

BAE 462:
Electric Power and
Controls

Laboratory
Exercises
2017

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Lab 1: Introduction to electrical tools, their uses and safety

Name(s) _____

Introduction

The first thing with electricity is to know the proper use of tools and understand the safety. This lab will help you understand proper use of basic tools involved with electrical wiring, and safety measurements.

Objectives

1. To become familiar with electrical tools their proper uses and safety.
2. Be able to do common electrical tasks properly.

Common items in an electrical toolbox

You will identify the following basic tools and learn about their uses in this lab

- | | | |
|---|---|---|
| 1. Safety glasses  |  | 11. Nose pliers  |
| 2. Safety gloves  |  | 12. Diagonal pliers  |
| 3. Digital multimeter (DMM) |  | 13. Linesmen pliers  |
| 4. Receptacle, CB and GFCI tester |  | 14. Screw driver set  |
| 5. Watt meter/power logger |  | 15. Hammer  |
| 6. Live wire tester |  | 16. Crescent wrench  |
| 7. Wire stripping tool |  | 17. Flash light  |
| 8. Wire connectors (wire nuts) |  | 18. Nonmetallic cable sheath splitter  |
| 9. Electrical tape | | 19. Wire gauge tester  |
| 10. Utility knife | | 20. Lock-out tag-out  |

Safety:

1. Wear safety glasses whenever you cut or work with wire as small piece of wire can fling out and hit your own or someone else's eye.
2. Wear insulating shoes or stand on a rubber mat while working with electricity for added protection.
3. Test to confirm the circuit is not live before you start working.
4. Use lock-out tag-out to the control panel from where the circuit may be unknowingly activated.
5. Use electrical resistant gloves when possible. Wearing insulated glove even in one hand is better than no gloves, as this will minimize risk of electricity flowing through your chest.
6. Do not turn ON the power to your circuit without making sure there are no short circuits. Use continuity tester (in DMM) without a load to detect the short circuit.
7. Develop a sense of what is safe and what is not safe based on principles and develop a safe working habit.
8. Use common sense and be extremely careful not to make any electrical path through your body.

Know your electrical tools

DMM: Used to measure voltage, current, resistance and to test for continuity, and diode polarity. Make sure the terminals are correctly connected before testing for current.

Receptacle Tester: Use this tool to detect the fault condition on a 120 V, single phase common household receptacle. Use the combination of light signals (usually 3) as shown on the tester itself to diagnose the fault condition. The common fault conditions are: Open (not connected) ground, open neutral, open hot, hot/ground reversed, and hot/neutral reversed.

GFCI tester: GFCI receptacles turn off the power when it detects current leak. Current leak happens during electrocution to ground, hence preventing accidents. GFCI enabled receptacles are found near wet areas such as sinks or outdoor. GFCI receptacle usually has a built in test circuit, but if not, an external GFCI tester can be used. The tester simulates the electrical leak through a high resistance from live wire to the ground when test button is pressed.

Live wire tester: There are two types of live wire tester one is conductive type and another is capacitive type. Capacitive type are non-contact, meaning no direct contact with live wire is needed for this to work.

Practice using tools:

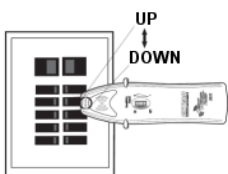
9. Use a diagonal pliers to cut off about 1 foot of 14/2 with ground cable from the cable roll.
10. Use wire stripper to strip off about ½ inch of #14 AWG wire (both black and white).
11. Use the nose pliers to make a '?' shaped loop from the bare ground wire. Show the loop to your instructor.
12. Connect the wire ends to a provided 10 AMP receptacle.
13. Strip off about ½ inch of insulation from other end of cable as well.
14. Use receptacle tester to check for the faulty outlet. There are four faulty receptacles on the bench marked 1,2,3 and 4. Find the type of fault for each receptacle:

Receptacle #	Fault type	Receptacle #	Fault type
1		2	
3		4	

1. Use non-contact live wire tester to find in the outlets are live.

Receptacle #	Live/Not Live	Receptacle	Live/Not Live
1		2	
3		4	

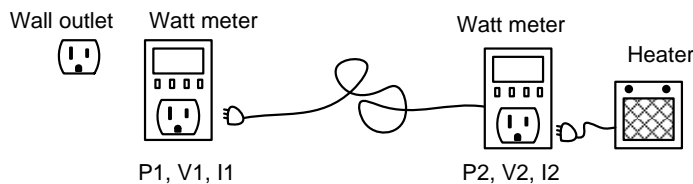
2. Use Ground Fault Circuit Interrupt (GFCI) tester to test a GFCI outlet for its proper operation.
3. Use Circuit Breaker (CB) Finder to find the circuit breaker for one of the electrical outlets.
 - a. Plug the Transmitter / Receptacle Tester into a powered outlet. The two green LED's should illuminate.
 - b. Rotate the Receiver's Sensitivity adjustment from the OFF position to the HI position. The red LED should turn on.
 - c. Test the operation of the Receiver by placing it in close proximity to the transmitter. The receiver should beep and the LED should flash.
 - d. At the breaker panel, set the sensitivity to the HI position and hold the receiver as indicated by the "UP – DOWN" label.



- e. Move the receiver along the row of breakers until the selected circuit is identified by the beep and flashing light.
- f. Reduce the sensitivity as needed to pinpoint the exact circuit breaker controlling the circuit.
- g. Note down the circuit breaker # corresponding to the outlet_____

Measurements

4. Use a DMM to test circuit continuity for the extension cable and measure the one-way wire resistance of the 100 ft, #16 cables.
5. Use DMM to measure heater resistance when cold.
6. Connect the circuit as follows and let the heater run until you get relatively steady measurements and the heater is hot.



P1=_____W	P2=_____W
V1 =_____V	V2=_____V
I1 =_____A	I2 =_____A
Rh(cold) =____	Rh(hot)=_____

7. Disconnect the heater when it is still hot and measure the heater resistance. Compare this resistance with cold resistance.
8. Note the V2 after the heater is disconnected.

Calculations:

1. Compare the resistance of the measured 100 ft wire to the calculated value as in the class example. Ignore temperature effect.
2. Use measured values when heater is running to calculate the power loss in the cable. What is the power transmission efficiency of this cable heater system?
3. Compare the heater's rated power to the actual power consumed and comment if there is any significant difference in two.

Discussions

4. Discuss the measures you can take to increase the system efficiency on your lab report.
5. If you have a choice of using 50' or 100' of similar extension cables to operate the same piece of equipment, which one would you chose? Explain why?
6. Turn in your group lab report with your observations and discussions.
7. Follow the Transactions of the ASABE Journal writing format (download a template form bblearn)

Lab 2: Understanding, measuring and correcting for Power Factor

Name _____ (Feel free to use the data from your group, but do your own calculations and turn it in as your lab report for this lab)

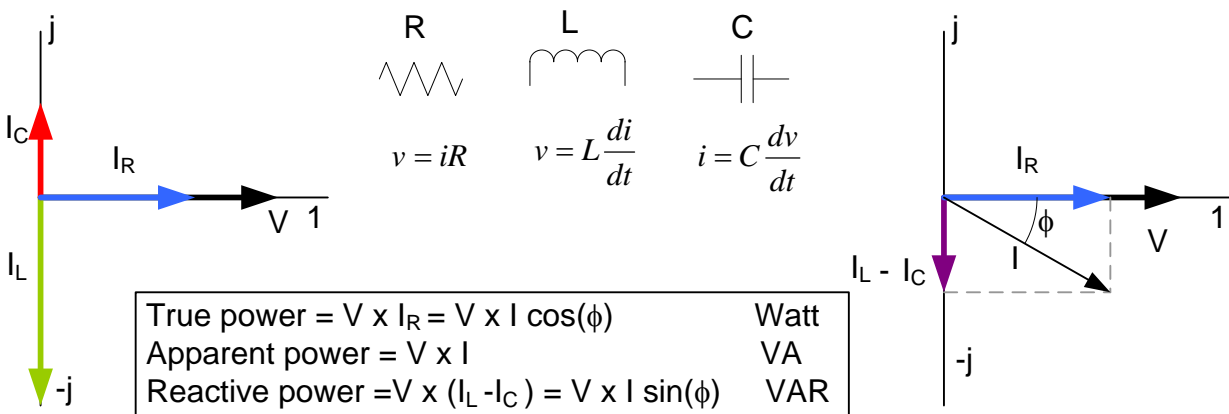
Objectives:

