-circuit tests and obtain the equivalent circuit of the transformer.
- To obtain the efficiency and voltage regulation from the test results.

BACKGROUND AND THEORETICAL DISCUSSION

The principle of transformer action is based on the work of Michael Faraday, who showed that, when mutual induction exists between two windings, a change in current through one induces a voltage in the other. Transformers are very versatile. They range in size from miniature units in transistor radios to huge units used in ac distribution and transmission systems.

When a transformer is in operation, AC currents flow in its winding and an alternating magnetic field is set up in the iron core. As a result, real power (watts) must be supplied due to the copper and iron losses. These losses cause the transformer to heat up. Also, reactive power is received from the supply to establish flux in the core. Because of the real power losses, the total real power delivered to the primary is always slightly larger than the total power delivered by the secondary winding. However, modern power transformers are highly effective and energy-efficient devices. Very large transformers have efficiencies close to 99 percent. The actual efficiency of a transformer is given by

$$\eta = \frac{\text{Real Power Output}}{\text{Real Power Input}} \tag{3.1}$$

The conventional efficiency of a transformer at n fraction of the full-load power is given by

$$\eta = \frac{n(S)(pf)}{n(S)(pf) + n^2 P_{Cu} + P_C} \tag{3.2}$$

Where S is the full-load rated volt-ampere, P_{Cu} is the full-load copper loss and P_C is the iron loss at rated voltage. Because of the internal impedance, $R_e + jX_e$, the output voltage of a transformer ordinarily changes under load from no-load to full-load. A figure of merit used to compare the relative performance of different transformers is the voltage regulation. Voltage regulation at full-load, usually expressed in percent, is defined by

$$\text{Voltage Regulation } = \frac{\text{Change in voltage magnitude}}{\text{Rated voltage magnitude at full-load}} \times 100 \tag{3.3}$$

An interesting feature arises with a capacitive load, because partial resonance is set up between the capacitance and the reactance, the secondary voltage may actually tend to rise as the capacitive load value increases. The voltage regulation can be calculated from the equivalent circuit of the transformer.

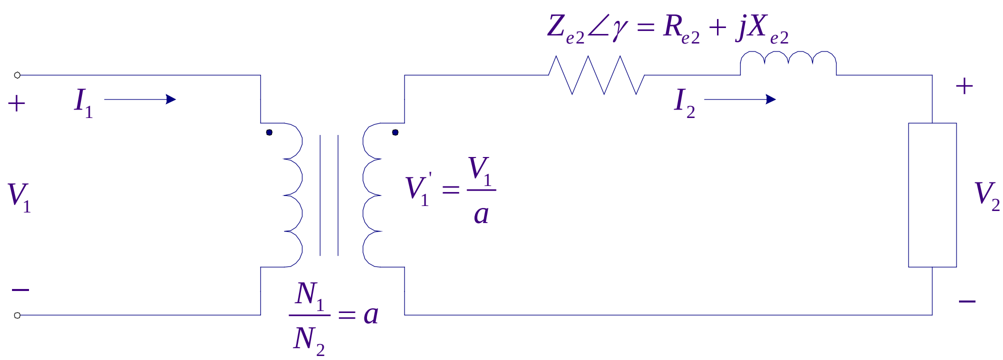


Figure 3.1 The equivalent circuit referred to the secondary

$$V_2' = V_2 + Z_{e2}\angle\gamma I_2\angle\theta \tag{3.4}$$

Where $Z_{e2}\angle\gamma$ is the transformer equivalent impedance referred to the secondary. θ is the phase angle between the secondary voltage and current. θ is negative for inductive load and positive for capacitive load.

These regulation effects can be illustrated with phasor diagrams as shown in Figure 3.2.

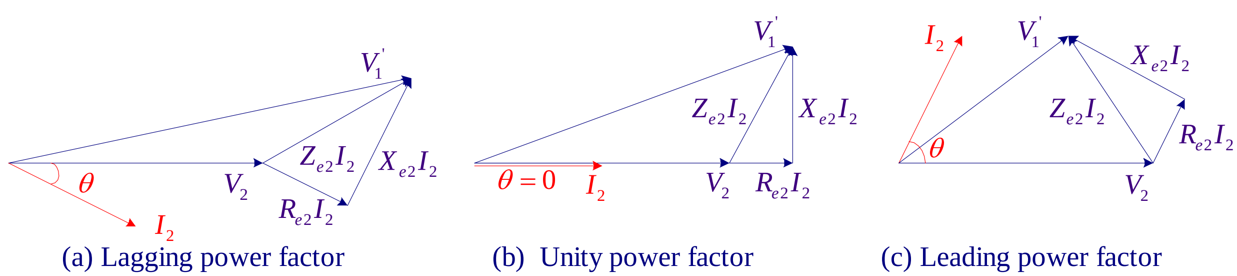


Figure 3.2

Magnetizing current waveform

At no load, $V_1 \cong E_1 = 4.44\, fN_1\phi$, i.e., if a sinusoidal voltage v_1 is applied to the primary of a transformer the flux produced in the core is also sinusoidal. The production of the flux in the core requires a current in the primary known as the *magnetizing* or *exciting current.* The magnetizing current can be determined from the B-H ($\phi - i_m$) curve and the flux waveform. The magnetizing current is not sinusoidal because of the nonlinearities of the B-H curve. The fundamental component or its harmonics content can be found by using the Fourier series analysis. It can be shown that the exciting current is made up of odd harmonics. With a low grade magnetic material the third harmonic can be as high as 40 percent of the fundamental.

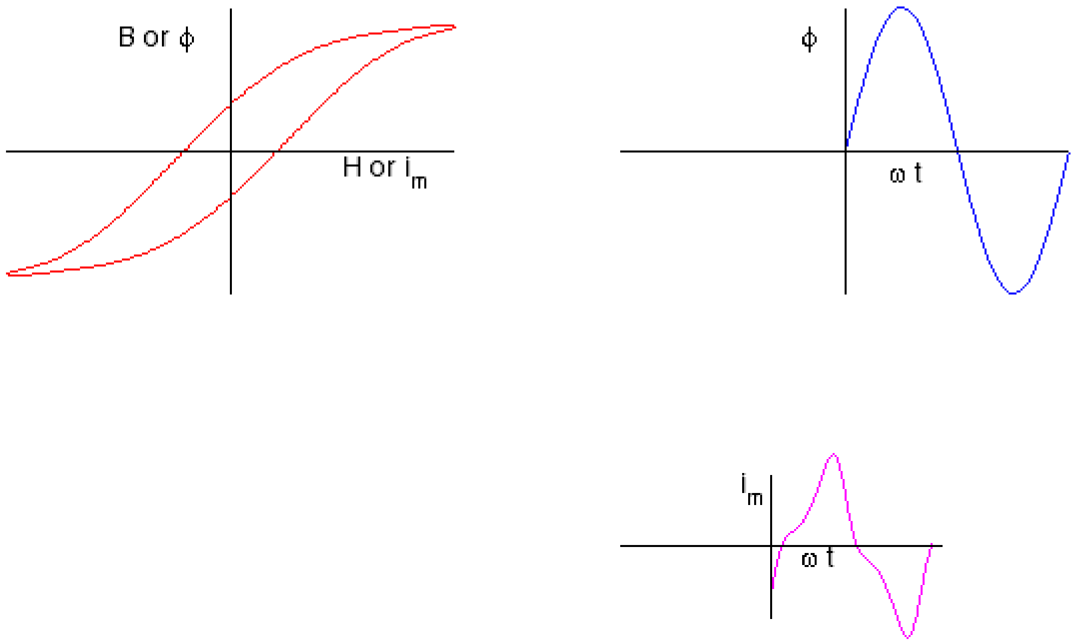


Figure 3.3 Typical B-H curve, flux and magnetizing waveforms

PROCEDURE

1. Rated Currents

Using the nameplate rated voltages (117V/40V) and rated volt-ampere (1.2 KVA) S, calculate the high-voltage and the low voltage rated currents. (Subscripts H and X are used for the high-voltage and the low voltage sides, respectively.)

$S =$___________ $V_H =$___________ $V_X =$___________

$\mathrm{I}_H =$___________ $\mathrm{I}_X =$___________

2. Polarity Test

Polarities of a transformer identify the relative direction of induced voltages in the two windings. The polarities result from the relative directions in which the two windings are wound on the core. The question of the polarity of transformers is of particular importance in making the proper connections for parallel operation. The winding polarities of a single-phase transformer can be checked by a simple test. Connect a primary terminal to one of the secondary terminals, and connect a voltmeter across the other two terminals as shown in Figure 3.4. Apply a voltage to the high voltage side and measure the voltmeter reading. If the voltmeter reads less than the value of the applied voltage, the polarity is subtractive and indicates that the joint terminals have the same instantaneous polarities. If the voltmeter reads the sum of the impressed primary voltage and the induced secondary voltage, it indicates that the joint terminals have opposite instantaneous polarities. The high-voltage terminals are marked H_1, H_2 and the low-voltage terminals are designated X_1, X_2.

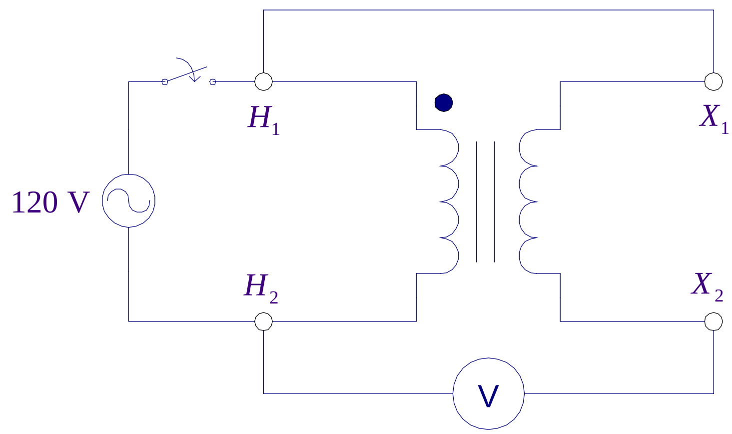


Figure 3.4 Circuit for Polarity Test of a Transformer

Voltmeter reading ________________ LV dotted terminal is _________________

3. Transformer Turns Ratio

Connect the circuit shown in Figure 3.5 and use the 120 V AC power cord to connect the high voltage winding to the 120 V AC power supply.

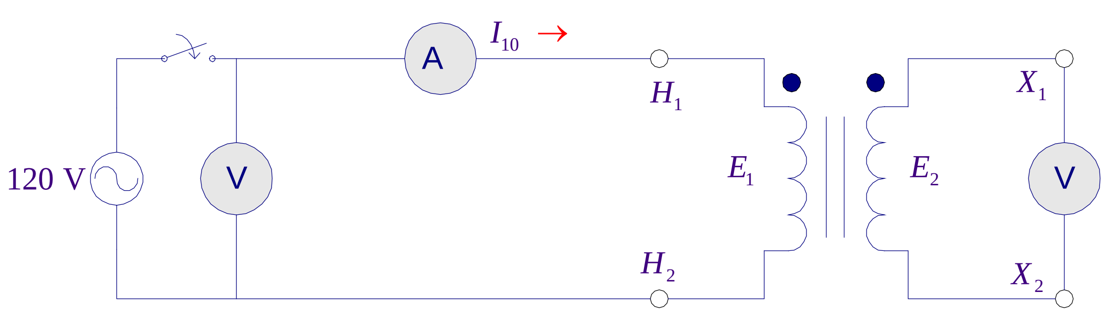


Figure 3.5 Transformer on No-load

Measure the no-load current (exciting current), primary voltage and secondary voltage.

I_{10} =__________ E_1 =__________ E_2 =__________

Calculate the turns ratio $a = \dfrac{N_1}{N_2} = \dfrac{E_1}{E_2} =$ ________________

TURN OFF THE POWER SUPPLY EACH TIME BEFORE YOU RECONNECT THE LEADS.

4. Magnetizing waveform

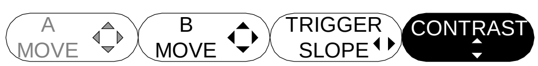
In this part the Fluke Industrial ScopeMeter 123 is used to display the transformer primary voltage and the no-load current. The major component of the no-load current is the magnetization current. This investigation will enable us to determine the harmonic components of the magnetization current. Before you start check out the Fluke AC/DC Current Probe (80i-110s) and a Banana-to-BNC Adapter Plug (BB120, 2X black) from the Technical Support Center.

Connect the red-shielded test lead (use ordinary lead) from the ScopeMeter input A to the transformer HV-side H_1 terminal and a black lead from the ScopeMeter COM terminal to the high voltage-side H_2 terminal. Connect the Current Probe to the ScopeMeter input B and clamp the Current Probe around the lead connecting the supply voltage to the transformer terminal. Be sure that the arrow marked on the jaw of the Current Probe points toward the direction of current and position the probe perpendicular to the conductor (lead). Turn on the Current Probe and select the least sensitive range (10mV/A). Ensure that the green On-indicator lights. Leave the transformer secondary open.

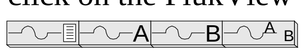
Press the bottom left hand button to turn on the ScopeMeter. Press SCOPE MENU to open the scope inputs menu. For input A , move curser to highlight AC (or DC), press F_4 to select it, highlight Normal and press F_4 to select it. Move cursor to input B, highlight and select AC (or DC) and normal for this input B. With the Scope Menu open press F_3 to display the Trigger submenu. Highlight Input A, and press F_4 to select triggering on the input A waveform. Also make sure that the FREE RUN is selected. With the circuit not energized slowly adjust the zero knob on the probe to have a reading as close as possible to zero. Exit the scope menu.

The Scope reading area can display many values such as VAC, VDC, VAC+VDC, dB, Hz, AMP and PEAK. To make sure that the Input A is set to display the RMS volts press V Hz A Ω to open the Input A highlight VAC and press F_4 to select it. To choose also an RMS Ampere measurement for input B press V Hz B highlight ON and press F_4 to turn input B on, then highlight AMP and press F_4 to select Ampere measurement.

Turn on the AC switch to energize the transformer. Press AUTO to automatically adjust the position, range, time base, and triggering. This assures a stable display on both waveforms. The trace identifier (A) identifies the input A waveform and the zero icon, (—) identifies the ground level for trace A. To move the zero icon ground identifier (—) for trace B to the same level as the ground identifier (—) for trace A press F_4 until you have left any open menu and the following menu appears at the bottom of the screen.



Press F_2 to choose B MOVE, press the up or down arrow ( ) to position the B ground identifier (—) at the same position as the ground identifier for trace A. If you need to smooth the waveform, do the following: Press the SCOPE MENU, and press F_1 to open the Scope options submenu. Highlight Normal and press F_4 to select it and jump to Waveform Mode. Highlight SMOOTH and press F_4 to select it.

Next turn on the PC and double-click on the FlukView ScopeMeter icon to run the ScopeMeter software. By clicking on one of  these toolbar buttons you can quickly display the ScopeMeter waveforms. Click on the first icon (the left Display Waveforms) to open its dialog box and check mark Acquisition Memory A and Acquisition Memory B to display the corresponding traces. Select the current waveform, select Tools/Spectrum to create and display the FFT spectrum of the no-load current. You may select Options to add a Description, View Data Block place Cursor and change Color. Record the values in Ampere for the fundamental, third and fifth harmonic components. Double-click on the Spectrum graph and open the Options Spectrum Scale, select Percent and note the fundamental, third, and fifth components in percent.

Print the current waveform and its spectrum. Save the current waveform and its spectrum graphs as a bitmap graphic (*.bmp) file on your F drive for inclusion in your report. Also, save the current and voltage traces with extension FVF, this way you can retrieve them again using Fluke software. You are allowed to install the ScopeMeter on your own computer (check out the software from the Tech Support Center).

5. Open-circuit Test

Add a wattmeter in the primary circuit of Figure 3.5 (high voltage side) and leave the low voltage side open as shown in Figure 3.6. Energize the primary from 120 V supply and record voltmeter, ammeter and wattmeter readings.

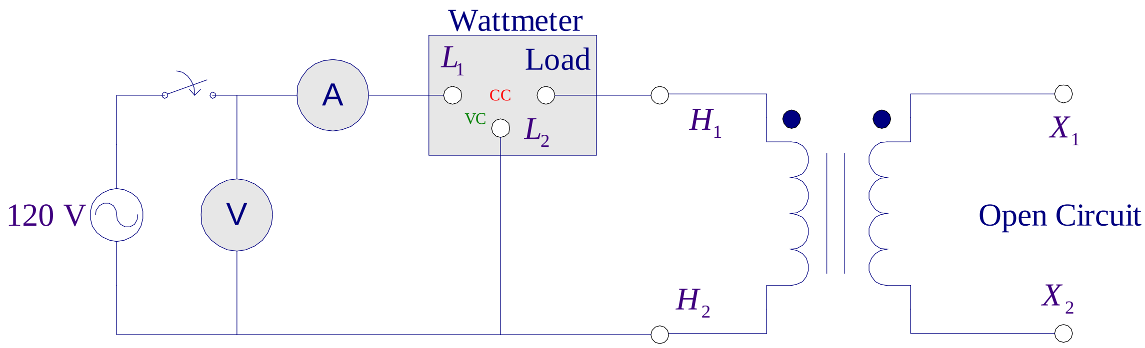


Figure 3.6 The open-circuit test.

$V_1 =$__________ $I_{01} =$__________ $P_{OC} =$__________

With the secondary open-circuited only a small no-load current will be drawn from the supply. The referred secondary current $I_2^{'}$ will be zero, and the equivalent circuit reduces to the form shown in Figure 3.7. The exciting current is only 2 to 6 percent of the full-load current. Therefore, windings copper loss is negligible and the wattmeter reading represents the iron loss, P_c.

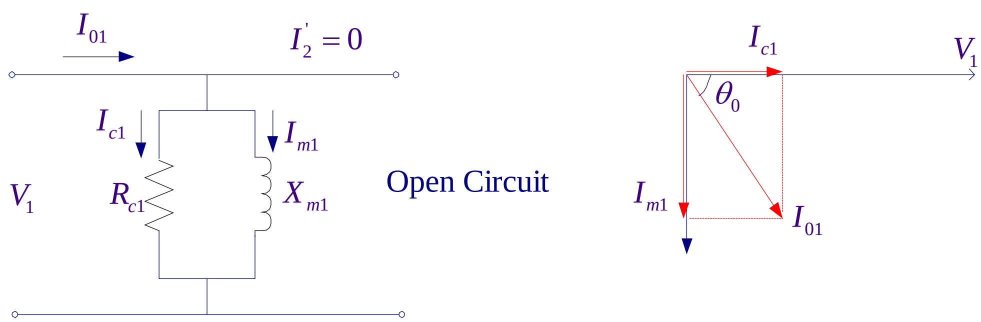


Figure 3.7 Equivalent-circuit for the open-circuit test

From this data determine the shunt branch impedance referred to the high-voltage side.

$$R_{c1} = \frac{V_1^2}{P_{oc}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \qquad I_{c1} = \frac{V_1}{R_{c1}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

$$I_{m1} = \sqrt{I_{o1}^2 - I_{c1}^2} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \qquad X_{m1} = \frac{V_1}{I_{m1}} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \qquad (3.5)$$

$$R_{c2} = \frac{1}{a^2} R_{c1} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \qquad X_{m2} = \frac{1}{a^2} X_{m1} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

6. Short-circuit Test

Replace the ac ammeter with a 0-10 A range and short circuit the low-voltage side as shown in Figure 3.8. The primary is supplied from a variac.

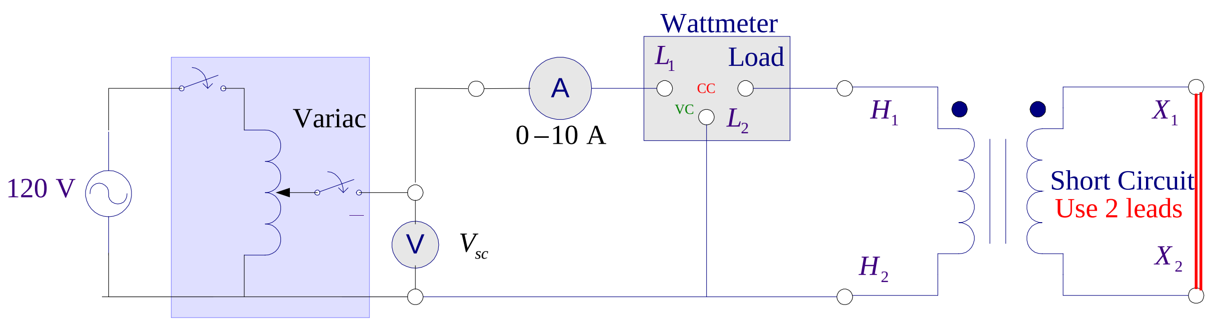


Figure 3-8 Short-circuit Test

<u>IT IS VERY IMPORTANT TO ADJUST THE VARIAC TO ZERO BEFORE TURNING ON THE AC POWER SWITCH.</u>

With the variac set for zero input voltage to the primary turn on the variac. While observing the primary current, increase the primary voltage slowly and with caution until 1/2 full-load rated current ($\approx$ 5 A) flows in the primary.