- To understand the power factor
- To measure the power factors and take necessary action to improve the power factor

Introduction

The '**power factor**' of an AC electric power system is defined as the ratio of the real power to the apparent power. Real power is average of power used by the load and measured in Watt. Real power is the product of voltage and the in-phase current. Apparent power is the product of voltage and current (RMS values) and has the unit of volt-ampere (VA). The apparent power does not take account of the phase-angle between volt and current. Therefore, apparent power is always \geq true power. Reactive power is the product of voltage and the quadrature current and is measured in VAR (Volt Ampere Reactive).

$$\text{Power Factor} = \frac{\text{True power (W)}}{\text{Apparant Power (VA)}}$$



Note that, even though the true power for inductive or capacitive circuit was zero, the current in the circuit was not zero. Non-zero current means there would be some transmission losses. For a circuit with combination of resistive and reactive circuit, the power factor will be between zero and one. The closer the power factor to one, the more efficient the power transmission would be.

Lab work

Measure the power factor for a given motor (mostly inductive circuit) and a heater using *the supplied watt meter*.

1. Connect a heater to the watt meter and record the frequency, power factor, voltage and the current

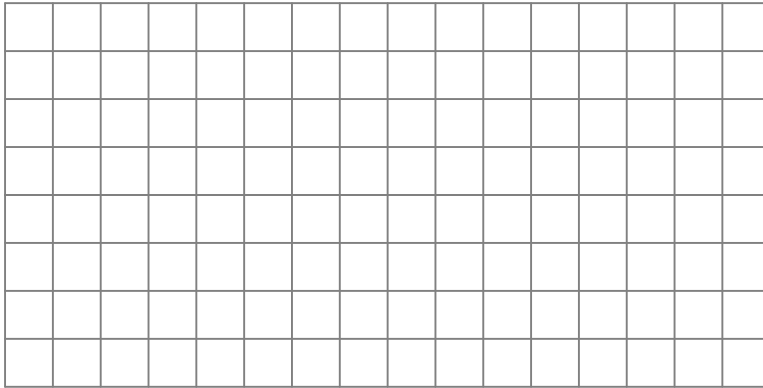
Line frequency = _____

Power factor = _____

Voltage = _____

Current = _____

2. Draw an approximate phasor diagram of the voltage and current for the heater assuming the power factor is due to inductive load.



3. Now disconnect the heater and connect a fan motor to the watt meter. Run the motor and record the power factor, voltage and the current

Power factor = _____

Voltage = _____

Current = _____

4. Discuss why heater circuit had inherently higher power factor than a motor circuit?

5. Calculate the phase angle and the impedance of the fan-motor system

Phase angle (ϕ) = _____

Impedance (Z) = _____

6. Calculate the in-phase current and the quadrature current.

In-phase current = _____

Quadrature current = _____

Active (Real) power = _____

Reactive Power = _____

7. Draw phasor diagram of the voltage, current and the impedance.

8. How much would be the quadrature current if the power factor were 0.9 for the fan motor system.

Quadrature current with 0.9 PF = _____

9. If you want to increase the power factor of this fan motor system to 0.9, what value of capacitor will you need? Calculate the capacitance. (Hint: $X_c = V/i_c = 1/j\omega C$, where X_c = reactance of the capacitor, V = supply voltage, i_c = capacitive current, ω = angular velocity of the sinusoid, C = capacitance)

10. Connect a given capacitor in **parallel** to motor- fan system.

Record the new power factor, voltage and current:

Power factor = _____

Voltage = _____

Current = _____

11. Based on your new observation, calculate the capacitance of the given capacitor. Neglect the resistance of the wire connected to capacitor.

Power factor charges:

Most utilities company charges for power factor. For instance Avista, the local utility company supplying power in Moscow area, has following rule for power factor charges:

“Where customer’s kilowatt demand is 50 kW or more, and customer’s maximum 15 minute reactive kilovolt amperes demand for that month is in excess of 48 percent of the Kw demand, customer will pay \$0.50 for each reactive kilovolt ampere of excess. The reactive kilovolt ampere demand may be determined by permanently installed instruments or periodic tests.”

12. From the above statement, calculate the power factor below which Avista will impose power factor charges.

13. A farmer had a motor consuming 100 HP for pumping water running at full load. He operates motor 20 hours per month. How much electric bill the farmer will pay without power factor charges if he pays 6.9 ¢/kWh.

14. How much the farmer will pay for power factor charge if his motor had PF of 0.5?

Lab 3: Residential or Farm Residence Wiring

PANELBOARD # _____

Name(s) _____

For this lab you will learn simple residential or farm residence wiring. You will construct an actual wiring on the board provided with proper wire for the following branch circuits. Use one panel of the board you pick. Write names of your team on a piece of paper and stick on the panel you work on (Max 3 person/team)

Task 1

1. Complete the practice wiring diagram in supplemental worksheet.
2. Examine the panel board to understand how two phases (live lines), neutral and the ground wire is connected.

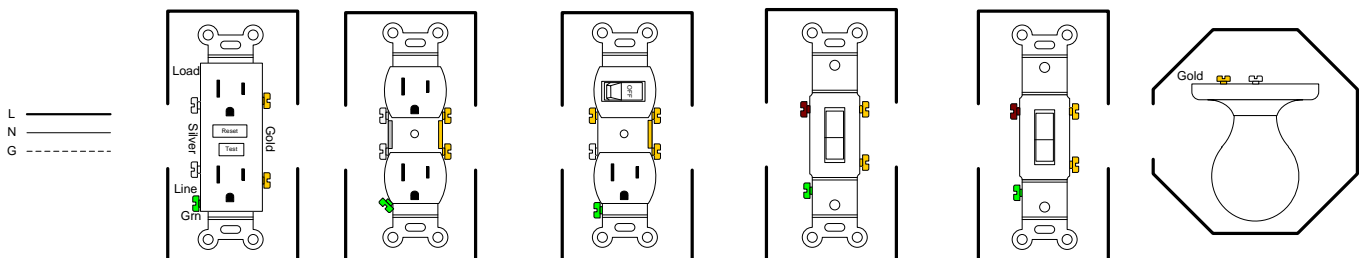
Identify:

- a. Main Breaker
- b. Connection point for L1
- c. Connection point for L2
- d. Connection point for Neutral
- e. Connection point for Ground
- f. Circuit breaker connection
- g. Ampere rating = _____



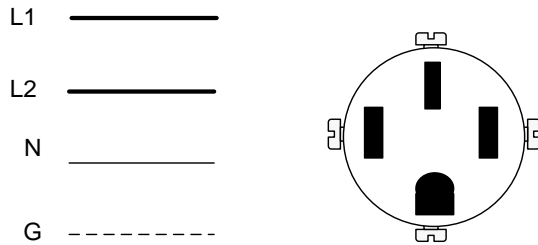
3. We would like to connect a 15 Amp branch circuit containing
 - a. One GFCI protected outlet. The GFCI outlet is followed by
 - b. One duplex convenient outlet
 - c. One duplex switched outlet
 - d. One light to be controlled by two 3 way switches.