Record voltmeter, ammeter and wattmeter readings.

V_{sc} =________________ I_1 =________________ P_{sc} =________________

Since the input voltage is so low during the short-circuit test, negligible current flows through the excitation branch and all the voltage drop in the transformer can be attributed to the series element. The equivalent circuit reduces to the form shown in Figure 3.9.

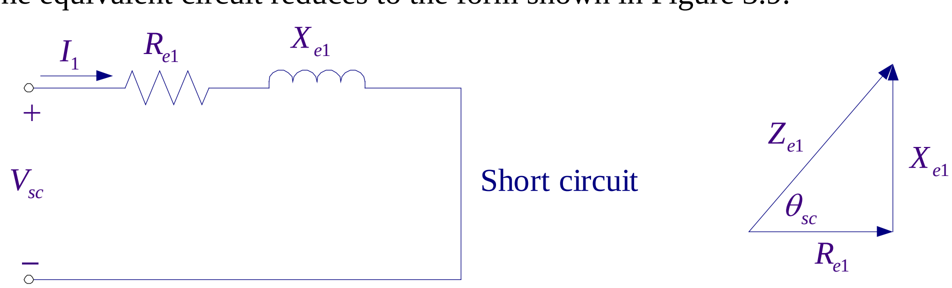


Figure 3.9 Equivalent-circuit for the short-circuit test

The iron loss is negligible and the wattmeter reading represents the windings copper loss. If the test is performed at 1/2 full-load, the power measured represents the copper loss at 1/2 full-load.

From this data determine the equivalent impedance referred to the high-voltage side and the low-voltage side.

$$Z_{e1} = \frac{V_{sc}}{I_1} = \_\_\_\_\_\_\_\_\_\_ \qquad R_{e1} = \frac{P_{sc}}{I_1^2} = \_\_\_\_\_\_\_\_\_\_ \qquad R_{e2} = \frac{1}{a^2} R_{e1} = \_\_\_\_\_\_\_\_\_\_$$

$$X_{e1} = \sqrt{Z_{e1}^2 - R_{e1}^2} = \_\_\_\_\_\_\_\_\_\_ \qquad X_{e2} = \frac{1}{a^2} X_{e1} = \_\_\_\_\_\_\_\_\_\_ \tag{3.6}$$

Copper loss is proportional to I^2. If P_{sc} is measured at $\frac{1}{2}$ full-load, then the full-load copper loss is

$$P_{cu} = (2)^2 P_{cu(1/2\,fl)} \tag{3.7}$$

Construct the equivalent circuit referred to the low voltage side and mark the impedances.

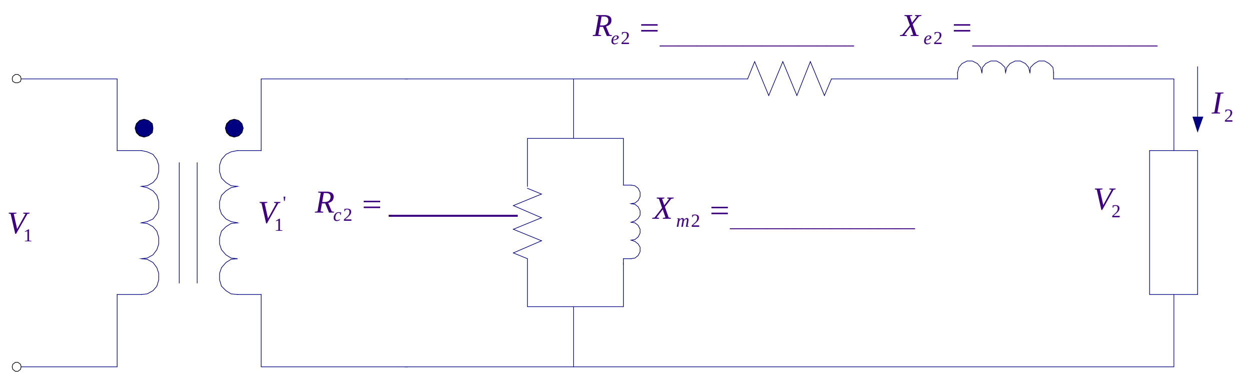


Figure 3.10 Equivalent-circuit referred to the low voltage side

7. Use the **transformer**[1] program and run the transformer tests to check your calculations, and obtain the equivalent circuit and the report requirements in steps 4 and 5 below.

[1]**transformer** A GUI program has been developed in MATLAB and is placed on the WARP network. To run this program type **transformer** at the MATLAB prompt. You may download this program and use it with your own MATAB Student Version, http://www.msoe.edu/~saadat/matlabgui.htm.

REPORT REQUIREMENTS

1. Identify similar polarities by dot marking, and explain why polarity check is important.
2. What does the rated load mean? (Discuss it in connection with the current, voltage, and temperature)
3. Describe the shape of the no-load current. State why the no-load current is not sinusoidal and describe its harmonic contents.
4. Draw the equivalent circuit of the transformer referred to the low-voltage side indicating the numerical values of the equivalent impedance. What are the value of the iron loss at rated voltage and the value of copper loss at full-load for the transformer under test? Why does the open-circuit test essentially show only iron loss and the short-circuit test show only the copper loss
5. From (3.2) determine the transformer efficiency at unity power factor from 20% to 120% of the rated KVA in 10% steps. Plot efficiency versus load KVA. From this curve determine the maximum efficiency, the load KVA at which maximum efficiency occurs and the copper loss. For maximum efficiency, how is winding loss related to iron loss? Using transformer program after finding the equivalent circuit continue with the transformer analysis to obtain the transformer performance at full-load unity power factor and full-load 0.8 power factor lagging.
6. Using (1.3) and (1.4), calculate the full-load voltage regulation at 0.8 lagging power factor, unity power factor, and 0.8 leading power factor. (Check with the transformer program result obtained above)
7. Discuss the voltage regulation versus load at unity power factor, and the effect on voltage regulation, as the power factor becomes more leading power factor.

LABORATORY SESSION 4
THREE PHASE TRANSFORMERS

CAUTION:
High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power should be turned off before the circuit is modified.

PURPOSE

To investigate the three phase transformer connections and characteristics

DISCUSSION

Most electrical energy is generated and transmitted using three phase systems. The three phase power may be transformed either by use of polyphase transformers or with a bank of single-phase transformers connected in three phase arrangements. The primary and secondary windings can be connected in either wye (Y) or delta Δ configurations, which result in four possible combinations of connections: Y-Y, Δ-Δ, Y-Δ and Δ-Y. Three arrangements are shown in Figure 4.2.

Y-Y Connection

The wye connection offers advantages of decreased insulation costs and the availability of the neutral for grounding purposes. One drawback of the Y-Y connections is that third harmonic problems exist. If the neutrals are ungrounded, there is no path for the third harmonic current to flow and the magnetizing currents are sinusoidal; however, the typical saturating magnetization curve of the transformer core causes the flux variation to be flat topped. In turn, this flat flux wave contains a large third harmonic component, which induces an appreciable third harmonic in phase voltages. The third harmonic components will cancel in the line-to-line voltages and the line voltages are essentially sinusoidal. For example with phase voltages containing third harmonics, the line-to-line voltage v_{ab} is given by

$$
\begin{aligned}
v_{an} &= V_{m1}\sin\omega t + V_{m3}\sin 3\omega t \\
v_{bn} &= V_{m1}\sin(\omega t - 120^\circ) + V_{m3}\sin 3(\omega t - 120^\circ) \qquad (4.1)\\
v_{ab} &= v_{an} - v_{bn} = \sqrt{3}V_{m1}\sin(\omega t + 30^\circ) + 0
\end{aligned}
$$

To eliminate the harmonics in phase voltages a third set of windings, called a tertiary winding, connected in Δ is normally fitted on the core so that the required third harmonic component of the exciting current can be supplied. This tertiary winding can also supply an auxiliary load if necessary.

If the source and both transformer neutrals are grounded, third harmonic currents can flow, thereby restoring a sinusoidal flux variation. In this case, all voltages are approximately sinusoidal (at fundamental frequency), but the third harmonic currents flow back to the source through the neutral ground. This can cause telephone or other related interference. This connection is rarely used because of harmonic magnetizing currents in the ground circuit. The relationships between the line and the phase voltages for the Y-Y connections are:

$$V_{HL} = \sqrt{3}V_{HP}, \qquad V_{XL} = \sqrt{3}V_{XP} \quad \Rightarrow \quad \frac{\mathrm{V_{HL}}}{\mathrm{V_{XL}}} = \frac{\mathrm{V_{HP}}}{\mathrm{V_{XP}}} = \frac{N_1}{N_2} = a \tag{4.2}$$

The letters *H* and *X* represent high and low voltages, respectively, and the subscript *L* stands for line, and *P* stands for phase quantities.

Δ - Δ Connection

The Δ connection provides no neutral connection and each transformer must withstand full line-to-line voltage. The Δ connection does, however, provide a path for third harmonic currents to flow. This results in a sinusoidal flux waveform producing sinusoidal phase voltages. This connection has the advantage that one transformer can be removed for repair and the remaining two can continue to deliver three-phase power at a reduced rating of 58% of that of the original bank. This is known as the V connection. The relationships between the line and the phase voltages for the Δ-Δ connections are:

$$V_{HL} = V_{HP}, \qquad V_{XL} = V_{XP} \quad \Rightarrow \quad \frac{\mathrm{V_{HL}}}{\mathrm{V_{XL}}} = \frac{\mathrm{V_{HP}}}{\mathrm{V_{XP}}} = \frac{N_1}{N_2} = a \tag{4.3}$$

Y- Δ Connection

The Y connection has no problem with third harmonic components in its voltages because the closed path provided by the secondary Δ connection permits the third harmonic magnetizing current to exist. In turn, this currents act to virtually eliminate the third harmonic component in the flux wave, thus ensuring a sinusoidal flux wave producing sinusoidal phase voltages. The Y neutral is grounded to reduce the undesirable effects with unbalanced loads. This connection is commonly used to step down a high voltage to a lower voltage.

$$V_{HL} = \sqrt{3}V_{HP}, \qquad V_{XL} = V_{XP} \quad \Rightarrow \quad \frac{\mathrm{V_{HL}}}{\mathrm{V_{XL}}} = \sqrt{3}\frac{\mathrm{V_{HP}}}{\mathrm{V_{XP}}} = \sqrt{3}\frac{N_1}{N_2} = \sqrt{3}a \tag{4.4}$$

Δ -Y Connection

The Δ-Y connection is the same as Y-Δ, except that the primary and secondary are reversed. If the Y connection is used on Δ the high voltage side, insulation costs are reduced. This connection is commonly used for stepping up to a high voltage.

The Y-Δ and the Δ-Y connections will result in a phase shift between the primary and secondary line-to-line voltages, with the low voltage lagging the high voltage by 30° as shown in Figure 4.1. Because of the phase shift inherent in Y-Δ and Δ-Y banks, they must not be paralleled with Y-Y, Δ-Δ, or V-V banks

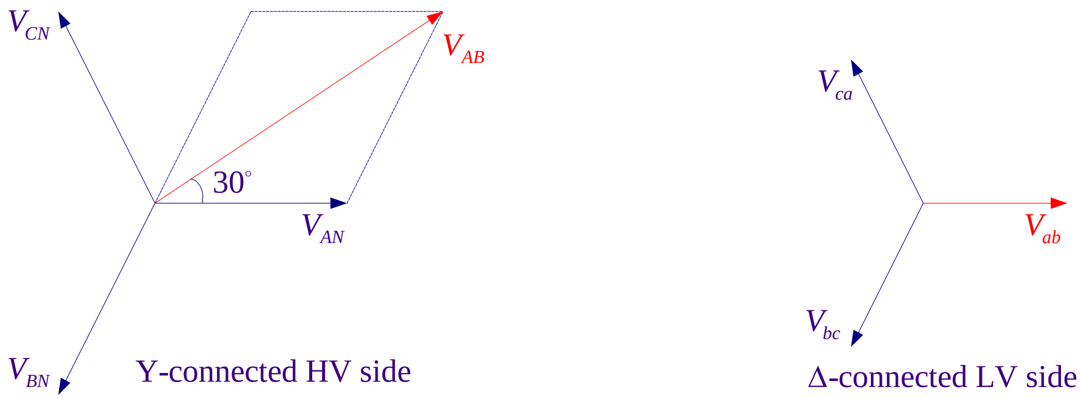


Figure 4.1 Phase shift in line-to-line voltages in a Y-Δ connection

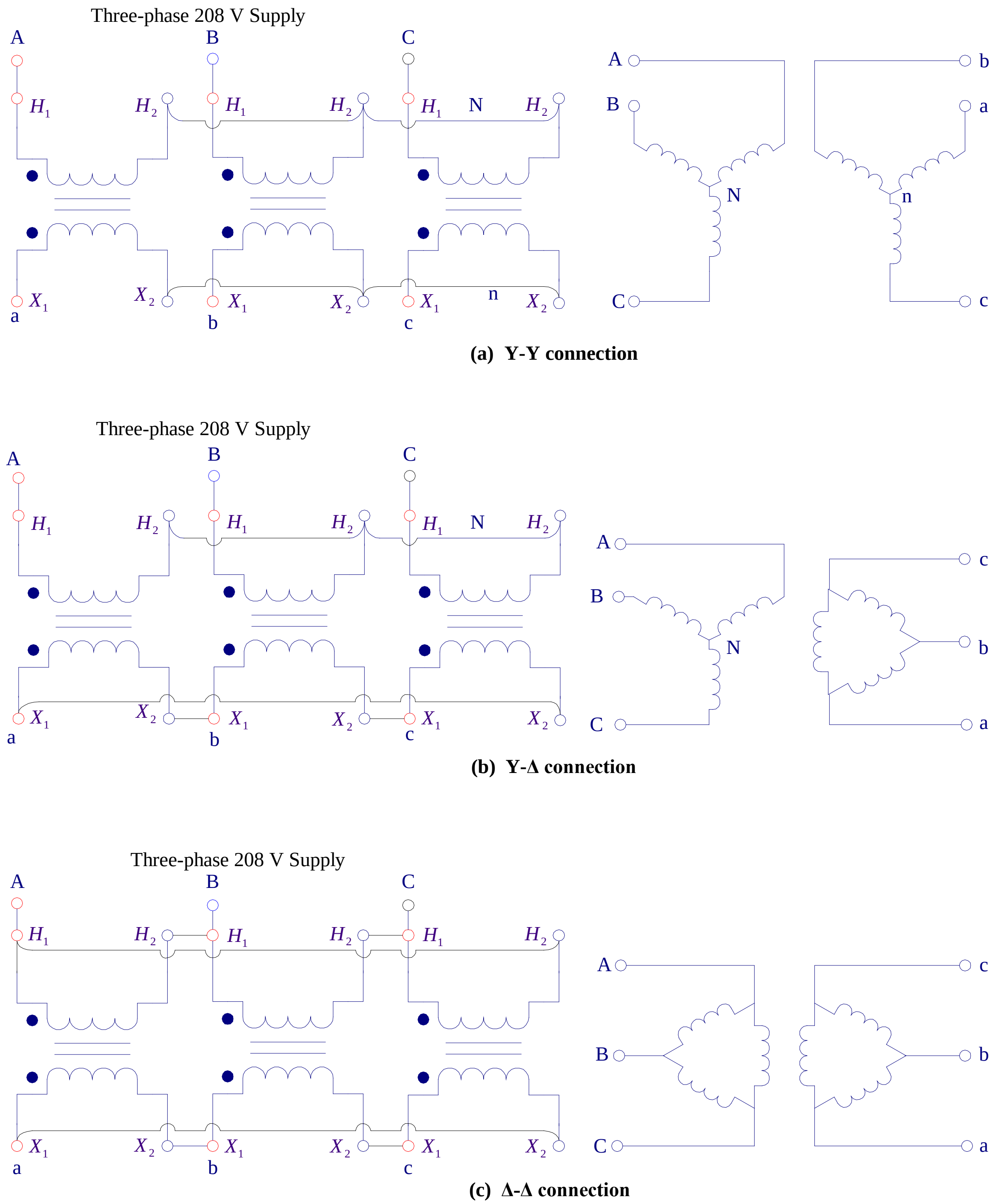
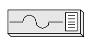


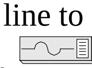
Figure 4.2 Three-phase connections of single-phase transformers

PROCEDURE

1. Y-Y Connection

(a) Line and phase RMS voltage Measurements – Connect the single-phase transformers Y-Y as shown in Figure 4.2 (a). Connect the high voltage winding to the three-phase 208 V power supply. Turn the power on and using a DMM measure the primary line-to-neutral voltages. You don't need to connect voltmeters permanently in the circuit. To measure the phase voltages connect the lead coming from the black terminal of the voltmeter to the neutral and carefully holding the lead coming from the voltmeter red terminal move from one phase to the next and measure the phase voltages (if slightly different consider a mean value for V_{HP}); also measure the primary line-to-line voltages V_{HL}. Repeat these measurements for the secondary side and measure V_{XP} and V_{XL}. Record in Table I.

(b) Turn on the PC and load the Fluke View ScopeMeter software. With both Y neutrals isolated connect the ScopeMeter input A to one phase of the secondary terminal X_1 and COM terminal to the secondary neutral. Turn on the ScopeMeter. Turn on input A to measure RMS voltage and make sure input A is selected for triggering. Press Auto to display the secondary line to neutral voltage. Click on the Display Waveforms icon  to open its dialog box and check mark Acquisition Memory A to display the secondary line-to-neutral voltage. Select Tool/Spectrum to create and display the voltage spectrum. Record the frequency, values in volt and the percent for fundamental, and up to the 7th harmonics. Save the voltage waveform and its spectrum graphs as a bitmap graphic (*.bmp) file on your F drive for inclusion in your report. Also, save the voltage traces with extension FVF, this way you can retrieve them again using Fluke software. Connect the ScopeMeter input A and COM to the secondary line-to-line terminals. Click on the Display Waveforms icon  to open its dialog box and check mark Acquisition Memory A to display and save the secondary line-to-line voltage and its spectrum.

(c) Connect the secondary neutral to the primary neutral and ground the neutrals. (You can find a ground terminal, a green plug on the right side of the AC supply box located behind your bench). Connect Input A and COM to measure the secondary line to neutral voltage. Turn on the ScopeMeter and click on the Display Waveforms icon  to open its dialog box and check mark Acquisition Memory A to display the secondary line-to-neutral voltage. Obtain the voltage spectrum. Is there any appreciable harmonics in the line-to-neutral voltage? Save these waveforms. Connect Input A and COM to measure the secondary line-to-line voltage and observe the harmonics content if any.

TURN OFF THE POWER SUPPLY EACH TIME BEFORE YOU RECONNECT THE LEADS

2. Y-Δ Connection

(a) Line and phase RMS voltage Measurements – Reconnect the single-phase transformers Y-Δ as shown in Figure 4.2(b). Connect the high voltage winding to the three-phase 208 V power supply. Turn the power on and using a DMM measure the primary line-to-neutral voltages (if slightly different consider a mean value for V_{HP}) also measure the primary line-to-line voltages V_{HL}. Repeat these measurements for the secondary side and measure $V_{XP} = V_{XL}$. Record in Table I.

Turn the power on and using a DMM record the primary and secondary line-to-line and line-to neutral voltages in Table I.

(b) Connect the ScopeMeter input A and COM to measure the phase voltage of one phase of the Δ connected secondary. Examine the voltage spectrum for its harmonic contents. There should be negligible third harmonic component in the phase voltages whether the primary neutral is grounded or isolated. Ground the primary neutral and investigate.