The schematic of the circuit components is shown below. Connect the wires properly so that the all the components downstream to GFCI is protected. (Label the cable as 14-2 or 14-3)



Note: Run 14-2 G cable between boxes

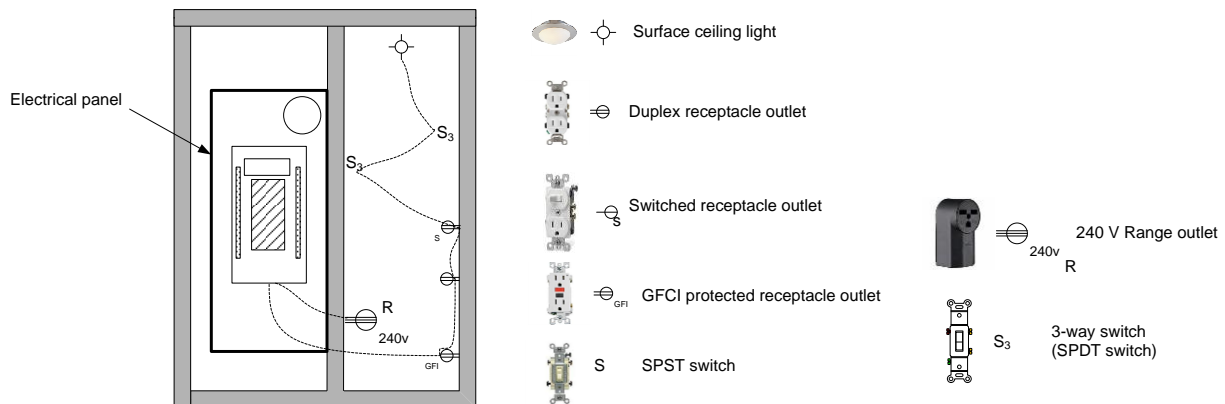
- Connect for a branch circuit powering a 240 V electric range. (In actual wiring you required to use AWG 6 or larger for 50 A circuit and AWG 8 or larger for 40 AMP circuit. For this exercise feel free to use 14-3 G cable for ease of handling if you find AWG 6 too hard to work with).



Show your work to the instructor

Task 2

- Connect the circuit following your diagram.
- Inspect the circuit to ensure no error has been made and test your circuit for continuity with a DMM
- Let your instructor examine the circuit
- Connect the circuit to the power. (Being very careful)
- Test the switches, and receptacles.



Draw a circuit wiring diagram for each branch circuit with neat labeling. Use the worksheet on back page to record your final connection diagram

Use proper grounding practice throughout. Note that boxes should be installed with recognition that wall will be finished with ½" sheetrock. Use proper wire, box sizes, terminals, wire nuts, etc., or explain why you did not.

Task 3

Your team is to construct part of a residential panel based on the following information:

A two story house 30 ft x 50 ft exterior dimension, no basement, no attached garage with following specialty purpose fixtures:

ITEM	VOLTAGE	Nameplate Rating (VA)
Range	240	18000
Furnace Fan	120	400
Clothes Dryer	240	5500
Electric Water Heater	240	4000

Specify the electrical circuits required for this house meeting the NEC requirement that includes:

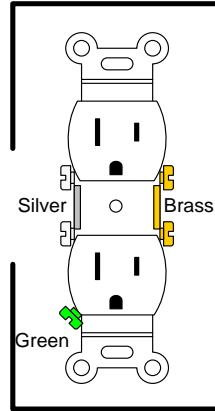
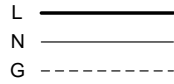
1. Minimum number of branch circuits needed for the house.
2. The ampacity of each branch circuit.
3. Branch circuits needed for general lighting load.
4. Calculate the panel size and then the copper service wire size (THW, 2% allowed voltage drop, 50 ft one way run length).

Task 4

Write a group lab report and turn in for the credit.

Practice wiring the following circuits. Use 14-2 G or 14-3 G cable between boxes.

1. A duplex receptacle outlet



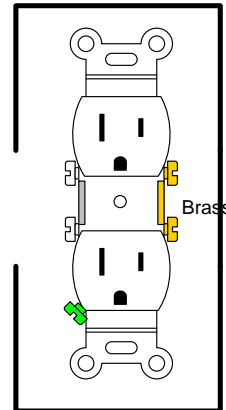
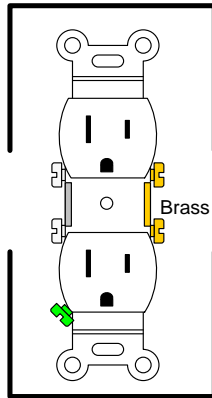
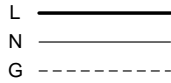
Black wire is hot (line). White wire is neutral. Green or bare wire is ground.

White wire connects to Silver or white tab

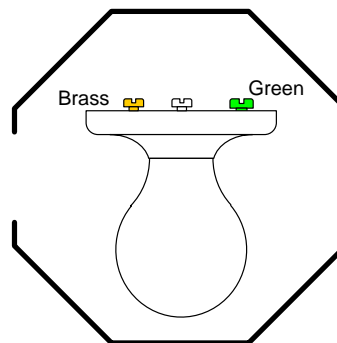
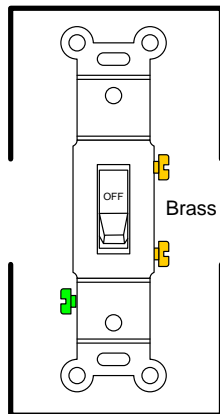
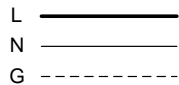
Live wire connects to brass or gold tab