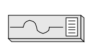
(c) Ground the Y neutral. Open one side of Δ (i.e., connection between two secondary windings) and insert the ScopeMeter input A and COM to measure the open loop voltage. Turn on the ScopeMeter. Measure the secondary open-loop voltage

$V_{LOOP} =$________________

With the primary neutral grounded, third harmonic magnetization current can flow in the primary resulting in sinusoidal secondary voltages, thus the secondary open-loop voltage measured should be approximately zero.

(d) Isolate the primary neutral. With Y-neutral not grounded and ScopeMeter connected as in part (c) in the open delta turn the power on and record the open loop voltage.

$V_{LOOP_{(rms)}} =$________________ $f =$________________

Click on the Display Waveforms icon  to open its dialog box and check mark Acquisition Memory A to display the secondary open-loop voltage Obtain the waveforms spectrum. Record the value in volts and percent and the frequency of the fundamental and up to the 7th harmonics. Save these waveforms.

When the primary neutral is not grounded the primary currents are essentially sinusoidal (No path for the third-harmonics current to flow). However, the flux because of the nonlinear B-H characteristics of the magnetic core is nonsinusoidal and contains odd harmonics, in particular third harmonics. The phase voltages are therefore nonsinusoidal, containing fundamental and third harmonic voltages, with instantaneous values given by

$$\begin{aligned} v_{an} &= V_{m1}\sin\omega t + V_{m3}\sin 3\omega t \\ v_{bn} &= V_{m1}\sin(\omega t - 120^\circ) + V_{m3}\sin 3(\omega t - 120^\circ) \\ v_{cn} &= V_{m1}\sin(\omega t - 240^\circ) + V_{m3}\sin 3(\omega t - 240^\circ) \end{aligned} \tag{4.5}$$

Note that fundamental phase voltages are phase shifted by 120° from each other, whereas third harmonic voltages are all in phase.

The open loop voltage around delta is the sum of phase voltages. The sum of fundamental components is zero, whereas the third harmonics will add up. The result is

$$V_{LOOP} = V_{an} + V_{bn} + V_{cn} = 3V_{m3}\sin 3\omega t \tag{4.6}$$

Note that when the secondary delta is closed, it permits the third harmonic current to flow in the secondary delta restoring sinusoidal flux and sinusoidal phase voltages as seen in part 2(b).

3. Δ - Δ Connection

(a) Line and phase RMS voltage Measurements – Reconnect the single-phase transformers Δ - Δ as shown in Figure 4.2(c). Connect the high voltage winding to the three-phase 208 V power supply. Turn the power on and using a DMM measure the primary line-to-line voltages $V_{HL} = V_{HP}$. Repeat these measurements for the secondary side and measure $V_{XP} = V_{XL}$. Record in Table I.

(b) Connect the ScopeMeter input A and COM to measure the phase voltage of one phase of the Δ connected secondary. Examine the voltage spectrum for its harmonic contents.

(c) Open one side of the secondary Δ (i.e., connection between two secondary windings) and insert the ScopeMeter input A and COM to measure the open loop voltage. Turn on the ScopeMeter. Measure the secondary open-loop voltage

$V_{LOOP} =$________________

The Δ - Δ connection provide a path for third harmonic currents to flow and therefore the phase voltages will not contain third harmonics. Thus, with identical transformers, the phase voltages are balanced and V_{LOOP} should be zero or small.

Table I

Transformer connections	**High voltage Measurements**		**Low-voltage Measurements**		**Line to phase ratio**		**Prim. to sec. ratio**	
	(L-L) V_{HL}	(L-N) V_{HP}	(L-L) V_{XL}	(L-n) V_{XP}	$\frac{V_{HL}}{V_{HP}}$	$\frac{V_{XL}}{V_{XP}}$	$\frac{V_{HL}}{V_{XL}}$	$\frac{V_{HP}}{V_{XP}}$
Wye-Wye								
Wye-Delta								
Delta-Delta								

Using the measured voltages determine the above ratios in Table I.

4. Improper Y connections

Connect the single-phase transformers Y-Y with connection to one phase of secondary (say phase a) reversed as shown in Figure 4.3.

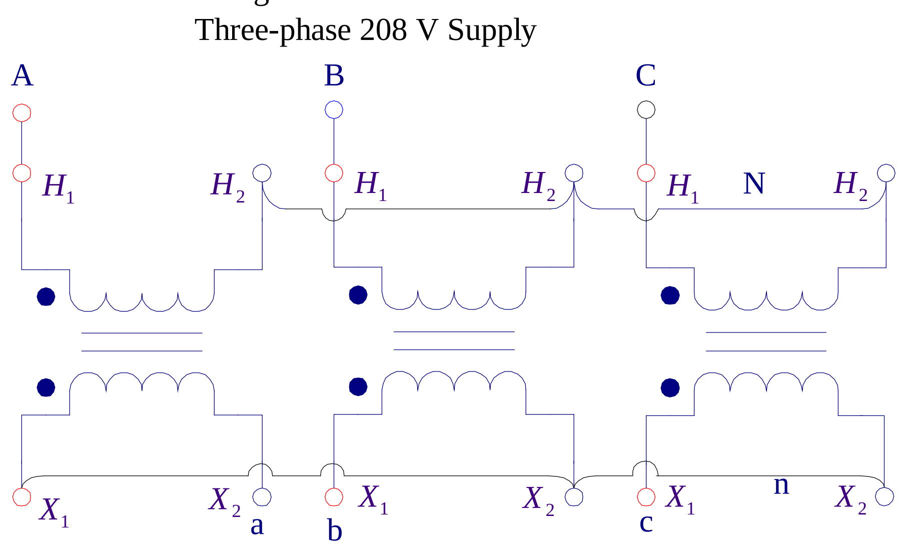


Figure 4.3 Improper Y-Y connections

Turn the power on and record all three secondary line-to- line and line-to-neutral voltages.

V_{an} =________________ V_{bn} =________________ V_{cn} =________________

V_{ab} =________________ V_{bc} =________________ V_{ca} =________________

For the above connections from Kirchhoff's voltage law the secondary line-to-line voltages are given by

$$
\begin{aligned}
V_{ab} &= V_{an} - V_{bn} = V_{XP}\angle 180^\circ - V_{XP}\angle -120^\circ = V_{XP}\angle 120^\circ \\
V_{bc} &= V_{bn} - V_{cn} = V_{XP}\angle -120^\circ - V_{XP}\angle 120^\circ = \sqrt{3}V_{XP}\angle -90^\circ \\
V_{ca} &= V_{cn} - V_{an} = V_{XP}\angle 120^\circ - V_{XP}\angle 180^\circ = V_{XP}\angle 60^\circ
\end{aligned}
\tag{4.7}
$$

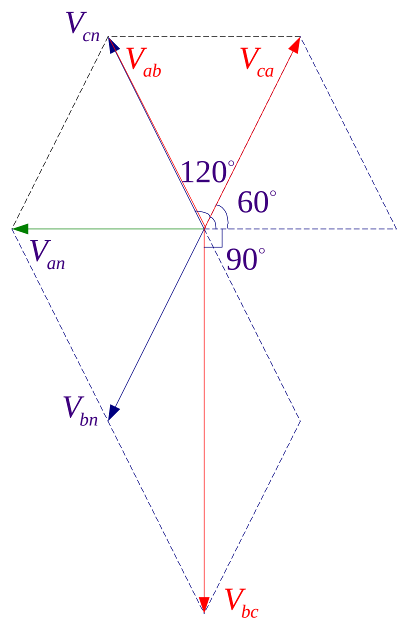


Figure 4.4 Phasor diagram for Improper Y connection.

5. Improper delta connection

In the Δ-Δ arrangement, reverse the connection of one phase of the secondary winding (say phase a). Open the secondary delta (connection between two secondary windings) and insert a voltmeter to read the open loop voltage as shown in Figure 4.5.

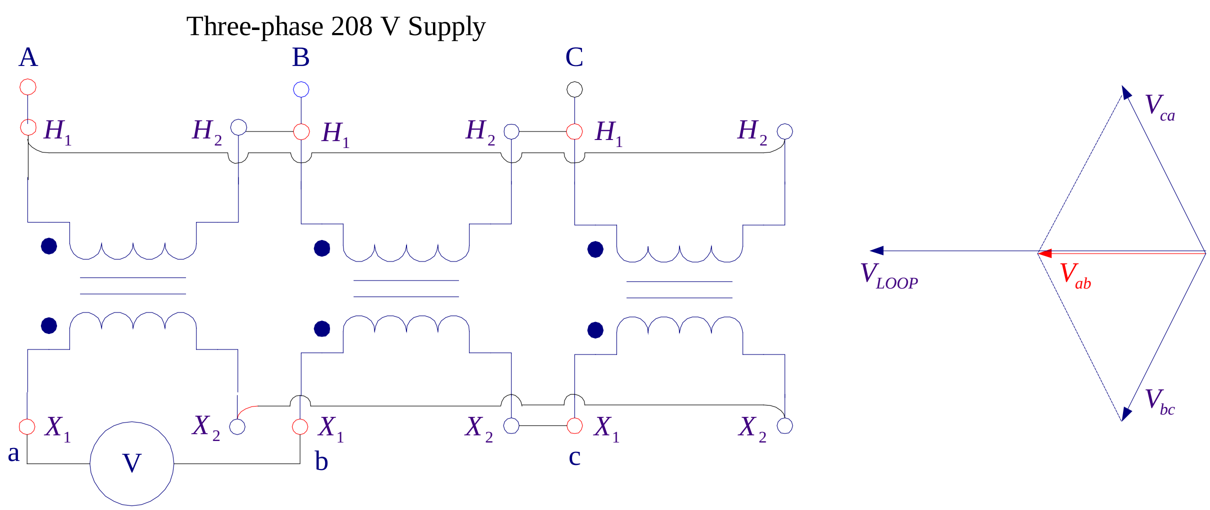


Figure 4.5 The improper Δ connection.

CAUTION: COMPLETE THE CIRCUIT FOR IMPROPER Δ THROUGH A VOLTMETER
DO NOT ENERGIZE THE IMPROPER Δ UNLESS YOU HAVE INSERTED A VOLTMETER IN THE LOOP.

Turn the power on and record the open loop voltage.

V_{LOOP} =________________

Neglecting harmonics, voltage around the open delta is given by

$$V_{LOOP} = V_{an} + V_{bn} + V_{cn} = V_{XP}\angle 180^\circ + V_{XP}\angle -120^\circ + V_{XP}\angle -240^\circ = 2V_{XP}\angle 180^\circ \quad (4.8)$$

REPORT REQUIREMENTS

1. Draw a phasor diagram showing the primary and secondary line-to-line and line-to neutral voltages for the Y-Y, Δ- Δ, and Y- Δ connections. For the Y-Δ connections determine the phase shift between the primary and secondary line-to-line voltages. Enumerate the necessary conditions for parallel operation of two three-phase transformers.

2. Using relations (4.2-4.4) calculate the voltage ratios and record in Table I. Compare with the measured values. What does the ratio of line-to-line to line-to-neutral voltage for Y connections in Table I demonstrate?

3. The ratios of primary to secondary phase or line voltages are all approximately equal for all connections in Table I except for the Y connection. Why?

4. What are the problems associated with the Y-Y three-phase transformer connection? Discuss the harmonics in the Y-Y connection and the observation made in parts 1(b) and 1(c). With isolated neutrals does the phase voltages contain third harmonics? Are there third harmonic in the line-to-line voltages (see equation 4.1).

5. Discuss the observation made in part 2(b). Is there any third harmonic component in the secondary of the Y-Δ connection? What is the value of the open loop voltage measured in part 2(c)? Is this value approximately zero with the Y neutral grounded? Is this value zero with the Y neutral ungrounded part 2(d)? If not, what does it represent and what is the approximate frequency of this voltage? What is the rms magnitude of the third-harmonic phase voltage of the secondary when third-harmonic voltages are present?

6. Discuss the observation made in part 3(b). Is there any third harmonic component in the secondary voltage of the Δ- Δ connection? What is the value of the open loop voltage measured in part 3(c)? Is this value approximately zero?

7. For the improper Y -Y connection of part 4, use (4.7) to compute the line voltages and compare with the measured values. Are the line voltages symmetrical?

8. For the improper Δ connection of part 5, use (4.8) to compute the open loop voltage and compare with the measured value. Is this an appropriate Δ connection? Why?

9. In a Δ-Δ connections can one of the transformers be removed with the remaining ones operating satisfactorily why? What is the name of this connection?

LABORATORY SESSION 5
MAGNETIZATION CURVE OF A DC GENERATOR

CAUTION: High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power must be turned off before the circuit is modified.

PURPOSE

The objectives of this experiment are to measure the parameters of the machine model and to obtain the dc machine magnetization curve.

DISCUSSION

The dc machine, as a generator was the first device used to provide a significant amount of electrical energy. They are widely used in vehicles that have electric storage batteries. However, most direct current generators are being increasingly replaced by solid-state devices, which convert available ac to direct current for dc drive systems and other dc applications. The dc motor was also the first electrical device to provide rotating mechanical energy. Because of the ease with which their speed can be controlled, dc motors are often used in applications requiring a wide range of motor speeds such as paper and steel industries.

There is no real difference between a generator and a motor except for the direction of the power flow. In the dc machine, the field winding is placed on the stator and the armature on the rotor. The field windings are wound around the poles of the stator and are supplied with dc current, which produces the main magnetic field of the machine. The armature windings are placed in the rotor slots, which are uniformly distributed around the rotor's periphery. Voltage induced in the armature winding is alternating. A mechanical commutator and a brush assembly function as a rectifier or inverter, making the armature terminal voltage unidirectional. The commutator is essentially a mechanical switch that is arranged to short out and then reverse the current direction in each coil of the armature winding consecutively.

The field current in a generator produces an mmf, which results in the field flux in accordance with the magnetization curve. When the machine is driven by a prime mover an emf is induced in the armature. The generated emf in the armature winding is proportional to the field flux times the speed ($E_a \propto \phi n$). The magnetization curve of a generator shows the relation between the field current and the armature terminal voltage on open circuit. The curve is drawn with induced armature voltage on the y-axis and field current on the x-axis. The magnetization curve is of great importance because it represents the saturation of the magnetic circuit of the dc machine.

DC generators are classified according to the manner in which their field flux is produced. These include separately excited generator, where the flux is derived from a separate dc source. When certain conditions are fulfilled, the generator own armature circuit may be employed as a source of field excitation. These machines are referred to as self-excited shunt generator, series generator and compounded generator. The first condition for self-excitation is that there must be some residual magnetism in the poles of the generators. In a shunt generator, the voltage generated by this residual flux produces a field current given by $I_f = \frac{V}{R_f}$. If the flux produced by this current is aiding the residual flux, it will result in the voltage buildup. The voltage will build up to a value given by the intersection of the field resistance line and the magnetization curve. At some resistance value $R_{f_{crit}}$, the resistance line is almost coincident with the linear portion of the magnetization curve. This coincidence condition results in an unstable voltage situation. This resistance is known as the critical field resistance. Thus, for voltage buildup the other requirements are: the field winding must be connected in such a way that its mmf would be aiding the residual magnetism; also, for a given speed the field circuit resistance must be less than the critical field circuit resistance.

PROCEDURE

1. Measurement of Machine Constants

Using the DMM as an ohmmeter, measure the resistance of the armature, the series field and the shunt field of the dc generator (dynamometer).

Armature resistance, $R_a =$________________

Series field resistance, $R_s =$________________

Shunt field resistance, $R_f =$________________

The resistance as measured between the armature terminals is composed of two distinct components. One component is the resistance of the copper winding, and the other is the combined resistance of the carbon brushes and the brush contact. The latter component is not constant and varies approximately inversely as the armature current.

2. Motor and Generator Connection and Operation

A 3-phase ac motor is used to drive the dc generator (dynamometer) at constant speed. Connect the ac motor to the 3-phase 208 V supply through a manual ac starter as shown. Separately excite the dc generator by connecting the dc shunt field through a dc ammeter and two rheostats (use two field rheostat in series) and a pushbutton switch to the 120 V dc source.

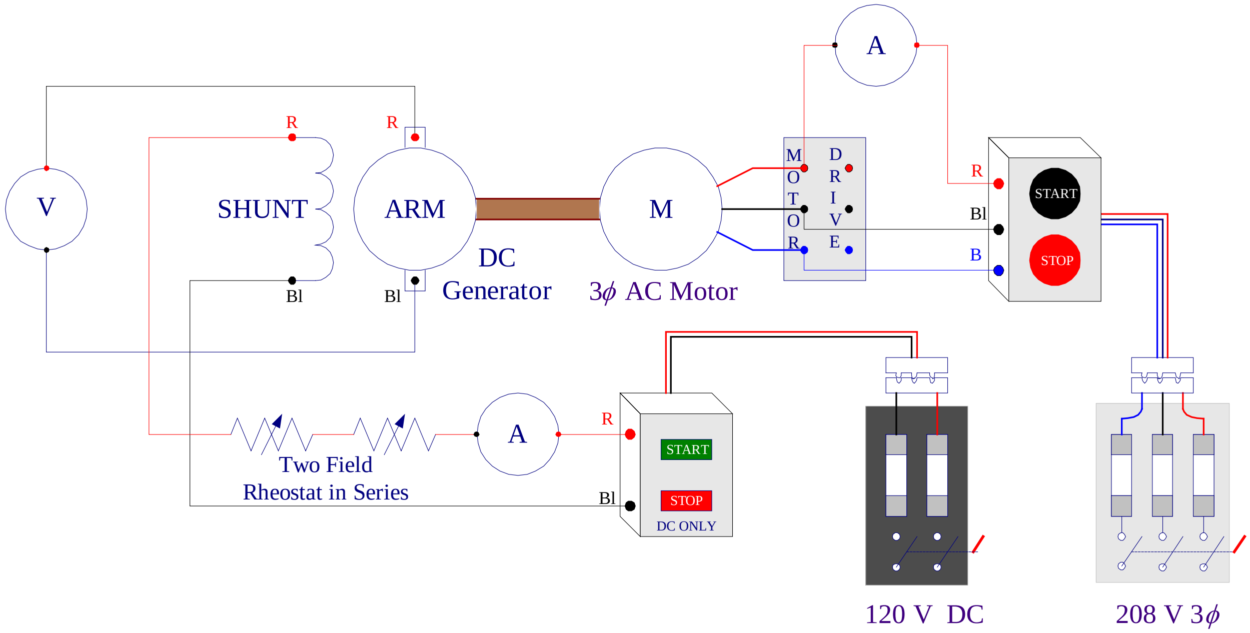


Figure 5.1 Ac motor and dc generator connections

Turn on the ac power and start the ac motor (do not turn on the dc power). The dc generator is now running with shunt field unexcited. Observe and record the following:

Table I (a)

Direction of Rotation (Looking towards the dynamometer from the motor end of the bench)	Speed RPM	Polarity of Voltage	Voltage, Volt

Stop the motor and interchange any two phases connected to the ac motor. Start the ac motor and with the dc power off observe and record the following:

Table I(b)

Direction of Rotation (Looking towards the dynamometer from the motor end of the bench)	Speed RPM	Polarity of Voltage	Voltage, Volt

Stop the motor.

3. Magnetization Curve and Hysteresis Effect

Reconnect the ac motor as per original diagram. Start the ac motor. Turn dc power on and check that the direction of rotation is correct and all meters read upscale. If necessary to minimize, eliminate or reverse the effect of residual magnetism, with the dc power off, reverse the shunt field terminal connections and turn the 120 V DC power supply on and off once quickly. With the shunt field terminal connection back to its proper color-coded connections and with the dc power off ($I_f = 0$) measure and record the generated voltage. With both rheostats set at maximum resistance turn the dc power on. Record the generated voltage and the field current as the field current is increased monotonically from minimum to maximum. Then take data, as field current is monotonically decreased.

Table 2. Data for dc generator magnetization curve

Increasing field current		Decreasing field current	
Field current I_f , A	Generated voltage E, Volts	Field current I_f , A	Generated voltage E, Volts
0			
		0	

Turn all power off.
Use the PC or your Laptop to plot the magnetization curve. See the instruction in Appendix.

4. Properties of Self -Excited Shunt Generator

Disconnect the dc motor shunt field from the power supply and connect it to the armature terminals as shown in Figure 5.2.