Ground connects to green tab

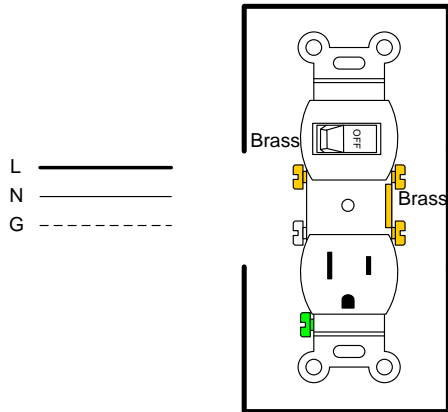
2. Two duplex receptacle outlets



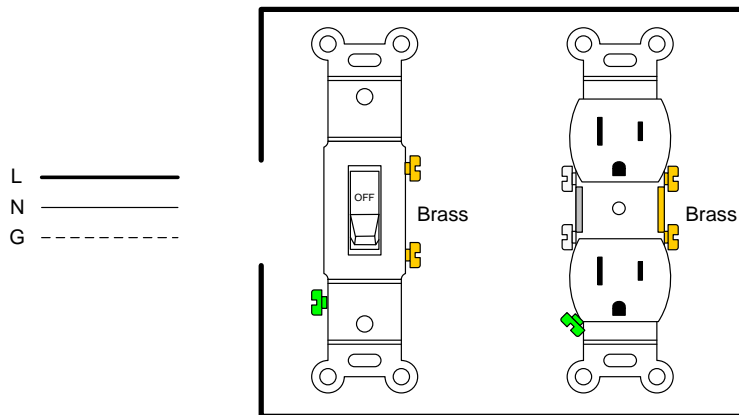
3. A switch controlling a lamp



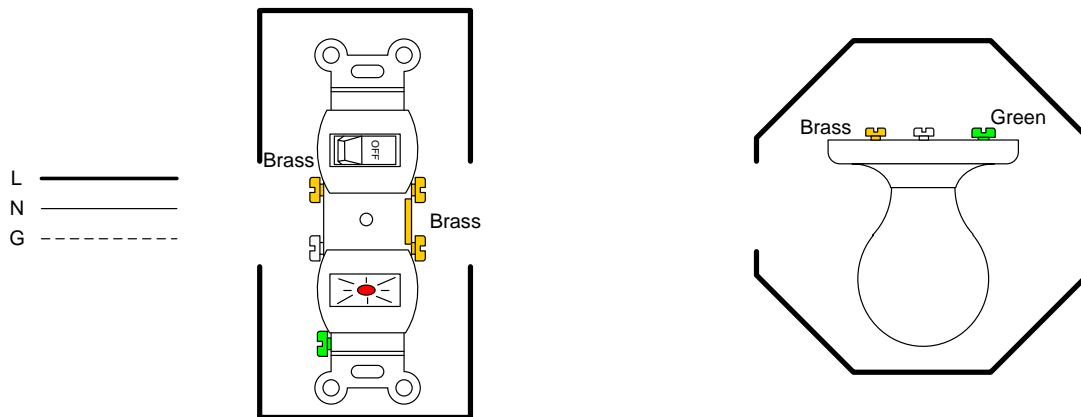
4. A switched receptacle outlet



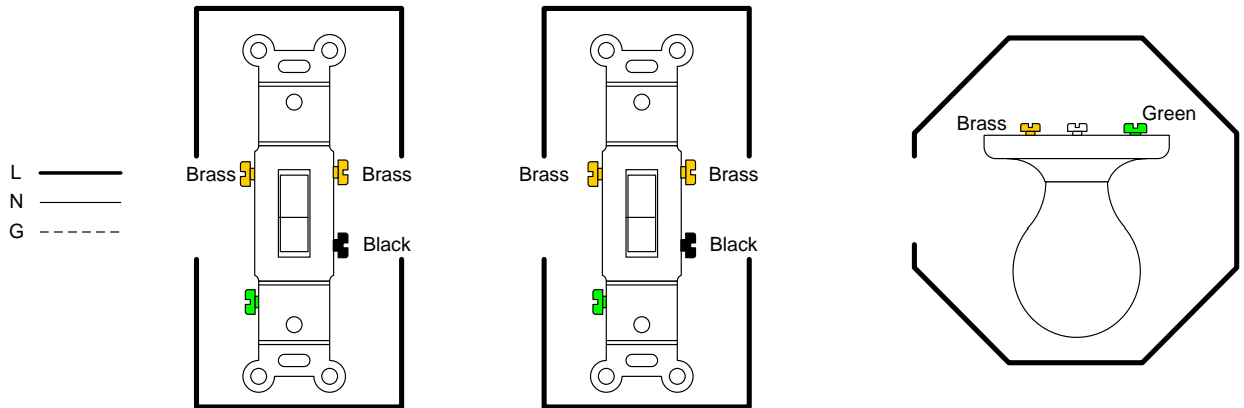
5. An upper half switched duplex receptacle outlet.



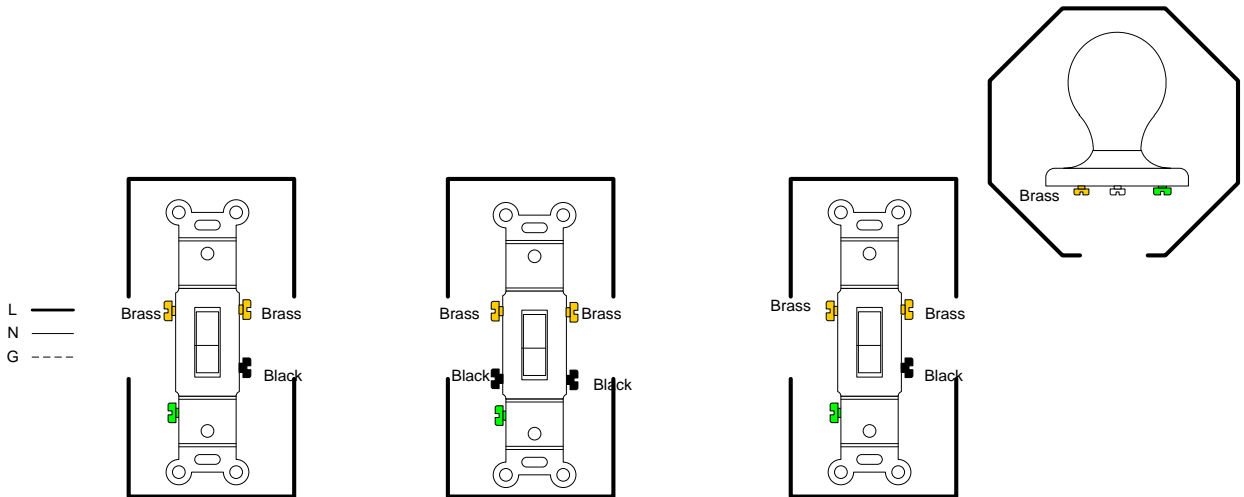
6. Draw the wiring diagram for a switch controlling a lighting outlet. The pilot lamp is on only when the lamp is on.



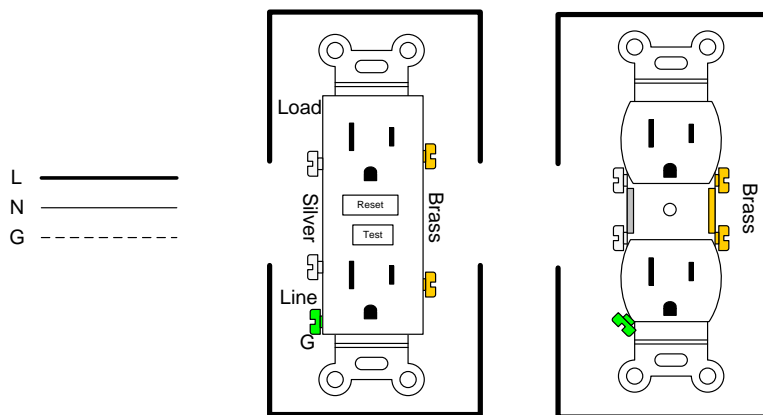
7. Connect the wiring to control the light from any of 2 control switches (two 3-way switches).



8. Connect the wiring to control the light from any of 3 control switches (two 3-way switches and one 4-way switch).

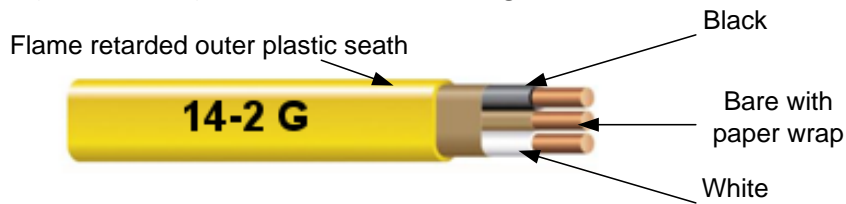


9. Connect the wiring for a GFCI protected outlet along with a duplex outlet protected by GFCI



Wiring tidbits


NM (Non Metallic) cable #14 two wire with ground



Allowed current for copper wire (Specified in NEC):

#14 15A | #12 20A | #10 30A | #8 40A | #6 55 A

The circuit breaker or fuse protecting a branch circuit should not be of higher capacity than allowed ampacity.

- 15  AMP circuit breaker → #14 wire cable
- 20 AMP circuit breaker → #12 wire cable

When connecting wires with wirenut, pre twisting of wire is optional. Pay attention to minimum and maximum number of wires along with their size allowed in a given wirenut.

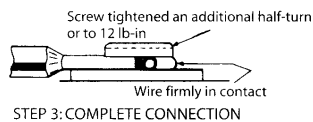
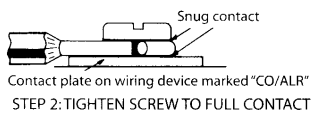
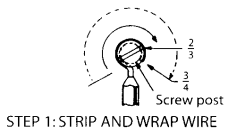
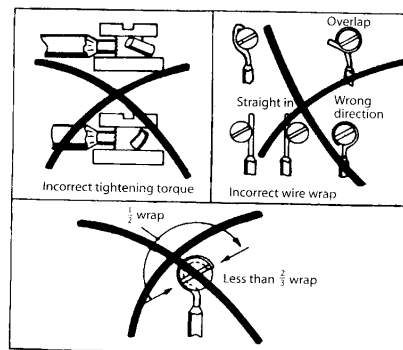


Fig. 4-13 Be sure wire is wrapped around terminal screw in clockwise fashion as in Step 1 so that tightening the screw tends to close the loop. Then complete Steps 2 and 3. (UL Inc.)



(Image source: Wiring Simplified 43 ed.)

A two story house 30 ft x 50 ft exterior dimension, no basement, no attached garage with following specialty purpose fixtures:

ITEM	VOLTAGE	Nameplate Rating (VA)
Range	240	18000
Furnace Fan	120	400
Clothes Dryer	240	5500
Electric Water Heater	240	4000

Specify the electrical circuits required for this house meeting the NEC requirement that includes:

1. Branch circuits needed for general lighting load.
2. Minimum number of branch circuits needed for the house.
3. The ampacity of each branch circuit.
4. Calculate the panel size and then the copper service wire size (THW, 2% allowed voltage drop, 50 ft one way run length).

Possible Faults

1. **Ground wire short circuited to live (Mainly due to over exposed wires, remind students not to take of insulation more than about ½ inch.) One group of student had ground terminal connected to live on the bulb because bulb did not have a terminal to connect to ground)**
2. **Neutral short circuited to live (for the same reason as mentioned above)**
3. **Line and load connections switched in GFCI**
4. **Broken tab on duplex**
5. **GFCI in fault position (some GFCI needs power to reset)**
6. **Misidentified common leg in 3-way switch**
7. **Power for downstream receptacles taken out of switched duplex after the switch**
8. **Faulty GFCI**

Fault identification and troubleshooting process

Lab 4: Farm electrical service design

Name _____

Objectives:

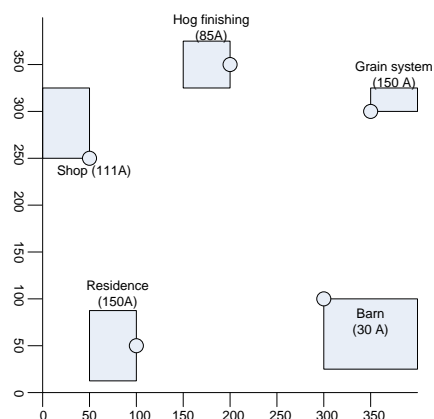
- Learn design procedure for computing building demand and selecting service equipment, calculating the load center, calculating the total farm load and selecting service conductor size.

Tasks:

1. Compute building demand and select service equipment for a farm shop. Electrical equipment in the shop is specified along with its current at 240 V.

	VA at 240V	LWD %
Air compressor, 5 hp	8400	100
Hydraulic pump, 5 hp	8400	
Drill Press, 2 hp	2880	
Lathe, 2 hp	2880	
Vent fan, ½ hp	1176	
Grinder, 1/3 hp	864	
LP furnace, 1/3 hp	864	100
Water heater – 4500 W	4800	100
Welder	8400	
12 lighting outlets	2160	100
20 duplex receptacles	3600	50

2. Locate the load center for the farmstead shown in Figure below. Also, calculate the total load for the farm at the load center.



3. Calculate the total farm load for the farm defined in above problem.
4. Design the service conductors for the farmstead in question #2. Use underground feeder (UF) branch circuit cable. Maximum allowable voltage drop in transmission is 2% of supply voltage (240 V).

Lab 5: Electric motors

OBJECTIVES

- To become familiar with physical make-up of common types of electric motors.
- To disassemble a motor, identify its' components, and discuss its' construction.
- Measure the starting torque of various motors
- Construct the equivalent circuit
- Understand the operational behavior of the motor at various loading condition.

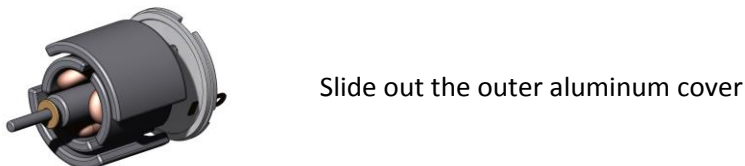
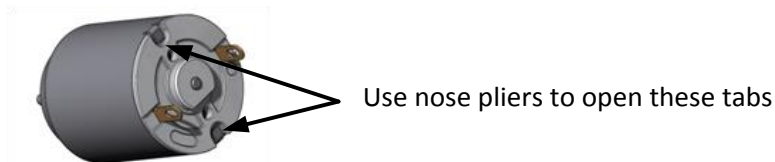
PROCEDURE

We will examine the following types of electric motors:

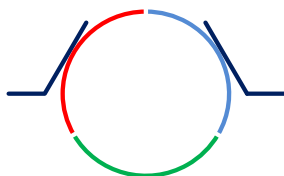
1. DC motor
2. Stepper motor
3. AC motor
 - A. Single Phase
 - a. shaded pole
 - b. split-phase
 - c. capacitor start-induction run
 - d. repulsion start-induction run
 - B. Three Phase

DC motor:

1. Take a small DC motor commonly used in toys and other non critical applications.
2. Use nose pliers to open up the tabs holding up the aluminum case and open the case.



3. Identify the stator magnet, brush, commutator, and armature. Note that only two out of three poles are energized at a time to ensure armature magnetic poles are never aligned with stator magnetic poles. This help start the motor regardless of its initial position.



- Carefully re-assessable the motor and connect he motor to 0-5V power source. The speed of a DC motor can be easily controlled by the changing the supply voltage. The direction of the motor rotation is changed by changing the polarity of the supply. Try changing the voltage and the polarity and observe how the motor behaves.
- Disassemble a battery operated electric drill to see how an electric drill varies its speed, direction and torque applied to a specific job. Write your discussion on DC motor speed, direction and torque control.

AC motor

AC induction motors are the most common type of motor and we will study that first. All induction type motor gets the armature current through induction. The speed of an induction motor cannot and should not be changed by changing the operational voltage. Since rotational speed of an armature is closely tied to synchronous speed, one way to change the speed of an induction motor is by changing the supply frequency. Supply frequency is changed using a variable frequency drive. However for application where speed does not need to change in big range, an inexpensive gearbox will also do the job.

- Examine the squirrel cage rotor (including the cutaway view) and understand its internal structure. You may notice that the aluminum bars are slightly slanted from axial direction. This is to help reduce the variation in torque (force) over the surface of the rotor. Slanting helps reduce the vibration of the motor by averaging the produced torque over several degrees of rotation. Identify the direction of induced current and direction of magnetic flux. Why the current flows from aluminum bar but does not flow from iron laminates?

7. Examine the stator winding of a given stator winding and find out the number of poles on this motor. Calculate the synchronous speed for power supply frequency (f) at 60 Hz.

Number of poles on the stator winding (N) = _____

Synchronous speed = $60 \times f / (N/2) =$ _____ rpm

Motor Nameplate Information

National Electrical Manufacturers Association (NEMA) defines some basic design and dimensional parameters of electric motors. These parameters are then coded onto the motor nameplate to give you basic motor parameters. Manufacturers often include additional information to further define some key motor features.

Note down the name plate information for each of the motors available on the test stand.

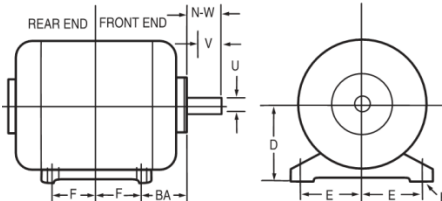
Name plate	Motor	1	2	3	4
	Type				
	Rated hp				
	Frame				
	Rated Volts				
	Rated Amps				
	No of Phase				
	Supply frequency				
	Duty				
	Service factor				
	Motor code				
	RPM				

Each nameplate information is briefly described below.