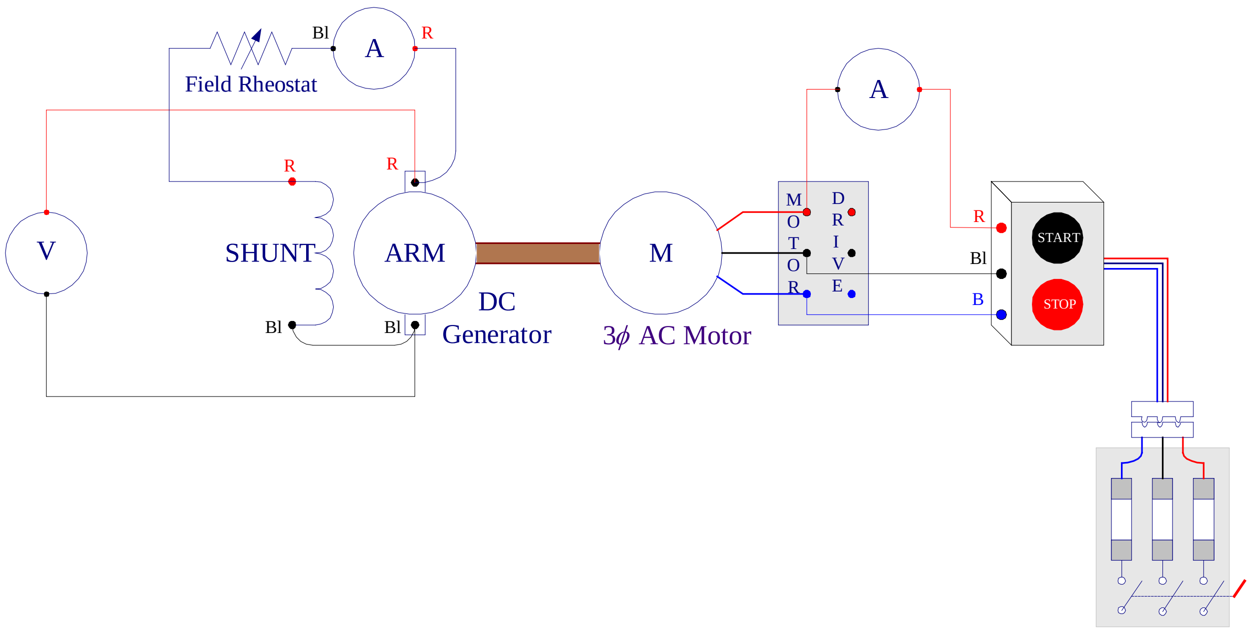


Figure 5.2 Circuit for studying the building up of the voltage of a shunt generator.

Start the motor. Check that the dc voltmeter is reading upscale and can be adjusted to 100 volts. If not, correct circuit before proceeding.

a. Set the field rheostat for minimum resistance and record the voltage and polarity of the armature voltage in the Table III. Repeat the test for the following changes and observe whether the machine does or does not build up in each case.

CAUTION: TURN OFF POWER BEFORE MAKING ANY CHANGES

b. Reverse the shunt field connections to the armature.

c. Reconnect the shunt field as per original circuit, but reverse the direction of rotation by interchanging the two phases of the ac motor terminals.

d. Reverse both the shunt field and direction of rotation.

Table III

Field connections and direction of rotation	**Direction of rotation**	**Voltage, V**	**Polarity**	**Build-up to rated value Y/N**
a. Circuit with color code				
b. Field connections reversed				
c. Direction of rotation reversed				
d. Both field connections and rotation reversed				

Turn the power off.

5. Critical Field Resistance

Reconnect the dc generator shunt field and the ac motor terminals with their proper color codes as in Figure 5.2. Set the field rheostat at its maximum value and start the motor. Gradually decrease the field rheostat to the point that you can just observe a voltage buildup beyond the residual value. Stop the motor, disconnect the shunt field from the armature and measure the field circuit resistance (including the rheostat).

$R_{f_{crit}} =$________________

REPORT REQUIREMENTS

1. Comment on the relative values of the armature, series field and the shunt field resistances.

2. With the dc field excitation off, explain the reason for the small generated-voltage as measured in part 2.

3. Plot the magnetization curves for increasing and decreasing of field current (See the Appendix). Discuss the theoretical basis for the shape of the magnetization curve and explain the difference between the two curves.

4. Draw a straight line through origin approximately tangent to the magnetization curve (increasing curve). Determine its slope. What does this value represent? Compare it to the value measured in part 5.

5. Comment on the results of part 4 and enumerate the necessary conditions for the dc shunt generator to build up.

Appendix

In MATLAB, from **F**ile/**N**ew/**M**-File, open the MATLAB Editor and type the following commands and save with a file name having extension m. This program can be used to plot dc generator magnetization curves for increasing and decreasing field current. The functions **polyfit** and **polyval** are used for curve fitting. Enter the recorded values of I_f and E inside the following brackets, as an array for increasing and decreasing filed current recorded in Table II. Run the program to obtain the plot. If necessary change the polynomial order *n* until you are satisfied with the results.

```
If1=[ ]; % Enter increasing field current data as a row array
E1 =[ ]; % Enter corresponding E data for increasing If1
If2=[ ]; % Enter decreasing field current data as a row array
E2 =[ ]; % Enter corresponding E data for decreasing If
n= 2;    % n is polynomial order, if necessary change n to
         % 3rd or higher to obtain a satisfactory curve
c1=polyfit(If1, E1,n); % Returns poly coeff. for increasing If1
c2=polyfit(If2, E2,n); % Returns poly coeff. for decreasing If2
E1fit=polyval(c1, If1); % Evaluates poly values for array If1
E2fit=polyval(c2, If2); % Evaluates polyn values for array If2
plot(If1,E1,'xr', If2,E2,'ob', If1,E1fit,'r', If2, E2fit,'b' )
title('DC Generator Magnetization curve')
xlabel('I_f, Amps'), ylabel('E, Volts')
legend('Increasing I_f', 'Decreasing I_f', 4)
```

LABORATORY SESSION 6
DC GENERATOR LOAD CHARACTERISTICS

CAUTION: High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power must be turned off before the circuit is modified.

PURPOSE

The purpose of this experiment is to obtain the load characteristics of separately-excited and self-excited dc generators, to show how compounding may be used to improve the voltage regulation and to obtain the generator efficiency.

DISCUSSION

One of the advantages of dc machines arise from the wide variety of operating characteristics which can be obtained by selection of the method of excitation of the field windings. The field windings may be separately excited from an external dc source, or they may be self-excited, i.e., the machine may supply its own excitation.

The field current in a generator produces an mmf, which results in the field flux in accordance with the magnetization curve. When the machine is driven by a prime mover an emf is induced in the armature. The internal generated emf of a dc generator is given by

$$E_a = K\omega\phi \tag{6.1}$$

where ω is the speed in radian per second. When the machine is loaded the armature current creates a flux whose axis is fixed at 90 electrical degrees from the main-field axis by the brush position. This flux interacts with the field flux to produce a unidirectional torque given by

$$T = KI_a\phi \tag{6.2}$$

The armature mmf distorts the flux density distribution (cross magnetizing effect) and also produces the demagnetizing effect. This is called armature reaction. The armature reaction causes poor commutation leading to sparking, especially when the armature current changes rapidly. To overcome this difficulty, dc machines are sometimes fitted with compensating windings. These take the form of conductors embedded in slots in the field pole faces; they are connected in series with the armature, but carry current in opposite direction so as to cancel the armature reaction flux. In addition, the voltage in the coils undergoing commutation can be canceled by providing commutating poles or inter-poles. The inter-poles are placed midway between the main poles and their windings are connected in series with the armature. An important generator characteristic is the effect that varying the load current has on the terminal voltage. The relation between the generated emf E_a and the terminal voltage V is given by

$$V = E_a - R_a I_a \tag{6.3}$$

The terminal voltage of a separately excited generator (Figure 6.1) decreases slightly with increase in the load current, principally by the $R_a I_a$ drop. Since the internal generated voltage is independent of I_a, if saturation is neglected, E_a is constant and the terminal voltage characteristic of the separately excited generator is a straight line. However, when measuring the terminal voltage for a real machine, it is noted that the drop is slightly greater than $R_a I_a$. This is due to the fact that an increase in I_a causes an increase in armature reaction, and armature reaction causes flux weakening. From (6.1) it is seen that this flux weakening causes a decrease in E_a.

The terminal characteristic of a dc shunt generator differs from that of a separately excited dc generator, because the amount of field current in the machine depends on its terminal voltage. The terminal voltage will decrease with an increase in load because of the armature $R_a I_a$ drop and the armature reaction. However, when V decreases, the field current in the machine decreases with it. This causes the flux in the machine to decrease, decreasing E_a, thereby causing the terminal voltage to drop still further. If the load is increased excessively and in an extreme case when the terminal voltage is short-circuited ($V = 0$), the field current ($I_f = V / R_f$) is zero and the field will collapse. Under this condition, there will be no generated emf except for a small voltage E_r due to the residual flux, resulting in a small circulating current given by E_r / R_a. Therefore, the dc generator is self-protected against a short circuit at its terminals.

In the series generator the field is connected in series with the armature and since it carries the armature current it is designed to have only a very few turns of wire, and the wire used is much thicker than the wire in the shunt field.

A series generator that is operated at no-load develops a small terminal voltage proportional to the residual flux. As the load increases, the field current rises, so E_a rises rapidly. The $(R_a + R_s)I_a$ drop goes up too, but at first the increase in E_a goes up more rapidly than the $(R_a + R_s)I_a$ drop rises, so V increases. After a while, the machine approaches saturation, and E_a becomes almost constant. At that point, the resistive drop is the predominant effect, and V starts to fall. Series generators are used only in a few specialized applications, where the steep voltage characteristic of the device can be exploited. One such application is arc welding.

A dc machine that has both the shunt and series windings is known as a compound dc machine. If the fluxes of the two coils aid each other, the machine is said to be cumulatively compounded. If the fluxes in the two coils oppose each other, the generator is said to be differentially compounded. Further, if there is enough turns of the series windings, so that the full-load voltage is greater than the no-load voltage, the generator is overcompounded. If the series turns are such a number that the no-load voltage is the same as the full-load voltage, the generator is flat compounded. If the turns are such that the full-load voltage is less than the no-load voltage, the generator is undercompounded. A flat compounded generator would provide a nearly constant voltage at the generator terminals.

DC generators are compared by their voltage ratings, power ratings, efficiencies, and voltage regulations. The voltage regulation of a dc generator is the percent change in terminal voltage from no-load to rated load, with respect to rated voltage.

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100 \qquad (6.4)$$

where V_{nl} is the no-load terminal voltage of the generator and V_{fl} is the full-load terminal voltage of the generator.

The efficiency of the generator is given by

$$\eta = \frac{P_o}{P_i} \times 100 \qquad (6.5)$$

In the case of generator output power is electrical and is given by

$$P_o = VI_L \qquad (6.6)$$

where I_L is the load current. For shunt and compound generator $I_L = I_a - I_f$.

The input power is computed from the measurement of the dynamometer as follows:

$$T = \text{Pull (Kg)} \times 9.81 \times \text{Arm radius (0.305m)} \quad \text{N-m N-m} \qquad (6.7)$$

$$P_i = \omega T \quad \text{Watts} \qquad (6.8)$$

where ω is speed in Rad/sec given by $\omega = \frac{2\pi n}{60}$, n is speed in RPM.

PROCEDURE

1. Separately-excited generator

Drive the dc generator at constant speed by means of the synchronous reluctance motor. Connect the synchronous reluctance motor to the 3-phase 208 V supply through a manual ac starter as shown. Place an ac ammeter in one phase. Because of the high starting current a toggle switch shorts the ammeter during starting. This ammeter indicates the current drawn by the ac motor. During the test observe this meter so as not to exceed the rated current of the ac motor.

Separately excite the dc generator by connecting the dc shunt field through a dc ammeter, a rheostat and a pushbutton switch to the 120 V dc source. Connect the 120 V resistor bank in series with a dc ammeter across the armature and use a dc voltmeter to measure the terminal voltage. Zero the dynamometer scale. The ac ammeter is provided with a bypass toggle switch, press the switch to read the ammeter. Turn on the ac power and start the ac motor. Turn on the dc power and adjust the open-circuit voltage to 80 V. With the load bank off record in Table I the field current I_f , armature current ($I_a = I_L$), the terminal voltage V , speed n , and the dynamometer pull. Now, without changing the field rheostat, load the generator using the load bank and repeat the measurements as each load is switched on. You may load the dynamometer up to 9 A for a short time if readings are taken quickly.

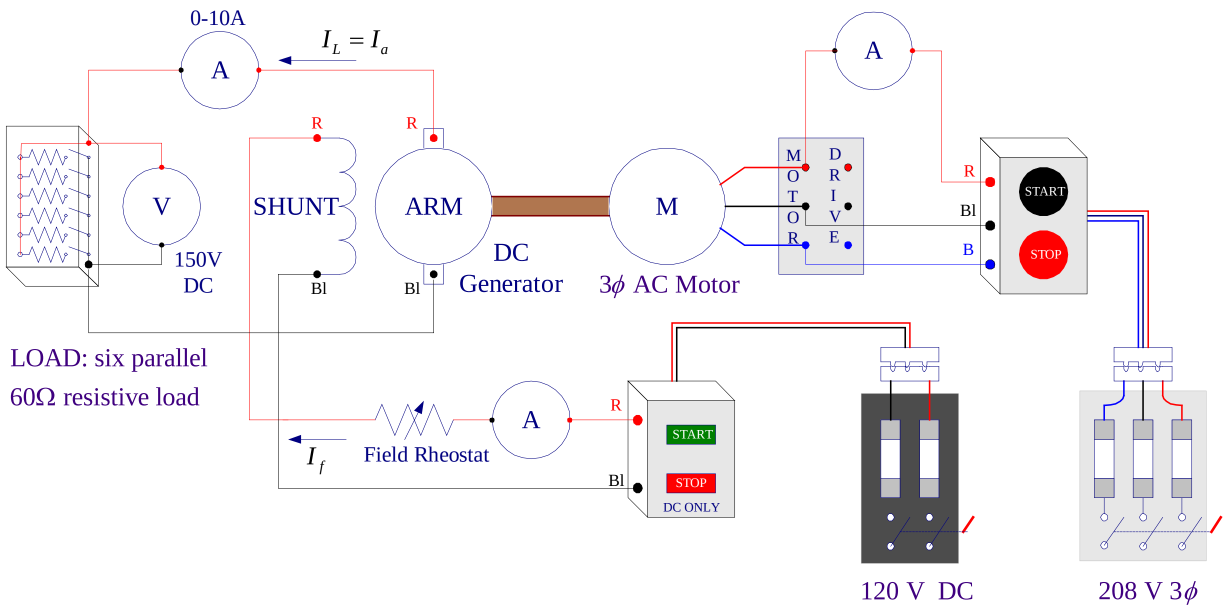


Figure 6.1 ac motor and dc generator connections

Table I Separately excited generator

Measured Data					Calculated Data				
V Volts	I_a Amps	I_f Amps	n RPM	Pull Kg	$I_L = I_a$ Amps	$P_0 = VI_L$ Watts	Torque N-m	$P_i = \omega T$ Watts	η Percent

Evaluate the calculated data and enter in Table I.

CAUTION: TURN OFF POWER BEFORE MAKING ANY CHANGES

2. Self-excited shunt generator

Disconnect the dc generator shunt field from the power supply and connect it to the armature terminals as shown in Figure 6.2.

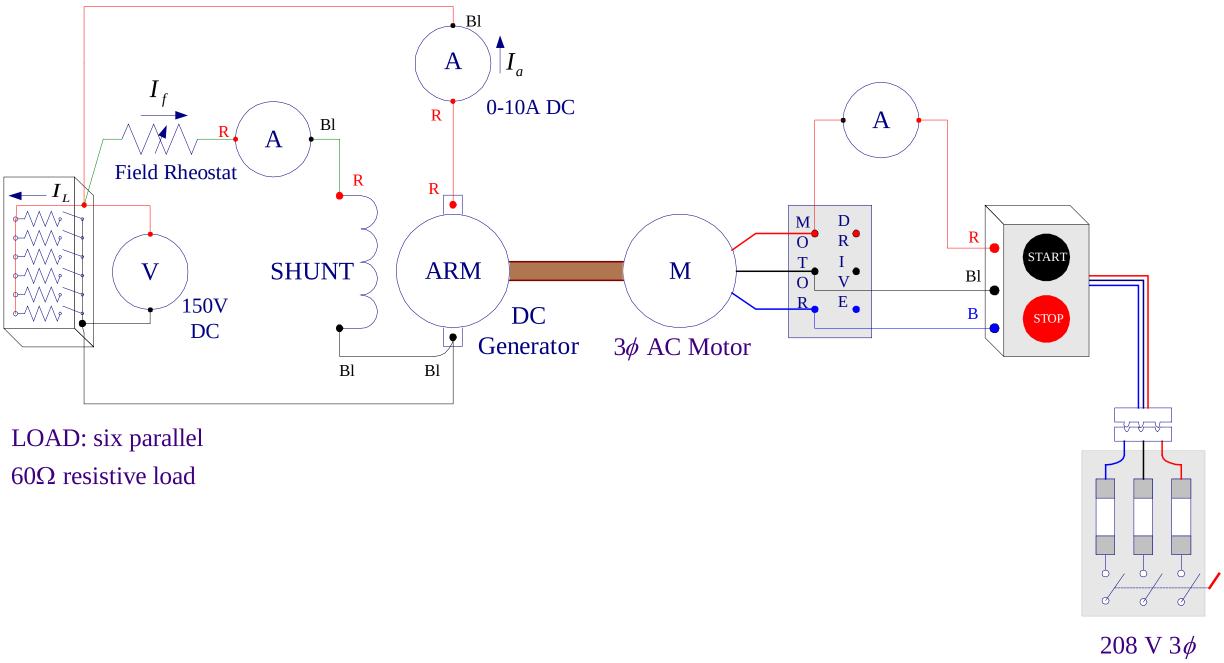


Figure 6.2 Circuit for self-excited shunt generator

Start the ac motor. Adjust the field rheostat for the same no-load generated emf as before (80 V), and record the measurements in Table II. Without any further adjustment of the field rheostat load the generator steadily and record all measurements for each load in Table II.

Table II Self-excited Shunt-excited generator

Measured Data					Calculated Data				
V Volts	I_a Amps	I_f Amps	n RPM	Pull Kg	$I_L = I_a - I_f$ Amps	$P_0 = VI_L$ Watts	Torque N-m	$P_i = \omega T$ Watts	η Percent

Turn the power off. Evaluate the calculated data and enter in Table II.

3. Self-excited cumulatively-compound generator

Connect the dc generator for long-shunt cumulatively compound operation as shown in Figure 6.3.

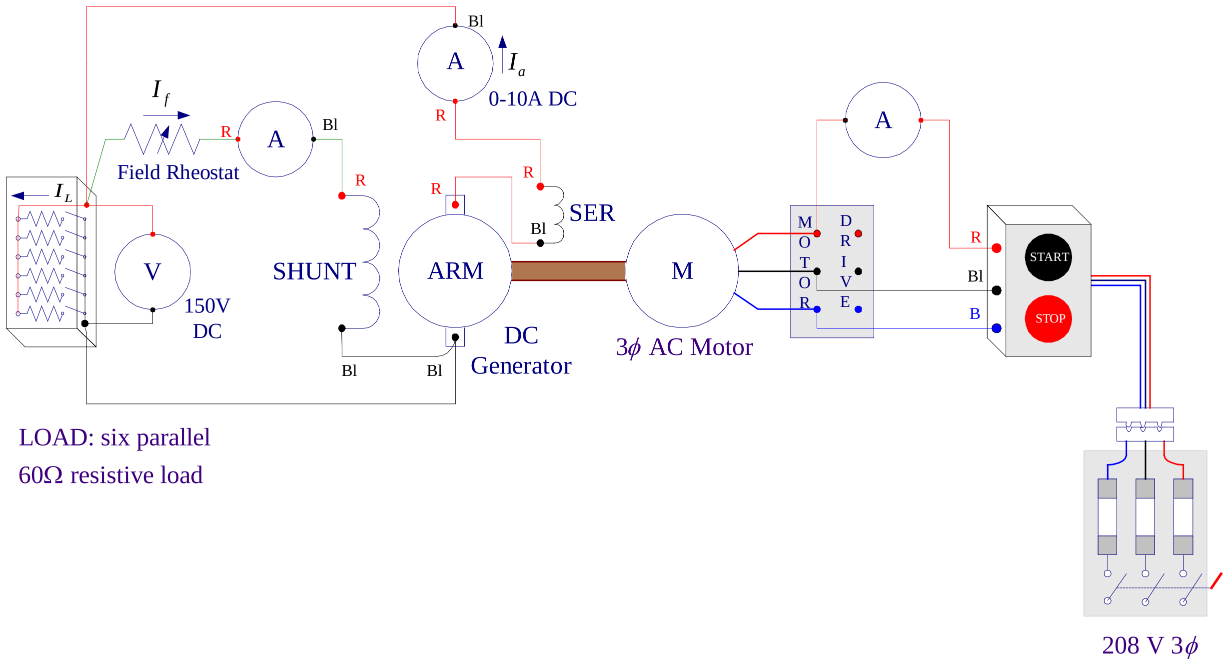


Figure 6.3 Circuit for self-excited long-shunt compound generator

Start the motor. Adjust the field rheostat for the same no-load generated emf as before (80 V), and record the measurements in Table III. Without any further adjustment of the field rheostat load the generator steadily and record all measurements for each load in Table III.