Type: NEMA requires manufacturer's type, but there is no industry standard regarding what this is. Some manufacturers use "Type" to define the motor as single or polyphase, single or multispeed, or even by type of construction. Type is of little use in defining a motor for replacement purposes unless you also note the specific motor manufacturer.

Rated HP: Shaft horsepower is a measure of the motor's mechanical output rating, its ability to deliver the torque required for the load at rated speed. It is usually given as "HP" on the nameplate. In general: $HP = (\text{Torque}) \times (\text{speed}) / 5,252$ where: Torque is in lb-ft Speed is in rpm

Frame: The frame size sets mounting dimensions such as foot hole mounting pattern, shaft diameter, and shaft height. Some example of motor frame size is given below. Frame size is important when you are replacing a motor or designing a system with specific dimension for the motor.



NEMA Frame	D*	2E	All Dimensions in Inches			N-W	U	VS Min.
			2F	BA	H			
42	2 ⁵ / ₈	3 ¹ / ₂	1 ¹¹ / ₁₆	2 ¹ / ₁₆	9/32 slot	1 ¹ / ₈	3/8	—
48	3	4 ¹ / ₄	2 ³ / ₄	2 ¹ / ₂	11/32 slot	1 ¹ / ₂	1/2	—
48H	3	4 ¹ / ₄	4 ³ / ₄	2 ¹ / ₂	11/32 slot	1 ¹ / ₂	1/2	—
56	3 ¹ / ₂	4 ⁷ / ₈	3	2 ³ / ₄	11/32 slot	1 ⁷ / ₈ †	5/8†	—

The first two digits of the frame size divided by 4 defines the height of the shaft centerline from the bottom of the feet. Thus, the shaft height of a 445T motor is $44 / 4 = 11$ in. The third digit (if present) in

the frame size determines the distance between the foot holes nearest the shaft and the opposite drive-end foot holes.

Rated Volts: It is common for manufacturers to nameplate a wide variety of voltages on one motor nameplate. A common example is a motor wound for 230 and 460 V. Follow the connection diagram for each voltage provided in the motor wiring. The voltage rating assumes that there is voltage drop from the network to the motor terminals. Thus, the 460-V motor is appropriate on a 480-V network

Rated Amps: Rated current at nameplate horsepower (HP) load with nameplate voltage and frequency.

Phase: Single or three-phase

Rated Frequency: Input frequency is usually 50 or 60 Hz. When more than one frequency is nameplated, other parameters that will differ at different input frequencies must be defined on the nameplate.

Duty: the length of time during which the motor can carry its nameplate rating safely. Most often, this is continuous ("Cont"). Some applications have only intermittent use and do not need motor full load continuously. Examples are garage door opener motor. The duty on such motors is usually expressed in minutes.

Service factor: The service factor (SF) is a measure of periodically overload capacity at which a motor can operate without overload or damage. A motor operating continuously at a service factor greater than 1 will have a reduced life expectancy compared to operating at its rated nameplate horsepower. It is required on a nameplate only if it is higher than 1.0.

Motor Code: A letter code defines the locked rotor kVA on a per-hp basis (A-V). Generally, the farther the code letter from A, the higher the inrush current per hp. A replacement motor with a "higher" code may require different upstream electrical equipment, such as motor starters.

RPM: Full load speed. The speed at which rated full-load torque is delivered.

Locked rotor test of a motor

Measure the starting torque (locked rotor torque) and current for each of the electric motors available in the test stand. Match the Motor number from previous table of name plate data.

For all tests with load, the motor shall be properly aligned and securely fastened. Testing of induction motors under locked-rotor conditions involves high mechanical stresses and high rates of heating.

Therefore, the following precautions are necessary:

- A. The mechanical means of locking the rotor must be of adequate strength to prevent possible injury to personnel or damage to equipment.
- B. The direction of rotation must be determined **prior to test** so that methods of fastening and of measuring torque can be properly applied.
- C. The motor is at approximately ambient temperature before the test is started.

Current and torque readings should be taken as quickly as possible after voltage is applied. The period of time between application of voltage and current and torque readings shall not exceed 5 s. The motor temperature should not exceed the rated temperature rise plus 40 °C. Use a watt meter for single phase power measurement and use a three phase power meter for three phase motor connection. Use a multimeter across the power plug to measure the stator winding resistance.

Arm length = _____ inches

Measured	Motor	1	2	3	4
	Applied voltage				
	Locked rotor current				
	Locked rotor power				
	Locked rotor force				
	No load current				
	No load power				
	Stator resistance				

Calculate the following parameters based on the nameplate data and measured values. Assume reasonable value for any missing information if needed.

Calculated	Motor	1	2	3	4
	Rated Slip				
	Rated torque				
	Starting torque				
	Starting torque/ Rated torque				
	Starting current/rated current				

Based on your observation and calculation discuss about which motor had the highest starting torque per rated hp, which motor had the highest inrush current per rated hp?

AC Motor Performance Test Single phase versus three phase

Single phase

Motor:

Make: _____ type _____

Dynamometer:

Make: _____ type _____

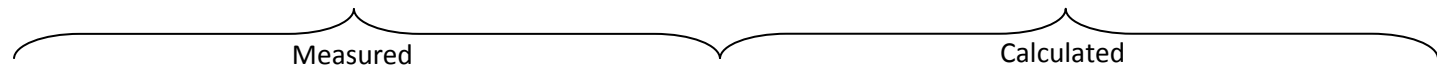
Rated Speed: _____ Volt _____

Brake Arm Length: _____ 6" = 0.5 ft _____

Rated Current: _____ hp: _____

Rated Torque (lb-ft) = Rated Power (hp) * 33000 / (2 * π * n) = _____ (n is speed in rpm)

Rated Load = Rated Torque (lb-ft) / arm length (ft) = _____ lb



Test No.	Load % Rated (Approx)	Applied Voltage V	Current I	Power input W	RPM	Dynamic Load lb	Torque Lb-in	% sync. speed	Output Power W	P.F.	Motor Eff.
1	0										
2	25										
3	50										
4	75										
5	100										

Conversion factors:

1 HP = 746 watts

Power (hp) = $\frac{2\pi FLn}{33000}$, where F is force in lbs, L is arm length in ft, n is speed in RPM.

Three phase

Motor:

Make: _____ type _____

Rated Speed: _____ Volt _____

Rated Current: _____ hp: _____

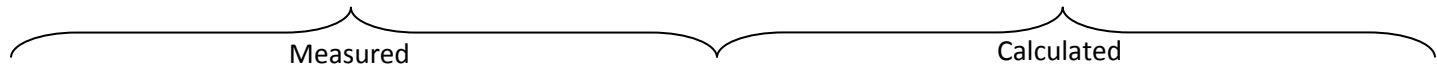
Rated Torque (lb-ft) = Rated Power (hp) * 33000/(2*πn) = _____

Rated Load = Rated Torque (lb-ft)/arm length (ft) = _____ lb

Dynamometer:

Make: _____ type _____

Brake Arm Length: _____ 6" = 0.5 ft _____



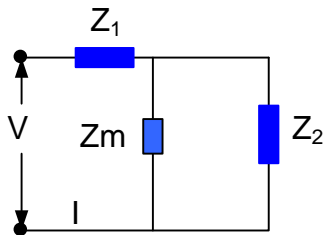
Test No.	Load % Rated (Approx)	Applied Voltage V	Current I	Power input W	RPM	Dynamic Load lb	Torque Lb-in	% sync. speed	Output Power W	P.F.	Motor Eff.
1	0										
2	25										
3	50										
4	75										
5	100										

Compare the performance of three phase motor vs single phase motor based on motor performance (smoothness in running), power factor and the motor efficiency.

Motor equivalent circuit

Calculate the approximate equivalent circuit for a chosen single phase motor with following assumptions:

- Resistance part of Z_1 is equal to the stator resistance measured using a DMM.
- Reactance of Z_1 is negligible compared to Z_m and hence can be assumed 0
- At no load Z_2 is very high and can be assumed to have no current flowing through it. That is Z_2 can be thought as open circuit.