Table III Long shunt Cumulatively compound dc generator

Measured Data					Calculated Data				
V Volts	I_a Amps	I_f Amps	n RPM	Pull Kg	$I_L = I_a - I_f$ Amps	$P_0 = VI_L$ Watts	Torque N-m	$P_i = \omega T$ Watts	η Percent

Turn the power off. Evaluate the calculated data and enter in Table III.

4. Self-excited differentially compound generator

Connect the dc generator for long-shunt differentially compound operation by reversing the series field connections. Start the motor. Adjust the field rheostat for the same no-load generated emf as before (80 V), and record the measurements in Table IV. Without any further adjustment of the field rheostat load the generator steadily and record all measurements for each load in Table IV. Do not exceed the ac motor rated current.

Table IV Long shunt Differentially compound dc generator

Measured Data					Calculated Data				
V Volts	I_a Amps	I_f Amps	n RPM	Pull Kg	$I_L = I_a - I_f$ Amps	$P_0 = VI_L$ Watts	Torque N-m	$P_i = \omega T$ Watts	η Percent

Turn the power off. Evaluate the calculated data and enter in Table IV.

5. Series generator

Connect the series field in series with the armature as shown in Figure 6.4. Add a 5Ω, 1000W resistor in parallel with the resistor load bank for additional load. If you are using the starting resistor for this purpose, make sure the switch is in the in position and do not switch to the position that replaces the resistor with a short circuit. For light loading you must physically remove the 5Ω resistor out of the circuit. Start the motor and load the generator steadily and record all measurements for each load in Table V. Do not exceed the ac motor rated current.

Turn the power off. Evaluate the calculated data and enter in Table V.

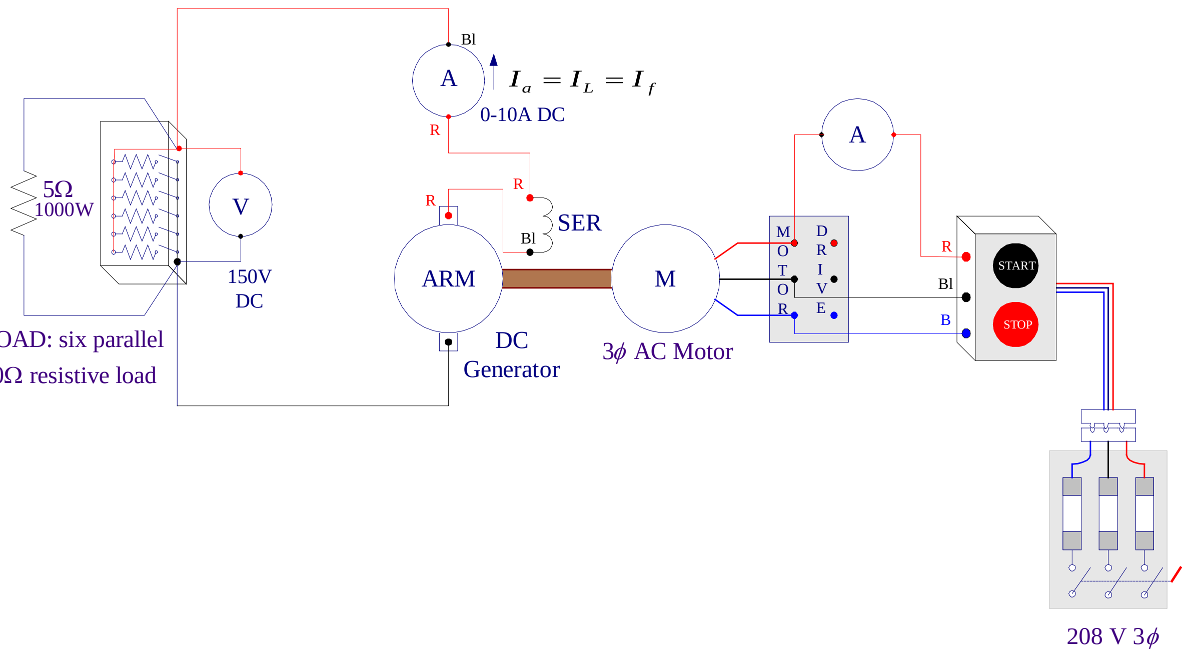


Figure 6.4 Circuit for series generator

Table V Series dc generator

Measured Data					Calculated Data				
V Volts	I_a Amps	$I_f = I_a$ Amps	n RPM	Pull Kg	$I_L = I_a$ Amps	$P_0 = VI_L$ Watts	Torque N-m	$P_i = \omega T$ Watts	η Percent

Turn the power off. Evaluate the calculated data and enter in Table V.

6. Resistance Measurements

Disconnect all circuits. Using an ohmmeter, measure the armature resistance, shunt field resistance, and the series field resistance of the dc generator.

7. Use **ee340lab6** function as explained in the Appendix to check your computed data.

REPORT

1. Using (6.4) determine the percentage voltage regulation at full-load for each type of connection except the differential compound. For the purpose of this experiment, assume that the full-load current of the dc generator is about 6 A. For the separately excited generator, using (6.3) and the measured terminal voltage at full-load compute the no-load generated voltage E_a and compare with the measured no-load generated voltage. How many volts difference are there and what is the reason for this difference?
2. Plot terminal voltage versus armature current on one graph paper for each type of connection. Explain the theoretical basis for the shape of all the curves. List all effects, if any that tend to cause the terminal voltage to decrease with load. Why does the terminal voltage fall so rapidly with simple shunt excitation? Why does the terminal voltage of the series generator rise with increase in load?
3. Using (6.5)-(6.8) compute and tabulate the power output, torque, the power input and efficiency of the generator for each type of connection. Include a sample calculation. Plot efficiency versus the power output for each connection. You may use the MATLAB commands to verify your calculations and obtain the required plots.

Appendix

In MATLAB, from **F**ile/**N**ew/**M**-File, open the MATLAB Editor. Enter the data for the separately excited dc generator in the $n \times 5$ matrix named Sep. Each column represents a variable that must be entered in the order shown below. Enter the data for the remaining cases. Use the function named **ee340lab6** as indicated below to obtain the calculated data and the required plots. The function **ee340lab6** has been added to the MATLAB available on the MSOE network. If you have your own MATLAB student version you may download this function to your Laptop.

```
%           V        Ia       If       n       Pull
Sep =     [
                                                    ];

%           V       Ia       If       n       Pull
Shunt =   [
                                                    ];

%           V       Ia       If       n       Pull
CumComp = [
                                                   ];

%           V       Ia       If       n       Pull
DiffComp =[
                                                   ];

%           V       Ia       If       n       Pull
Series =  [
                                                    ];
ee340lab6(Sep, Shunt, CumComp, DiffComp, Series)
```

Once you have finished entering all the data save with a file name having extension m and run at the MATLAB prompt.

LABORATORY SESSION 7
DC MOTOR LOAD CHARACTERISTICS

CAUTION: High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power must be turned off before the circuit is modified.

PURPOSE

The purpose of this experiment is to obtain the load characteristics of dc motors, and show how these depend upon the nature of the field excitation, and to demonstrate the speed control and reversing direction of rotation of a dc motor.

DISCUSSION

The dc motor is a highly versatile machine. It has superior torque and speed range capabilities as compared to induction motors driven from constant frequency supply. It is capable of quick reversal, and speed control over a wide range is achieved relatively easily. For this reason they are selected for use in applications requiring these characteristics, such as rolling mills, power shovels and railroad locomotives. Today, induction motors with solid-state drives are competitive with dc motors in speed control applications.

The torque developed by the dc motor is directly proportional to the armature current and the field flux.

$$T = KI_a\phi \tag{7.1}$$

On the other hand, the motor back emf is proportional to the motor speed and the field flux.

$$E = K\omega\phi \tag{7.2}$$

or

$$\omega = \frac{E}{K\phi} = \frac{V - R_a I_a}{K\phi} \tag{7.3}$$

Where ω is the motor speed in radian per second. Neglecting saturation effect, flux is proportional to the field current, i.e., $\phi = K_f I_f$. Letting $K_m = KK_f$, the above equation may be written as

$$\omega = \frac{V - R_a I_a}{K_m I_f} \tag{7.4}$$

Equation (7.4) suggests that speed control in dc machines can be achieved by three methods: Voltage control (V), field control (I_f), and armature resistance control.

Voltage control requires a controllable voltage source; but most available dc sources - main batteries - are essentially fixed voltages. Techniques of power electronics enable a variable voltage to be derived from an ac source, and the combination of an electronic controller with a dc motor makes a most effective variable speed drive system. This system dominated the market for over a decade, but it faces growing competition from the ac variable-frequency induction motor drive systems.

For a constant dc supply voltage, speed above normal can be obtained by reducing the field current (field weakening). For example, in a shunt motor, placing a resistance in series with the shunt field reduces the field current, yielding a higher operating speed. General-purpose shunt motors are designed to provide a 200% increase in rated speed by this method of speed control. However, because of the weakened flux, the permissible torque that can be delivered at the higher speed is correspondingly reduced in order to prevent excessive armature current. Speed below normal can be obtained by placing a resistance in series with the armature circuit. Since this resistance must carry the full armature current, its size and cost is considerably greater than those of the field rheostat. The main disadvantage of armature resistance control is the poor efficiency of operation.

Substituting for armature current from (7.1) into (7.4), the speed torque characteristic is given by

$$\omega = -\frac{R_a}{\left(K_m I_f\right)^2} T + \frac{V}{K_m I_f} \tag{7.5}$$

The great virtue of the dc motor is that three useful operating characteristics may be obtained by using the field winding in different ways. For shunt motor I_f, is constant and the speed torque characteristic can be written as

$$\omega = -K_1 T + K_2 \tag{7.6}$$

where $K_1 = \dfrac{R_a}{\left(K_m I_f\right)^2}$, and $K_2 = \dfrac{V}{K_m I_f}$.

This equation is just a straight line with a negative slope.

In series motor $I_a = I_f$, neglecting saturation (7.1) may be written as $T = K_m I_a^2$, and from (7.4) the speed torque characteristic of a series motor can be expressed as

$$\omega = K_3 \frac{1}{\sqrt{T}} - K_4 \tag{7.7}$$

where $K_3 = \dfrac{V}{\sqrt{K_m}}$, and $K_4 = \dfrac{R_a}{K_m}$.

From the above equation it can be seen that for an unsaturated series motor the speed is inversely proportional to the square root of the torque. A high torque is obtained at low speed and a low torque is obtained at high speed. With a small machine the windage and friction torque is sufficient to limit the no-load speed to a safe value, but a large series motor must never be started without a load or the speed will rise to a very high value and armature may burst under the rotational stresses. Series motors are used where large torque are required, as in subway cars, automobile starters, hoists, cranes, and blenders.

A series dc motor will operate quite well from a single-phase ac supply. Universal motors of this kind are widely used in portable power tools and domestic appliances such as food mixers.

A compound dc motor is a motor with both a shunt and a series field, which combines the best features of both the shunt and a series motor.

In order to reverse the direction of rotation of a dc motor, it is necessary to reverse the direction of current through the armature with respect to the current of the field circuit. This is done simply by reversing either the armature circuit connections with respect to the field circuit or vice versa. Reversal of both circuit connections will produce the same direction of rotation. In designing automatic starters and control equipment, the armature circuit is usually selected for reversal for several reasons. First the field is highly inductive circuit, and frequent reversal induces undesirable high emfs. Second, if the shunt field is reversed, the series field must also be reversed; otherwise the motor will be differentially compounded. Third, if the reversing switch is defective and field circuit fails to close, the motor may ``run away."

Just as dc generators are compared by their voltage regulations, dc motors are compared by their speed regulations. The speed regulation (SR) is defined by

$$SR = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100 \tag{7.8}$$

The motor efficiency is given by

$$\eta = \frac{P_O}{P_i} \times 100 \tag{7.9}$$

In the case of motor, input power is electrical and is given by

$$P_i = VI_L \tag{7.10}$$

I_L is the line current. For shunt and compound motors $I_L = I_a + I_f$. The output power is computed from the measurement of the dynamometer pull as follows:

$$T = Pull\ \text{(Kg)} \times 9.81 \times \text{Arm radius (0.305 m)} \quad \text{N-m} \tag{7.11}$$

$$P_o = \omega T \quad \text{Watts} \tag{7.12}$$

where ω is speed in rad/sec given by $\omega = \frac{2\pi n}{60}$, n is speed in RPM.

PROCEDURE

1. Shunt motor

Connect the dc motor for shunt operation as shown in Figure 7.1. For this part you don't need to complete the dynamometer wiring. Use two DC ammeters to measure the armature and the field currents, and a dc voltmeter to measure the motor terminal voltage. At start, the motor back emf, E_a, is zero and the starting current is very high. In order to limit the starting current, a $5\,\Omega$ resistor is inserted in the armature circuit.

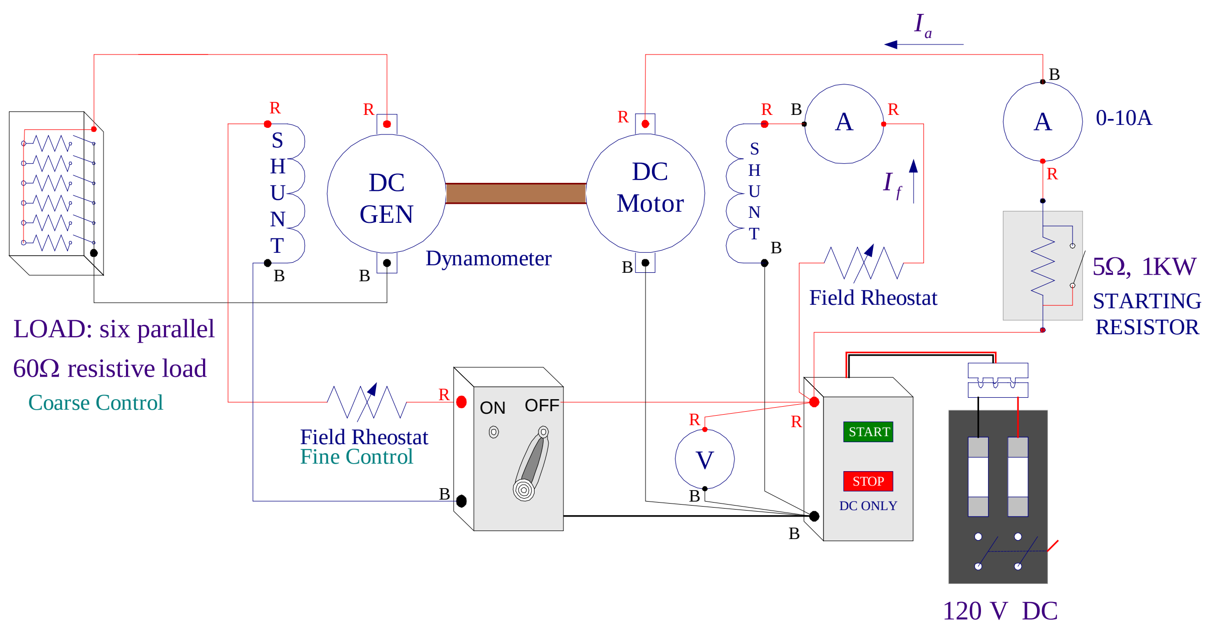


Figure 7.1 DC shunt motor connections

1.1 Speed Control

With starting resistance at the IN position and the field rheostat set for minimum resistance, start only the motor (Dynamometer is off). When the motor comes to speed, short the starting resistor. Note the direction of rotation (looking in from the motor end of the bench).

Direction of rotation=____________________

Observe the effect of changing the shunt field resistance on the motor speed. An increase in field resistance results in

____

Turn the starting resistance to the IN position and observe the effect of increasing the armature circuit resistance on the motor speed. An increase in armature circuit resistance results in

____

Turn the power off.

1.2 Reversal of direction of rotation of a dc motor

Investigate the effect on the direction of rotation for the following changes:

CAUTION: TURN THE POWER OFF WHEN MAKING ANY CHANGES. ALWAYS WHEN STARTING THE MOTOR MAKE SURE THE STARTING RESISTOR SWITCH IS TURNED TO THE **IN** POSITION AND THE FIELD RHEOSTAT IS SET FOR **MINIMUM** RESISTANCE.

a. Reverse the shunt field. Start the motor and observe the direction of rotation.

Direction of rotation = ________________________

b. Reconnect the shunt field as per original circuit, but reverse the armature connections. Start the motor and observe the direction of rotation.

Direction of rotation = ________________________

c. Reverse both the shunt field and armature connections. Start the motor and observe the direction of rotation.

Direction of rotation = ________________________

2. Shunt motor load characteristics

The shunt motor is loaded by means of the dynamometer. Connect the dynamometer as a separately-excited dc generator as shown in Figure 7.1.

If necessary, zero the dynamometer scale. With starting resistance at the IN position and the field rheostat set for minimum resistance, start the motor. When the motor comes to speed, short the starting resistor. With the dynamometer on no-load and its field winding open (dc supply off) adjust the dc motor field rheostat for no-load speed (with field rheostat set to its minimum value). Record the following data for the motor in Table 1: the dc supply voltage, armature current, field current, motor speed and the dynamometer pull. Keep the motor field rheostat constant through this test. Energize the dynamometer field and adjust its field rheostat for a generated emf in the range of 50-110 V (to observe the dynamometer voltage connect a voltmeter across the load bank). Using the load resistor for coarse adjustments and the dynamometer field rheostat for fine adjustment, load the motor in step until it draws an armature current of approximately 8 A. Record the indicated load data in Table 1.

Table I Shunt motor

Measured Data					Calculated Data				
V Volts	I_a Amps	I_f Amps	n RPM	Pull Kg	$I_L = I_a + I_f$ Amps	$P_i = VI_L$ Watts	Torque N-m	$P_o = \omega T$ Watts	η Percent

Evaluate the calculated data and enter in Table I.

CAUTION: TURN OFF POWER BEFORE MAKING ANY CHANGES

3. Cumulatively-compound motor

Connect the dc motor for long-shunt cumulatively-compound operation by inserting the series field between armature and the ammeter shown in Figure 7.2. The black terminal of the series field should be connected to the red terminal of the armature. Leave all other connections unchanged.

Zero the dynamometer scale. With starting resistance at the IN position and the field rheostat set for minimum resistance, start the motor. When the motor comes to speed, short the starting resistor. With the dynamometer on no-load and its field winding open (dc supply off) adjust the dc motor field rheostat for the same no-load speed as before. Record the no-load data in Table II. Keep the motor field rheostat constant through this test. Energize the dynamometer field and adjust its field rheostat for a generated emf in the range of 50-110 V. Using the load resistor for coarse adjustments and the dynamometer field rheostat for fine adjustment, load the motor in step until it draws an armature current of approximately 8 A. Record the indicated load data in Table II.

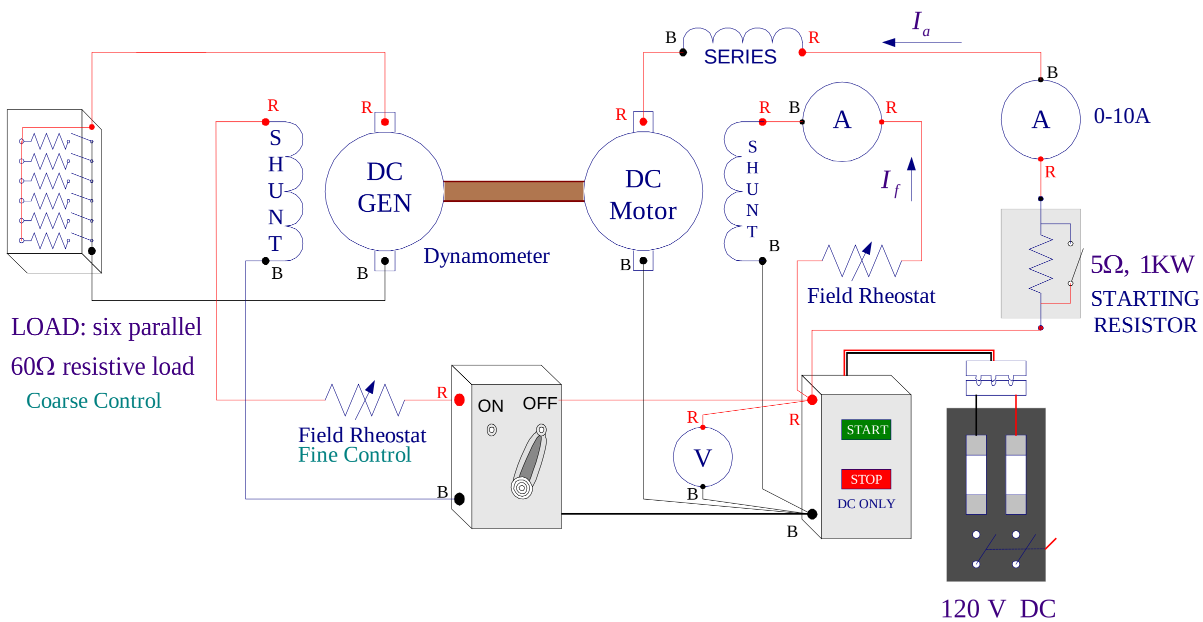


Figure 7.2 Circuit for long-shunt compound motor

Table II Cumulatively Compound Motor

Measured Data					Calculated Data				
V Volts	I_a Amps	I_f Amps	n RPM	Pull Kg	$I_L = I_a + I_f$ Amps	$P_i = VI_L$ Watts	Torque N-m	$P_o = \omega T$ Watts	η Percent

Evaluate the calculated data and enter in Table II.

Turn the power off.

4. Series motor

Remove the shunt field connection and connect the motor for series operation as shown in Figure 7.3.

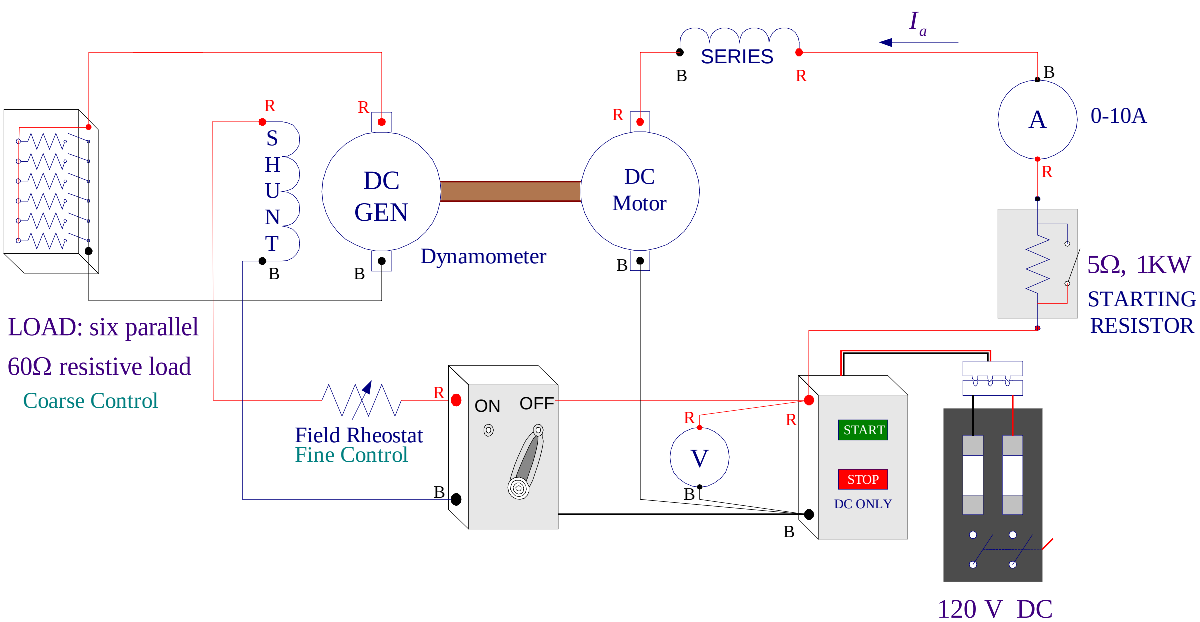


Figure 7.3 Circuit for series motor

A series motor at no-load will attain a dangerously high speed. To prevent overspeed, before starting the motor turn the dynamometer field supply on and leave one load resistor in. Start the motor. If the motor speed is too high add more load resistor on the dynamometer. Short the starting resistor. Adjust the load for an armature current of approximately 8 A. Record all the load data in Table III. Reduce the load in step until speed reaches almost 3000 rpm and at each step measure the readings. (Do not exceed 3000 rpm).

Table III Series Motor

Measured Data					Calculated Data				
V Volts	I_a Amps	$I_f = I_a$ Amps	n RPM	Pull Kg	$I_L = I_a$ Amps	$P_i = VI_L$ Watts	Torque N-m	$P_O = \omega T$ Watts	η Percent

Evaluate the calculated data and enter in Table III.

5. Use **ee340lab7** function as explained in the Appendix to check your computed data and obtain the required plots.

REPORT REQUIREMENTS

1. Discuss the observation made in part 1.1 and explain how speed above normal and below normal are obtained for a shunt motor driven from a constant dc voltage source. Is the result consistent with equation (7.4)?

2. In what two ways may the rotation of a shunt connected dc motor be reversed and which way is the preferred method?

3. Using (7.8) determine the percentage speed regulation at full-load for each type of connection and compare. For the purpose of this experiment, assume that the full-load armature current is 8 A.

4. Perform the indicated calculations in Tables I-III, and show sample calculations.

5. Plot speed versus torque for each motor on the same sheet. Compare speed torque characteristic for different connections, and explain the theoretical basis for the shape of all the curves. Refer to (7.6) and (7.7).

6. Plot torque versus armature current for each motor on the same sheet and discuss the curves.

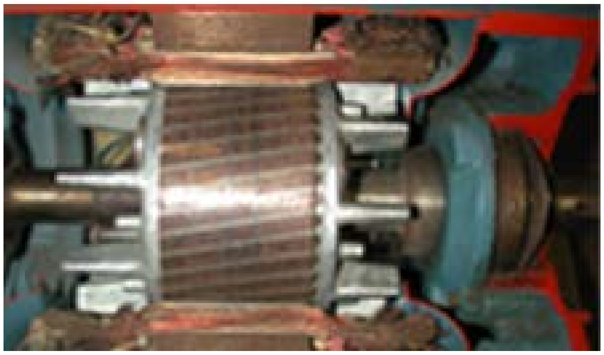
7. Plot efficiency versus output for each connection and discuss the motor efficiency.

Appendix

In MATLAB, from **F**ile/**N**ew/**M**-File, open the MATLAB Editor. Enter the data for the shunt excited dc motor in the $n \times 5$ matrix named Shunt. Each column represents a variable that must be entered in the order shown below. Enter the data for the remaining cases. Use the function named **ee340lab7** as indicated below to obtain the calculated data and the required plots. The function **ee340lab7** has been added to the MATLAB available on the MSOE network. If you have your own MATLAB student version you may download this function to your Laptop.

```
%          V        Ia        If        n        Pull
Shunt = [



                                                        ];

   %       V        Ia        If        n        Pull
Comp =  [




                                                        ];

 %         V        Ia        If        n        Pull
Series =[


                                                        ];
ee340lab7(Shunt, Comp, Series)
```

LABORATORY SESSION 8
SQUIRREL CAGE INDUCTION MOTOR CHARACTERISTICS



CAUTION: High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power must be turned off before the circuit is modified.

PURPOSE

The purpose of this experiment is to obtain the performance characteristics of a three-phase squirrel cage induction motor and to demonstrate the forward and reverse motor control using PLC. Become familiar with the use of a variable frequency AC drive.

DISCUSSION

Three-phase induction motors are by far the most widely used in industry. They constitute about 80% of the total number of motors used in industry. Three-phase induction motors are popular because they are more economical, last longer, and require less maintenance than other types of motors. The stator is composed of laminations of high-grade sheet steel. A three-phase winding is put in slots cut on the inner surface of the stator frame. The stator windings can be either wye- or delta-connected. The simplest and most widely-used rotor for induction motors is the squirrel cage rotor. A squirrel cage rotor consists of bare aluminum bars that are connected at their terminals to shorted end rings. The rotor bars are not parallel to the rotor axis but are set at a slight skew. This reduces mechanical vibrations, so the motor is less noisy.

The operation of three-phase induction motors is based on the generation of a revolving field, the transformer action, and the alignment of the magnetic field axis. When balanced three-phase currents are injected in the stator windings, a rotating magnetic field is created in the stator. To see a demonstration of the rotating magnetic field type **rotfield** at the MATLAB prompt. The speed of the stator revolving field is known as synchronous speed and the speed in rpm is given by

$$n_s = \frac{120 f_s}{p} \tag{8.1}$$

Where f_s is the supply voltage frequency and p is the number of poles, resulting from the stator winding design.

This revolving field cuts the rotor bars and generates voltages in them by electromagnetic induction. Because rotor bars are short-circuited, the induced voltages circulate currents in the rotor. The circulating rotor currents then produce their own revolving fields. The magnetic fields of the stator and rotor try to align their magnetic axes - a natural phenomenon - and in so doing, a torque is developed and the rotor will come up to speed. The rotor cannot revolve with the same speed as the stator revolving-field. Because if the rotor could be running at synchronous speed there would be no induced voltage in the rotor, no rotor current and no torque to overcome the rotational losses. The difference between the synchronous speed of the stator field (n_s) and the actual rotor speed (n_r) expressed to the base of synchronous speed is called the motor slip, i.e.

$$s = \frac{n_s - n_r}{n_s} \tag{8.2}$$

From (8.2) rotor speed can be expressed as

$$n_r = (1-s)n_s \tag{8.3}$$

Since the induced voltage in the rotor is proportional to the relative motion ($n_s - n_r$), the rotor voltage frequency is given by

$$f_r = sf_s \tag{8.4}$$

Which sets up a rotor field traveling with speed sn_s rpm with respect to the rotor. The speed of rotor field with respect to the stationary stator is the sum of this rotation and the rotor speed

$$sn_s + n_r = sn_s + (1-s)n_s = n_s \tag{8.5}$$

The stator and rotor fields are therefore stationary with respect to each other, and a steady torque is produced, and rotation is maintained.

When rotor is stationary, $s = 1$ and the rotor frequency is the same as the stator frequency. This is similar to the transformer action, and the rotor emf at standstill E_2, is proportional to the turns ratio. At any other speed the rotor emf is given by sE_2. Also, showing the rotor reactance per phase at standstill by X_2, when rotor is running its reactance is sX_2. In the squirrel cage rotor there is no access to the rotor circuit and the rotor resistance is constant. The torque-speed characteristic of an induction motor is directly related to the resistance and reactance of the rotor. Hence, different torque-speed characteristics may be obtained by designing rotor circuits with different ratios of rotor resistance to rotor reactance. In some special designs the rotor may have double squirrel windings, each with a different resistance. This construction gives higher starting torque, lower starting current, and higher full-load power factor. The National Electrical Manufacturers Association (NEMA) has developed a code by which a letter (A, B, C, or D) designates a particular class of motors with specific characteristics.

The analysis of the 3-phase induction motor is simplified by means of the per phase equivalent circuits. The per-phase equivalent circuit is shown in Figure 8.1 and is similar to the equivalent circuit of a transformer. The difference is that a variable resistance representing the mechanical load has been added. The resistance $R_2'(1-s)/s$ represents the gross mechanical load, including rotational losses. Note that the equivalent load resistance plus the rotor resistance is simply R_2'/s.

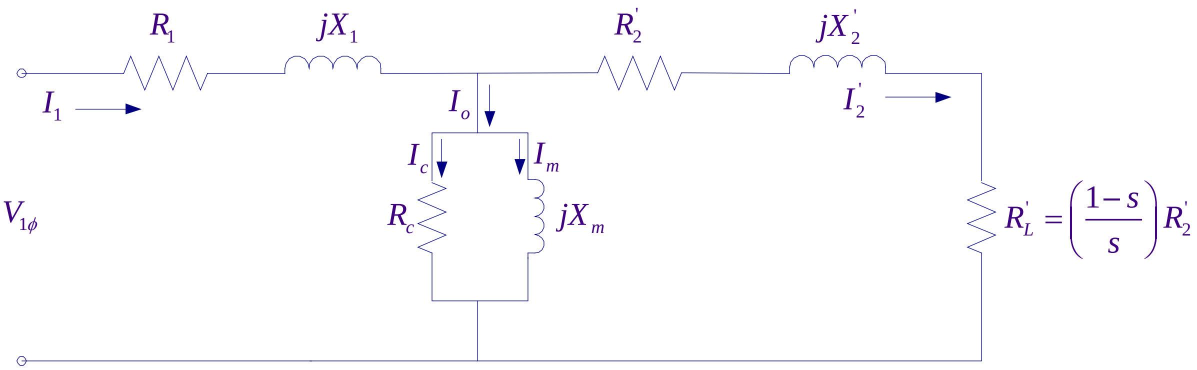


Figure 8.1 The per phase equivalent circuit of a three-phase induction motor

The cross mechanical power or internal power is

$$P_m = 3\frac{(1-s)}{s}R_2' I_2'^2 \tag{8.6}$$

and the power transferred to rotor or power across air-gap is

$$P_{ag} = 3\frac{R_2'}{s}I_2'^2 \tag{8.7}$$

and the internal torque is

$$T = \frac{P_m}{\omega_r} = \frac{P_{ag}}{\omega_s} = 3\frac{R_2'}{s\omega_s}I_2'^2 \tag{8.8}$$

The referred rotor current can be computed from the above equivalent circuit and thus the torque-slip relation can be obtained in terms of the circuit parameters. From this expression the slip at maximum torque and/or pullout torque can be computed. It can also be shown that, for a certain range of rotor resistance, the starting torque of the motor is proportional to the rotor resistance. The total input power to the motor is given by

$$P_i = 3V_{1\phi}I_1\cos\theta = \sqrt{3}V_L I_1\cos\theta \tag{8.9}$$

Where V_L is the supply line-to-line voltage, I_1 is the stator line current, and $\cos\theta$ is the motor power factor.

Three-phase power measurement - A single wattmeter can be used to measure the average power per phase of a three-phase balanced load if a neutral is available. The two wattmeters method is the most commonly used method for three-phase power measurements. The algebraic sum of the two-wattmeter readings equals the total average power absorbed by the load, regardless of whether it is wye- or delta-connected, balanced or unbalanced. When a neutral is not available. Consider two wattmeters connected as in Figure 8.2 to measure the power supplied to a balanced Y-connected load.

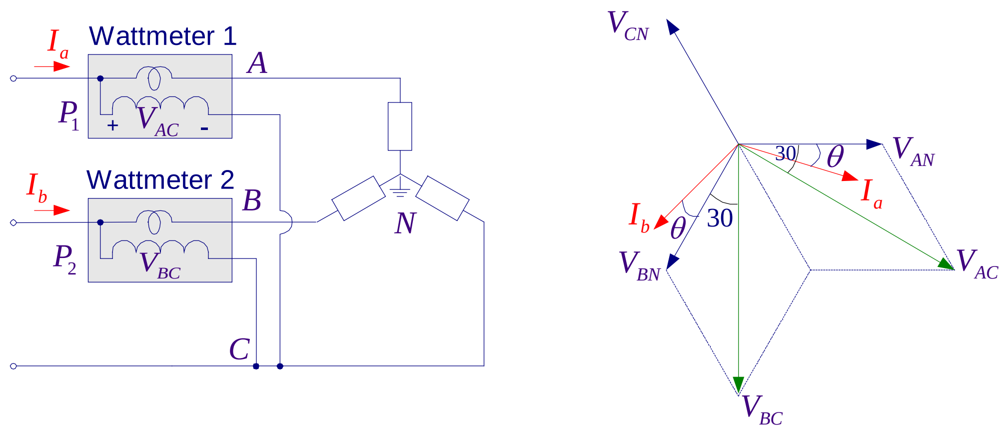


Figure 8.2 Two-wattmeter method for measuring three-phase power

Assume the source phase-sequence is abc and the load impedance is $Z = |Z| \angle \theta$. The wattmeter reads the product of the voltage across its potential coil times current in its current coil times the cosine of the phase angle between them. For a balanced load, if θ is the angle between the line current and the phase voltage as shown in Figure 8.2 (b), then for connection depicted in Figure 8.2(a), the wattmeter readings are:

$$\begin{aligned} P_1 &= V_{AC} I_a \cos(30^\circ - \theta) = V_L I_1 \cos(30^\circ - \theta) = V_L I_1 \left(\frac{\sqrt{3}}{2} \cos\theta + 0.5 \sin\theta \right) \\ P_2 &= V_{BC} I_b \cos(30^\circ + \theta) = V_L I_1 \cos(30^\circ + \theta) = V_L I_1 \left(\frac{\sqrt{3}}{2} \cos\theta - 0.5 \sin\theta \right) \end{aligned} \tag{8.10}$$

The sum of the two wattmeters is

$$P_1 + P_2 = \sqrt{3} V_L I_1 \cos\theta \tag{8.11}$$

This indeed is the three-phase power in a balanced system therefore if the above two wattmeters are properly connected to measure the power input to a three-phase induction motor, the total power input is given by

$$P_i = P_1 + P_2 \tag{8.12}$$

When power factor is less than 0.5, i.e. when $\theta > 60^\circ$, P_2 will indicate negative. From (8.11) the power factor can be computed.

$$pf = \cos\theta = \frac{P_i}{\sqrt{3} V_L I_1} \tag{8.13}$$

Or in (8.10) subtracting P_2 from P_1

$$P_1 - P_2 = V_L I_1 \sin\theta \tag{8.14}$$

From (8.11) and (8.14)

$$pf = \cos\theta = \cos\left[\tan^{-1}\left(\sqrt{3} \frac{P_1 - P_2}{P_1 + P_2} \right) \right] \tag{8.15}$$

The motor power factor depends on the operating load. At no-load referred rotor current is very small and the stator current is mainly a magnetizing component I_m and a small component due to stator iron loss I_c, thus the no-load power factor is very small, but as motor is loaded the power factor will improve.

The input power is given by (8.12). The output power is computed from the measurement of the dynamometer pull as follows:

$$T_o = \text{pull (Kg)} \times 9.81 \times \text{Arm radius (0.305 m)} \quad \text{N-m} \tag{8.16}$$

$$P_o = \omega_r T_o \quad \text{Watts} \tag{8.17}$$

Where, ω_r is the rotor speed in Rad/second given by, $\omega_r = \dfrac{2\pi n_r}{60}$ and n_r is the speed in RPM.

The motor efficiency is given by

$$\eta = \frac{P_o}{P_i} \times 100 \tag{8.18}$$

2. Reversing direction of rotation

In order to reverse the direction of rotation of an induction motor it is necessary to reverse the direction of the stator revolving field. This is done by simply interchanging two phases of the stator. A motor can be stopped by means of plugging. In this procedure when the motor is running two phases are interchanged. When the motor approaches zero speed the supply voltage is disconnected.

3. Variable Speed Drive

Induction motors are normally designed to work with a small value of slip (generally less than 5 percent) at full-load, and the deviation of the rotor speed from the synchronous speed is therefore small. There are certain applications, however, which require substantial variation of the rotor speed. The motor speed can conveniently be controlled by means of the variable frequency solid-state drives. Frequency-controlled induction motors are now comparable in cost with voltage-controlled dc motors for variable speed drives; the higher cost of the electronic controller is offset by the lower cost of the motor. Induction motors require little maintenance, and are better suited than dc motors to operation in hazardous or dusty environments.