Following the above discussion, here are the steps to calculate the equivalent circuit:

Step1: Use rotor resistance to estimate Z_1

Z_1 = Stator resistance is measured using a DMM

Step2: Use no load measurements to estimate Z_m

$$Z_m + Z_1 = \frac{V}{I} \angle \theta$$

Where V is supply voltage, I is measured current and θ is phase angle. Z_m can be calculated from measured V, I, Z_1 and θ .

Step 3: Use locked rotor measurements to estimate Z_2

$$\frac{Z_m * Z_2}{Z_m + Z_2} + Z_1 = \frac{V}{I} \angle \theta$$

Or,

$$Z_2 = \frac{Z_m * (Z - Z_1)}{Z + Z_m + Z_2}$$

where,

$$Z = \frac{V}{I} \angle \theta$$

Show your calculations and turn in your formal group lab report for credit.

Lab 6: VFD for motor controls

OBJECTIVE

- Understand how does a VFD works
- Get familiar with an actual VFD and connecting it to circuit.
- Use VFD to control the motor speed.
- Understand the limitations and potential problems with VFD controls

EQUIPMENT

1. Three phase induction motor
2. VFD unit
3. Tachometer

BACKGROUND

The synchronous speed in revolutions per minute (rpm) of an induction motor is determined by the line frequency given by:

$$N_s = \frac{120 f}{p}$$

For a four pole motor ($p=4$), and 60 Hz line frequency ($f= 60$), the synchronous speed of the motor is 1800 rpm. When the motor is loaded, slip (s) develops in proportional to the load up to at least the full load of the motor. The actual speed of the motor is then given by.

$$N = N_s(1 - s)$$

A variable frequency drive (VFD) controls the motor speed by varying the line frequency (f) which is the most efficient way of controlling the induction motor speed. To produce the same torque output, the applied voltage has to be reduced in proportion to the frequency. The maximum torque produced by a motor is given by:

$$\frac{T_2}{T_1} = \left(\frac{V_r}{f_r}\right)^2$$

Where T_2 is the torque developed after frequency change. T_1 is the original torque. V_r is the fractional change from original voltage and f_r is the fractional change in frequency. For sample if frequency is halved ($f_r = 0.5$) while keeping the voltage constant ($V_r= 1$). The maximum torque output will be four times that of original torque. To keep the constant torque at reduced speed, V_r need to be equal to f_r . Proportionately higher voltage would produce higher torque and vice versa. A typical speed to torque relation when both frequency and the voltage are changed proportionately is shown below.

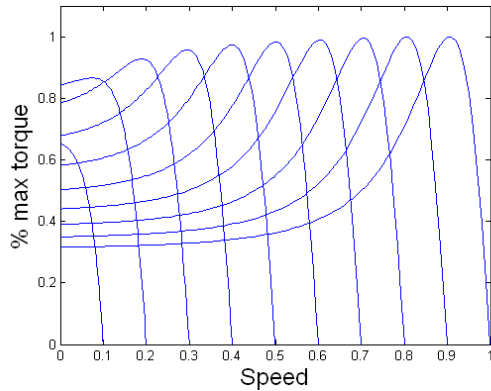


Figure 1. A typical speed torque relation of VFD driven motor various fraction of design synchronous speed.

Note that when the speed is reduce less than about 15% of the design synchronous speed, the motor can no longer deliver the rated maximum torque even after V_r was kept equal to f_r . This may cause the motor to stall at very low speed. So the VFD speed control is should not be used to run the motor at very low speed (as a rule of thumb not less than 20% of design speed). A combination of gearbox and VFD may provide a better speed control in those situations.

Another characteristics of the VFD drive is that the drive does not produce pure sine wave. Being a digital device, the VFD produces a pulse width modulated sine wave. Pulse width modulated sine wave is generated by turning on and off the DC voltage to have the same RMS voltage as sine wave.

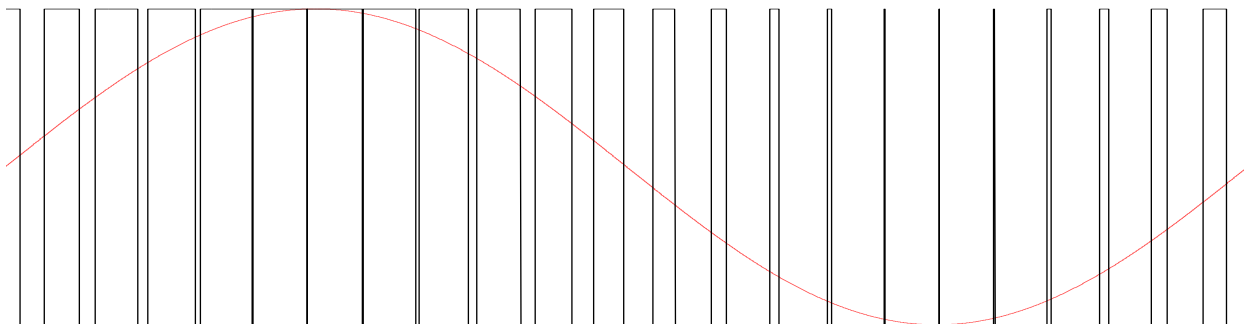


Figure 2. PWM simulated sine wave. The ON-pulse width if proportional to the magnitude of the sine wave.

VFD controller first converts the incoming AC voltage to a DC voltage and then produces the three phase AC of varying voltage through PWM modulation. Therefore, a VFD is also called and inverter drive for this reason. Since PWM is not a pure sine wave, the produced voltage has higher frequency components called harmonics. The amount of harmonics produced by a VFD may depend on the number of pulses it uses to simulate the sine wave. Higher the number of pulses better is the VFD quality on simulating the real sine wave. The power delivered at higher frequency is dissipated as heat in the motor. Therefore, be aware that a motor without inverter duty specification may not be able to handle extra heat generated by the high frequency power when connected to a VFD .

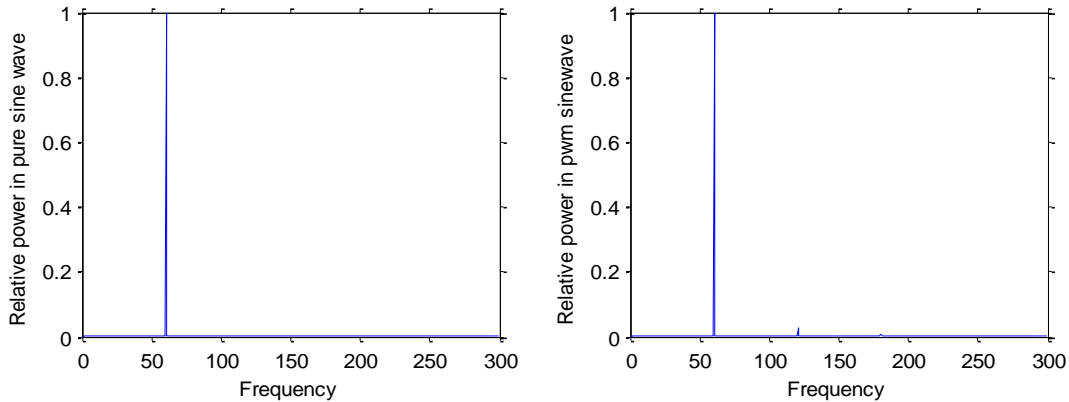


Figure 3: Relative power delivered to the motor at various frequency. Although most of the power is delivered in PWM sine wave at 60 Hz, notice small power spike at higher frequencies as well.

In addition to the controlling the motor at the set speed, VFD also help to reduce starting current by ramping up the motor speed as soft starter. A VFD may be used for a fixed speed application for soft starting purpose. When an induction motor is connected to a full voltage supply, it draws several times its rated current. By contrast, when a VFD starts a motor, it initially applies a low frequency and low voltage to the motor.