Today, there is a relatively simple and economical way to covert 60 Hertz to a pseudo frequency that varies from almost zero Hz to at least 90 Hz. The actual waveform is not a sinusoidal wave, but is actually a very high frequency DC pulse whose width varies over the period of one-half of the cycle. The high inductance of the motor smooths out this waveform and allows the motor to function satisfactorily. Many schemes are used for producing a variable frequency supply.

The most commonly used adjustable speed motor drive technology is based upon the Pulse Width Modulation (PWM) inverter in which the three-phase 60 Hz AC line voltage is first rectified by a full-wave or a diode bridge rectifier and LC filter to form a single DC supply. Then solid-state transistors selectively fire as shown in Figure 8.3 and cause the waveform as shown in Figure 8.4 to be created. The output voltage is controlled by varying the on-off periods so that the on periods (pulse width) are longest at the peak of the wave. Figure 8.4 illustrates that by varying the width of the pulse the magnitude of the effective voltage can be varied. This variation over time can cause the output voltage to resemble a sine wave for each phase. The illustration is analytical since the number of pulses per second will be well over 5000. This will reduce the ripple in the motor currents and thus reducing the ripple in the electromagnetic torque.

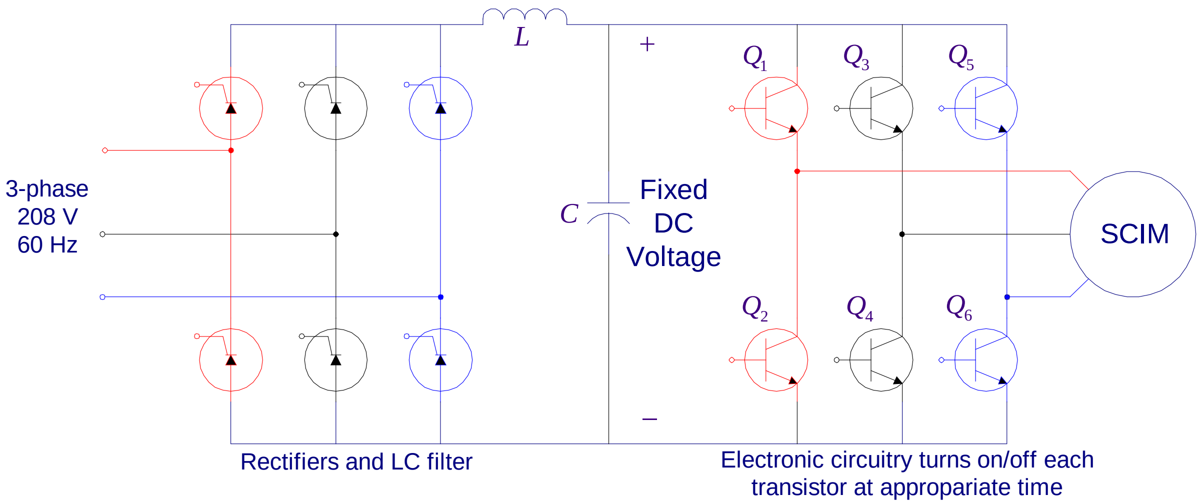


Figure 8.3 Basic rectifiers and PWM circuit diagram

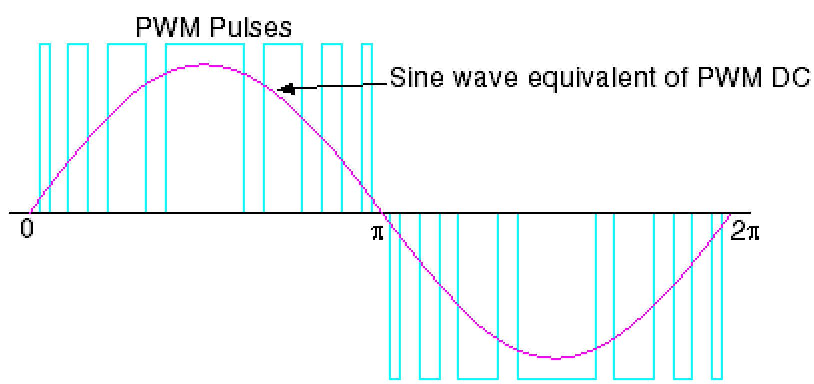


Figure 8.4 PWM waveform and its pseudo sine wave

PROCEDURE

1. PERFORMANCE CHARACTERISTICS

Check out the Fluke Power Quality Analyzer from the Technical Support Center.

Connect the induction motor to the 208V, three-phase supply as shown in Figure 8.5. Connect the red-shielded test lead (you may use ordinary lead) from the Power Quality Analyzer input 1 to the black terminal of the three-phase supply and a black lead from the COM terminal to the blue terminal of the thee-phase supply. This will provide V_{B-Blue} voltage for the wattmeter.
Connect the Current Probe to the meter input 2 and clamp the Current Probe around the lead connecting the supply black terminal to the motor black terminal. Be sure that the arrow marked on the jaw of the Current Probe points toward the direction of current (supply to load). This will

provide the current I_B for the wattmeter. The real power recorded with this connection is designated as P_1. Same meter is to be used to measure P_2 by moving the lead coming from input 1 and the current probe to the red phase and keeping the black test lead (COM) attached to the blue phase. To measure voltage and current open the main menu and select VOLTS/AMPS/HERTZ, and to measure Watt open the main menu and select POWER.

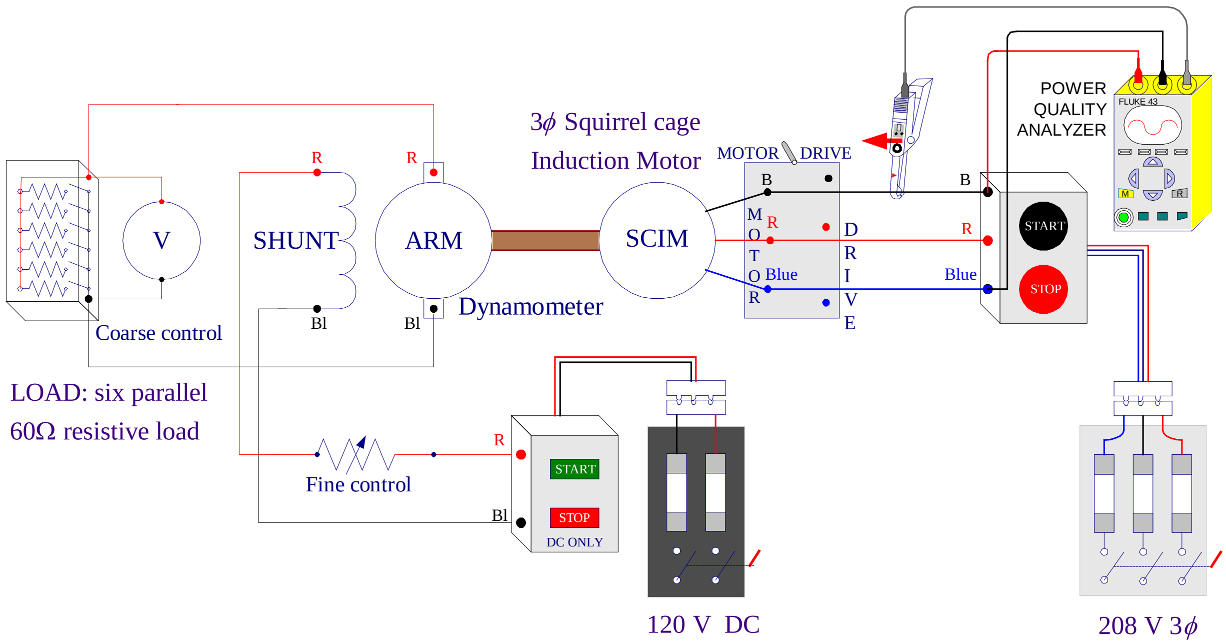


Figure 8.5 Circuit connections for induction motor and dynamometer

The induction motor is to be loaded by means of the dynamometer. Connect the dynamometer as a separately-excited dc generator as shown in Figure 8.5.

Zero the dynamometer scale. Start the induction motor. With the dynamometer on no-load and its field winding open (dc supply off) record the following data for the motor in Table 1: input line-to-line voltage, stator current I_1, real power reading P_1, motor speed and the dynamometer pull. Move the red test lead (Coming from input 1) and the Current Probe to the red phase (keep the black test lead (COM) attached to the blue phase. Be sure that the arrow marked on the jaw of the Current Probe points toward the direction of current (supply to load). This will provide V_{R-Blue} and the current I_{Red} for the wattmeter. Measure the real power and record it in Table I as P_2.

At no-load, the motor power factor is low, if $\theta > 60^{\circ}$ according to (8.10), one wattmeter (P_2) will read negative. When the motor power factor is 0.5, ($\theta = 60^{\circ}$), P_2 will read zero and P_1 will indicate the total power taken by the motor. As the motor is loaded more, its power factor will become greater than 0.5 and both wattmeter readings will be positive.

Using the load resistor for coarse adjustments and the dynamometer field rheostat for fine adjustment, load the motor in step until it draws the full-load current. Repeat the above procedure and at each step record the phase current I_1, the real power measurements P_1 and P_2, motor speed and dynamometer pull in Table I. Record the synchronous speed as given by (8.1).

$n_s =$________________

TABLE I Data for determination of SCIM characteristics

Measured Data						**Calculated Data**					
V_{L-L} V	I_1 Amps	P_1 Watts	P_2 Watts	n_r RPM	Pull Kg	$P_i = P_1 + P_2$ Watts	T_o N-m	$P_O = \omega T$ Watts	$s = \frac{n_s - n_r}{n_s}$	pf (8.15)	η %

Stop the motor, and disconnect it from the 208V. Evaluate the calculated data and enter in Table I.

Use **ee340lab8** function as explained in the Appendix I to check your computed data and obtain the required plots.

2. FORWARD AND REVERSE MOTOR CONTROL CIRCUIT

In many controller applications the motor must be operable in both forward and reverse directions. Interchanging two phases of the stator connections to the three-phase supply will reverse the stator revolving field and the direction of rotation of the rotor. The requirement is that the motor be able to start and stop in either the forward or reverse direction and that the stop pushbutton be pressed in order to change from forward to reverse or from reverse to forward. Interlock must be provided so that both starters cannot be energized at the same time.

The ladder logic shown in Figure 8.6 provides start and stop in the forward direction and in the reverse direction. Only one stop pushbutton is used to stop the motor, regardless of the direction in which it is running. The normally closed contact C0 in the third rung will be opened whenever OUTPUT_C0 in the second rung is energized, thus preventing OUTPUT_C1 in the third rung from being energized at the same time. Similarly, the normally closed contact C1 in the second rung will be opened whenever OUTPUT_C1 in the third rung is energized, thus preventing OUTPUT_C0 in the second rung from being energized at the same time.

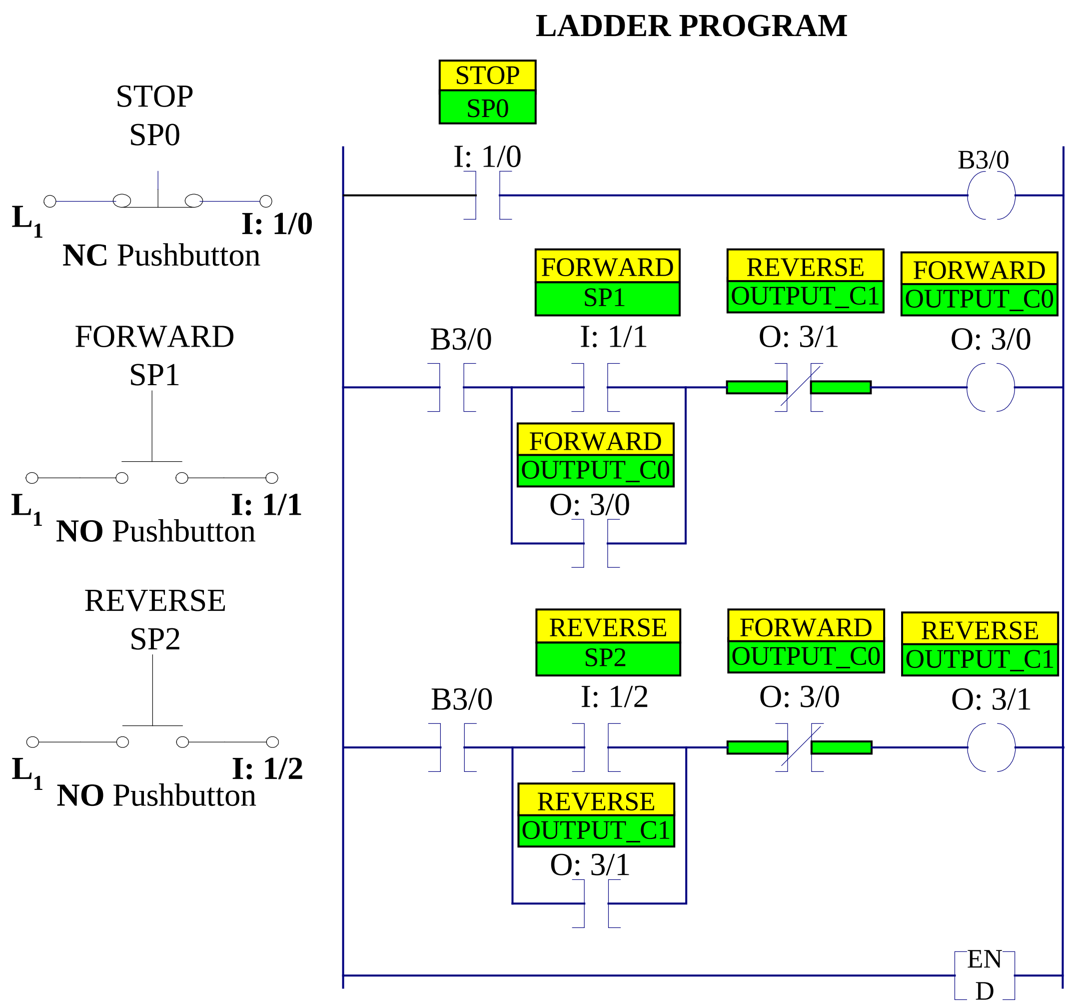


Figure 8.6 Ladder diagram for forward and reverse motor control

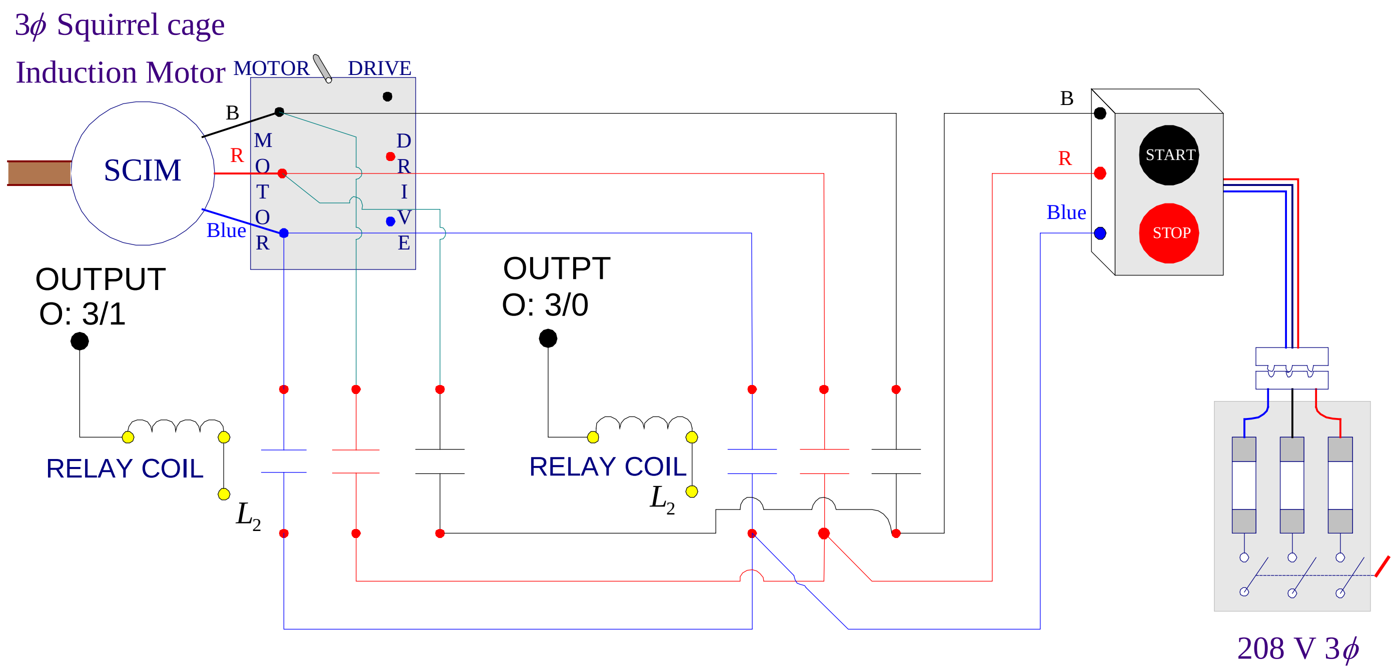


Figure 8.7 Circuit connections for forward and reverse motor control.

Program the ladder diagram shown in Figure 8.6 using RSLogix 500 software (refer to Laboratory Session 1 section 2.3 EDITING LADDER LOGIC). Connect the input circuit using three pushbuttons. Disconnect the dynamometer. Use the three-phase contactors C0 and C1 to connect the induction motor to the 208 V, three-phase supply. Connect the contactor yellow terminals to the related output addresses as shown in Figure 8.7. After I/O circuits and your ladder logic program have been checked by the instructor turn on the Processor Main Power. Follow the procedure in part 2.4 and 2.5 in Experiment # 1 to download the program to SLC-500 and demonstrate its operation in Test and run mode.

3. Variable Speed Drive

For a description of the MagneTex InteliPac 100 Digital Operator Display refer to Appendix II. For more information check out the InteliPac 100 Technical Manual.

Connect the three-phase 208 V supply to the AC Drive terminals and turn the switch to the DRIVE position. Turn on input power to the InteliPac 100. The digital display will indicate the FREF (frequency reference) setting with the operator display status flashing 6.0. Go through the following steps while the motor is running:

- Press the **DSPL** key until the **FREF** is illuminated, if the frequency displayed is not 60 Hz press $\wedge$ or $\vee$ key until Digital Operator display reads 60 Hz and press **ENTER** key to keep the setting. Note the input frequency and measure the motor speed.

- Press the **DSPL** key until the **FMAX** is illuminated, press $\wedge$ key until Digital Operator display reads 85 Hz. Press the **ENTER** key. Press the **DSPL** key until **FREF** is illuminated, increase the frequency to a higher value (say 80 Hz), press the **ENTER** key. Note the frequency and measure the motor speed.

- Press the **DSPL** key until **FREF** is illuminated decrease the frequency to a lower value (say 40 Hz), press the **ENTER** key. Note the frequency and measure the motor speed.

- Press **DSPL** until **F/R** (FWD/REV selection) is illuminated, press $\wedge$ or $\vee$ to display **rEU** for reverse and press **ENTER** and then press **RUN.** Not how the motor will decelerate and run in the reverse direction. Reset all the functions to their original setting and press **STOP** to stop the motor.

There are many factory settings for all the parameters on the drive. Modifications include changing display, acceleration, deceleration, etc. Following are examples of two methods for setting the acceleration time (**n20**). The first example shows how to utilize the ACC function LED, and the second example shows how to access constant **n20** through the **PROGM** function LED when the drive is stopped.

Example 1: Using **ACC** LED

	Display
• Press the **DSPL key** until the **ACC** led is illuminated.	10.0
• To set the acceleration time to 5 seconds, press the $\vee$ key until the Operator Digital display reads 5.0	5.0
• Press the **ENTER** key.	5.0
• Press **RUN** and observe how the motor accelerates to the running condition. Stop the motor.	

Example 2: Using **PRGM** LED

• Press **DSPL** key until the **PRGM** LED is illuminated.	n01
• Press the $\wedge$ key to access constant **n20**.	n20
• Press the **ENTER**. The current set value is displayed.	5.0
To set the acceleration time to 15 seconds, press $\wedge$ key until Digital Operator display reads 15.0.	15.0
• Press the **ENTER** key.	n20
• Press the **DSPL** key until the **FREF** LED is illuminated.	60.0
• Press **RUN** and observe how the motor accelerates to the running condition. Stop the motor.	

- Set the acceleration to the default setting (10.0).

REPORT REQUIREMENTS

1. Using Equations (8.13)-(8.18) calculate the load torque, power output, power input, power factor and efficiency of the induction motor from measured data at each loading. Show sample calculations. Power factor can be computed either by (8.13) or (8.15).

2. Plot on one graph curves of stator current and torque versus speed. On a second graph, plot curves of power factor and efficiency versus speed. Explain the theoretical basis for the shape of all the curves. Explain the reason why the power factor is low at no-load.

3. Outline the step-by-step sequence of operation for the forward and reverse motor control circuit. Interlocking has been provided by means of two NC contacts so that both starters cannot be started at the same time. What would happen if this were not included in the ladder logic diagram?

4. One of the popularity of the dc motor in the industry in the past has been the ease with which the speed of a dc motor can be changed. Is a wide range of speed control possible with a squirrel cage induction motor driven by a constant frequency supply? State how the starting and speed control of induction motors are achieved and why induction motors have gained overwhelming popularity in industry and applications requiring variable speed operation.

5. Briefly discuss the observation made in part 3 using the MagneTex AC drive with some concluding remark.

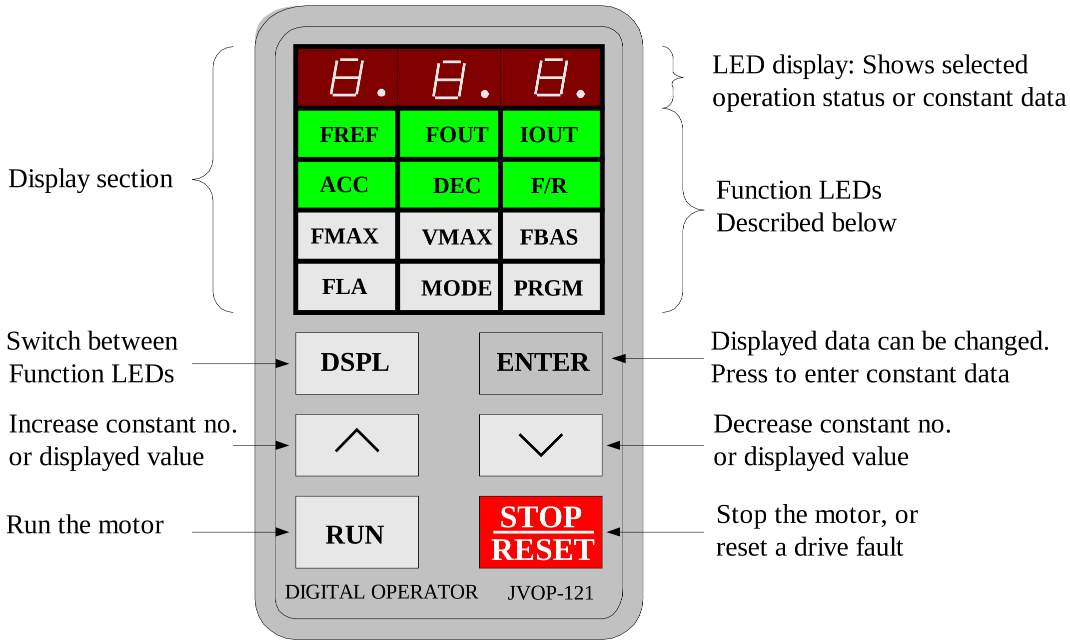
Appendix I

In MATLAB, from **F**ile/**N**ew/**M**-File, open the MATLAB Editor. Enter the data for the squirrel cage induction motor in the $n \times 6$ matrix named IMinput. Each column represents a variable that must be entered in the order shown below. Use the function named **ee340lab8** as indicated below to obtain the calculated data and the required plots. The function **ee340lab8** has been added to the MATLAB available on the MSOE network. If you have your own MATLAB student version you may download this function to your Laptop.

```
%          V      I1      P1      P2      n      Pull
IMinput = [



                                                      ];
ee340lab8(IMinput)
```

Appendix II

InteliPac 100 Digital Operator Display



LED Description

By pressing the **DSPL** key on the Digital Operator can step to each of the twelve function LEDs. While the drive is running only the first six (GREEN) function LEDs can be selected.

FREF — Frequency Reference Setting [constant **n11**]: Sets the frequency Hz or (speed).

FOUT — Output Frequency Monitor: Displays the output frequency (monitor only).

IOUT — Output current Monitor: Displays the output current (monitor only)

ACC — Acceleration Time [constant **n20**]: Sets the time (seconds) it will take the drive to accelerate the motor from standstill to maximum output frequency.

DEC — Deceleration Time [constant **n21**]: Sets the time (seconds) it will take the drive to decelerate the motor from the maximum output frequency to standstill.

F/R — FWD/REV Run Selection [constant **n04**]: Sets the rotation direction of the motor when a run command is given by the Digital Operator

FMAX —. Maximum Output Frequency {constant **n24**]: Sets the maximum output frequency (Hz) of the drive.

VMAX —. Maximum Voltage {constant **n25**]: Sets the maximum voltage (V) that can be output from the drive.

FBAS —. Maximum Voltage Output Frequency {constant **n26**]: Sets the frequency at which the maximum output voltage level is reached.

FLA —. Electronic Thermal Reference Current [constant **n31**]: Sets the motor overload.

MODE —. Operation Mode Selection [constant **no2**]: Selects the operation from the Digital Operator or Control Circuit Terminals.

PRGM —. Constant Programming: Selects or reads constant data using constant numbers (nxx). Constant data is displayed by pressing the **ENTER** key, and can be changed by pressing $\wedge$ or $\vee$ keys. Any change can be saved by again pressing the **ENTER** key. Pressing the **DSPL** key exits from programming mode.

LABORATORY SESSION 9
WOUND ROTOR INDUCTION MOTOR CHARACTERISTICS

CAUTION: High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power must be turned off before the circuit is modified.

PURPOSE

The purpose of this experiment is to obtain the performance characteristics of a wound rotor induction motor and to show that the wound rotor motor can be used as a power source of variable voltage and frequency.

DISCUSSION

For the discussion on the principle operation of induction motor, its equivalent circuit and formulas refer to Experiment # 8 on the squirrel cage induction motor.

A very small percentage of induction motors have a wound rotor. A wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator. The three phases of the rotor windings are usually Y-connected, and the ends of the three rotor wires are tied to slip rings on the rotor's shaft on which the brushes rest. The brushes can then be connected to a three-phase variable resistor and the resistance of the rotor winding can be externally controlled. This variable resistor controls the torque-speed characteristics of the motor. As the rotor circuit resistance is increased, the pullout speed of the rotor deceases, but the maximum torque remains constant. The external resistance can be adjusted to make the maximum torque occur at starting conditions. This external resistance can be decreased as the motor speeds up, making the maximum torque available over the whole accelerating range. Induction machines with wound rotors are used for special applications, but because they are less efficient at higher slips, they are being replaced by squirrel-cage induction motor with variable-speed drives.

Three-phase wound rotor induction machines can be used to furnish, at their slip-ring terminals, a three-phase source of variable voltage and frequency. For this application, the induction machine is connected to a normal voltage and frequency supply and is driven by a variable-speed motor as shown in Figure 9.1. The voltage induced in the rotor, and its frequency, are directly proportional to the operating slip.

$$E_r = sE_2 \tag{9.1}$$

$$f_r = sf_s \tag{9.2}$$

Where E_2 is the rotor emf when motor is at standstill, and f_s is the stator frequency. When the rotor is running in the same direction as its synchronously rotating magnetic field, the slip is

$$s = \frac{n_s - n_r}{n_s} \tag{9.3}$$

For small slip the rotor frequency is low. If the direction of the synchronously rotating magnetic field is opposite to the rotor direction, the slip is

$$s = \frac{-n_s - n_r}{-n_s} = 1 + \frac{n_r}{n_s} \tag{9.4}$$

The slip will be greater than unity, the rotor voltage will be larger and its frequency will be larger than that of the stator. The slip rings of the wound rotor can thus become a power source of variable voltage and frequency.

PROCEDURE

1. Induction Frequency Changer

Connect the dynamometer as a shunt motor. Connect the induction motor stator terminals to the three-phase supply and the ScopeMeter to two of the rotor slip ring terminals as shown in Figure 9.1.

(a) Turn on the three-phase ac power supply. With the motor at standstill (dc power off) measure the standstill rotor emf

$E_2 =$ _______________

(b) With the dc motor starter resistance in and the field rheostat set for minimum value, start the dc motor. Adjust the dc motor speed by means of the field rheostat at a low value, say 1400 rpm and record rotor voltage and frequency in Table I. Adjust the dc motor speed to higher values, around 1500, 1600, 1800, 1900 rpm and record the corresponding rotor voltage in Table I.

(c) Turn the power off, and interchange any two of the three-phase leads to the induction motor stator. Make sure the dc motor starter is in and the field rheostat is at its minimum value. Start the dc motor; turn on the three-phase power supply. Repeat the measurements in part (b) and record in Table I.

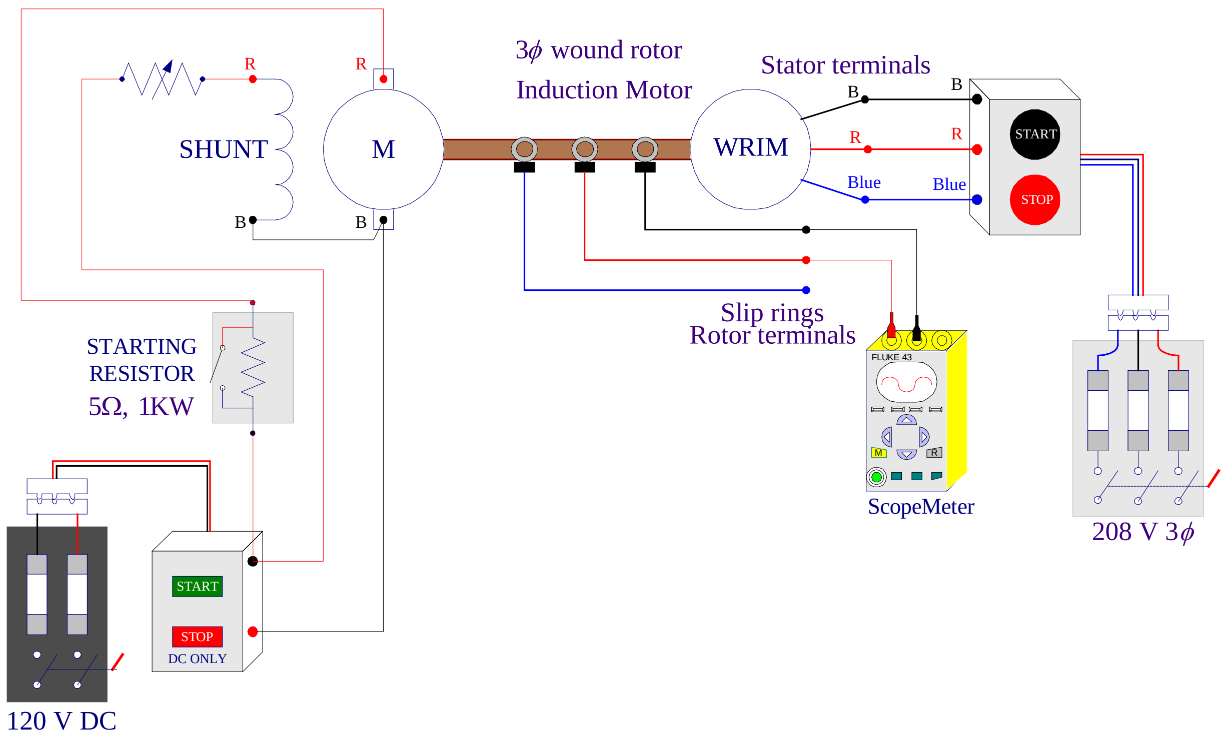


Figure 9.1 Induction frequency changer

Table I

Direction of rotating magnetic field	Measured Data			Calculated Data		
	Speed RPM	E_r Volt	f_r Hz	Slip s	$E_r = \|s\| E_2$ Volt	$f_r = \|s\| f_s$ Hz
Same as the rotor direction						
Opposite the rotor direction						

2. PERFORMANCE CHARACTERISTICS

Check out the Fluke Power Quality Analyzer from the Technical Support Center.

Connect the induction motor to the 208V, three-phase supply as shown in Figure 9.2. Connect the red-shielded test lead (you may use ordinary lead) from the Power Quality Analyzer input 1 to the black terminal of the three-phase supply and a black lead from the COM terminal to the blue terminal of the thee-phase supply. This will provide V_{B-Blue} voltage for the wattmeter. Connect the Current Probe to the meter input 2 and clamp the Current Probe around the lead connecting the supply black terminal to the motor black terminal. Be sure that the arrow marked on the jaw of the Current Probe points toward the direction of current (supply to load). This will provide the current I_B for the wattmeter. The real power recorded with this connection is designated as P_1. Same meter is to be used to measure P_2 by moving the lead coming from input 1 and the current probe to the red phase and keeping the black test lead (COM) attached to the blue phase. To measure voltage and current open the main menu and select VOLTS/AMPS/HERTZ, and to measure Watt open the main menu and select POWER.

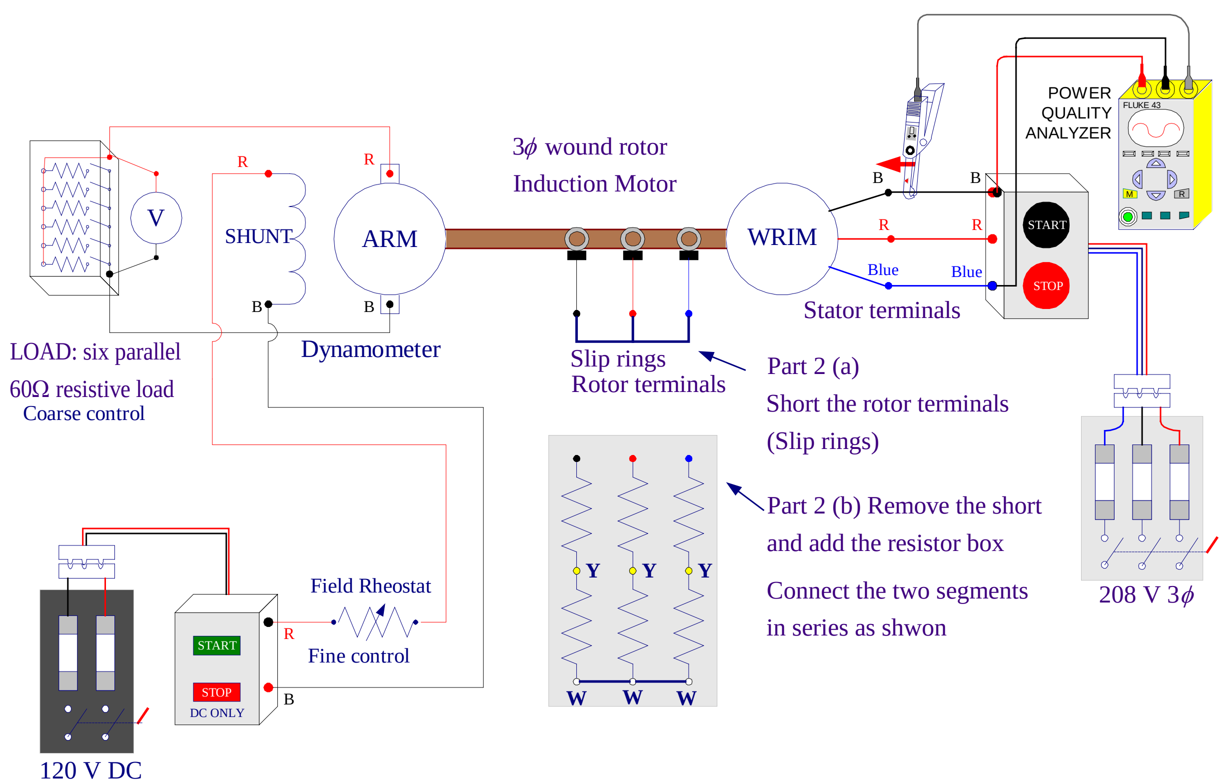


Figure 9.2 Circuit connections for wound rotor induction motor and dynamometer.

The induction motor is to be loaded by means of the dynamometer. Connect the dynamometer as a separately-excited dc generator as shown in Figure 9.2.

(a) No external rotor resistance

Short the rotor terminals (no external rotor resistance). Zero the dynamometer scale. Start the induction motor.

Zero the dynamometer scale. Start the induction motor. With the dynamometer on no-load and its field winding open (dc supply off) record the following data for the motor in Table 1: input line-to-line voltage, stator current I_1, real power reading P_1, motor speed and the dynamometer pull. Move the red test lead (Coming from input 1) and the Current Probe to the red phase (keep the black test lead (COM) attached to the blue phase. Be sure that the arrow marked on the jaw of the Current Probe points toward the direction of current (supply to load). This will provide V_{R-Blue} and the current $I_{\mathrm{Re}d}$ for the wattmeter. Measure the real power and record it in Table I as P_2.

At no-load, the motor power factor is low, if $\theta > 60^{\circ}$ according to (8.10), one wattmeter (P_2) will read negative. When the motor power factor is 0.5, ($\theta = 60^{\circ}$), P_2 will read zero and P_1 will indicate the total power taken by the motor. As the motor is loaded more, its power factor will become greater than 0.5 and both wattmeter readings will be positive.

Using the load resistor for coarse adjustments and the dynamometer field rheostat for fine adjustment, load the motor in step until it draws the full-load current. Repeat the above procedure and at each step record the phase current I_1, the real power measurements P_1 and P_2, motor speed and dynamometer pull in Table I. Record the synchronous speed.

Stop the motor, and disconnect it from the 208V. Evaluate the calculated data and enter in Table I.

(b) External resistance added in the rotor circuit

Place the three-phase resistor board in the rotor circuit as shown in Figure 9.2. Start the motor and repeat the above procedure and record the measurements in Table II.

$n_s =$ _______________

TABLE I Data for determination of WRIM characteristics

Measured Data						**Calculated Data**					
V_{L-L} V	I_1 Amps	P_1 Watts	P_2 Watts	n_r RPM	Pull Kg	$P_i = P_1 + P_2$ Watts	T_o N-m	$P_O = \omega T$ Watts	$s = \frac{n_s - n_r}{n_s}$	pf (8.15)	η %

TABLE II Data for determination of WRIM characteristics with external rotor resistance

Measured Data						**Calculated Data**					
V_{L-L} V	I_1 Amps	P_1 Watts	P_2 Watts	n_r RPM	Pull Kg	$P_i = P_1 + P_2$ Watts	T_o N-m	$P_O = \omega T$ Watts	$s = \frac{n_s - n_r}{n_s}$	pf (8.15)	η %

Stop the motor, and disconnect it from the 208V. Evaluate the calculated data and enter in Table II.

3. Use **ee340lab9** function as explained in the Appendix to check your computed data and obtain the required plots.

REPORT REQUIREMENTS

1. Using (9.3) and (9.4) compute the slip and from (9.1) and (9.2) compute the rotor emf and frequency, record in table I and compare with the measured values. Discuss the application and disadvantages of the induction frequency changer and explain by what means a modern variable frequency supply is obtained these days.

2. Using Equations (8.13)-(8.18), calculate the load torque, power output, power input, slip, power factor and efficiency of the induction motor from measured data at each loading. Show sample calculations.

3. Plot on one graph curves of stator current and torque versus speed. On a second graph, plot curves of power factor and efficiency versus speed. Draw the results with added rotor resistance on same graphs. Explain the theoretical basis for the shape of all the curves. Discuss the effect of adding rotor resistance on the motor characteristics.

Appendix

In MATLAB, from **F**ile/**N**ew/**M**-File, open the MATLAB Editor. Enter the data for the wound rotor induction motor part 2(a) and (b) in two $n \times 6$ matrix named WRIM1 and WRIM2. Each column represents a variable that must be entered in the order shown below. Use the function named **ee340lab9** as indicated below to obtain the calculated data and the required plots. The function **ee340lab9** has been added to the MATLAB available on the MSOE network. If you have your own MATLAB student version you may download this function to your Laptop.

```
%       V       I1       P1       P2         n        Pull
WRIM1=[



                                                              ];

WRIM2=[



                                                              ];
ee340lab9(WRIM1, WRIM2)
```