L100-M Series VFD



Procedure

Part 1: Learn the front panel

- Run LED – ON when the inverter output is ON and the motor is developing torque, and OFF when the inverter output is OFF (Stop Mode).
- PRG LED – ON when the inverter is ready for parameter editing (Program Mode). It is OFF when the parameter display is monitoring data (Monitor Mode).
- Run key enabled LED (Not printed) – ON when the inverter is ready to respond to the Run key, OFF when the Run key is disabled.

- Run Key – Press this key to run the motor (at programmed acceleration rate, the Run Enable LED must be ON first).
- Stop/Reset Key – Press this key to stop the motor (at programmed deceleration rate) when it is running
- Potentiometer – Allows an operator to directly set the motor speed when the potentiometer is enabled for output frequency control.
- Potentiometer LED (Not printed) – ON when the potentiometer is enabled.
- Display – A 4-digit display for parameters and function codes.
- Display Units: Hz/A – One of these LEDs will be ON to indicate the units associated with the parameter display (frequency or current).
- Power LED – ON when the power input to the inverter is ON.

The following keys are visible when you open lift tab located lower right corner of the front panel near safety warning message. Lift the corner to open

- Function Key – Use to navigate through the lists of parameters and functions for setting and monitoring parameter values.
- Up/Down Keys – Use to move up or down the lists of parameter and functions shown in the display, and to increment/decrement values.
- Store Key – Writes the new value to the EEPROM.

Part 2: Speed control:

1. Make sure that the Input power line and output lines to the motor are securely connected in terminals.
2. Plug in the provided cord into the 120Vac wall outlet.
3. Press the run button for the motor to run. Use the potentiometer knob on the front panel to adjust the motor speed.
4. Set the motor speed to 30 Hz. Once motor reaches the steady speed, press the stop button.
5. Turn the motor back on, does VFD goes back up to 30 Hz or it runs at full speed? _____

Pat 3: Voltage, frequency and speed relation

6. Connect an AC voltmeter to the output section of the VFD between two phases using an insulated prob. For extra security make sure you are wearing an insulated shoe or standing on a rubber mat.
7. For each frequency set, measure the AC voltage and motor speed using a tachometer.
8. Record your measurements in the following table from 60 to 20 Hz at 10 Hz interval.

Frequency =					
Voltage =					
RPM =					

Part 4: Change the display from frequency to Current

9. Press function key. This will display the current display value D01 which is to display frequency.
10. Press up button to change this to D02 to display the current.
11. Press function key again to exit out of monitor setting. The front panel should display the current now.

Part 4: Change the ramp rate to 30 s

1. Press function key. This will display the current display value D02.
2. Press down button repeatedly until F02 is displayed.
3. Press function key to display the ramp rate in seconds. Use up/down key to set the ramp rate to 30 s (This is time taken to ramp from 0 to maximum frequency which could be set up to 360 Hz for this VFD). Ramp rate can vary from 0.1s to 3000s.
4. Press STR to store the new value to EEPROM and return to function F02.
5. Press up arrow until you see D01 again.
6. Press function key to exit.
7. Press run key to see the change in ramp rate.

Discussion questions:

1. How does a VFD control the speed of an induction motor?
2. Why is a VFD also called an inverter drive?
3. What are harmonics?
4. What might happen if you use a VFD on a non-inverter duty motor?
5. What are the advantages of ramping the motor up?
6. Plot the frequency Vs. Voltage relation. Are they proportional? What will happen if they are not proportionally changed?
7. From your calculation, what may be the number of poles in this motor?

Lab 7: Motor Control Circuit

OBJECTIVE

- Understand the basic symbols for motor control circuit
- Understand working principle of the magnetic contacts.
- Use motor controls, on/off switches, and time delay relays to control motors.

PROCEDURE

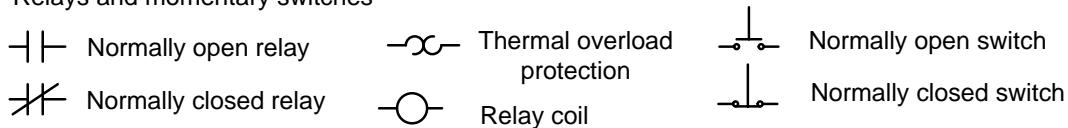
1. Understand the basic symbols

Switches

S=Single, D= Double, P=Pole, T= Throw



Relays and momentary switches

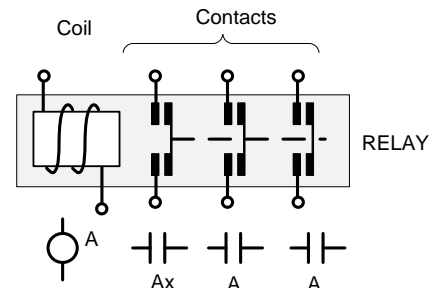
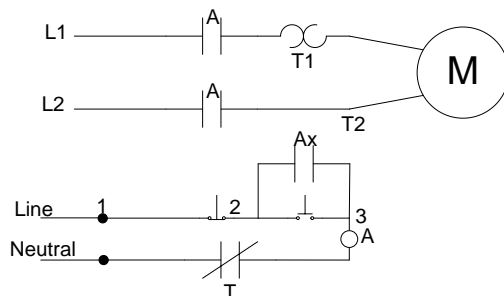


Time delay switch



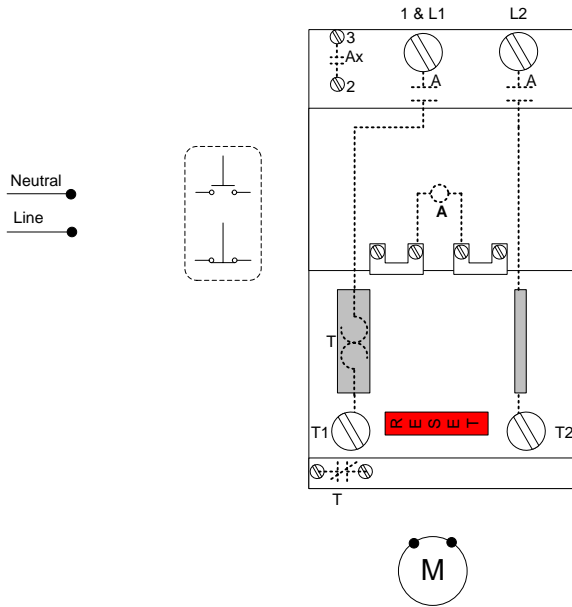
NO= Normally open, NC = Normally closed

2. Develop a circuit for one single phase motor to be turned on and off by a NEMA 0 motor controller with one start/stop switch.



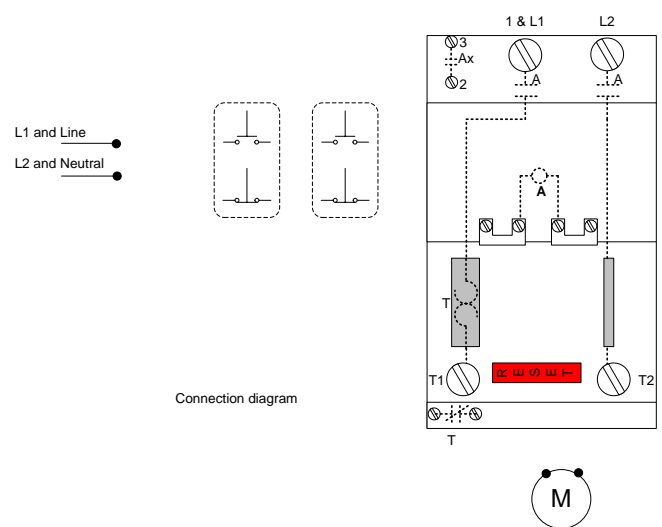
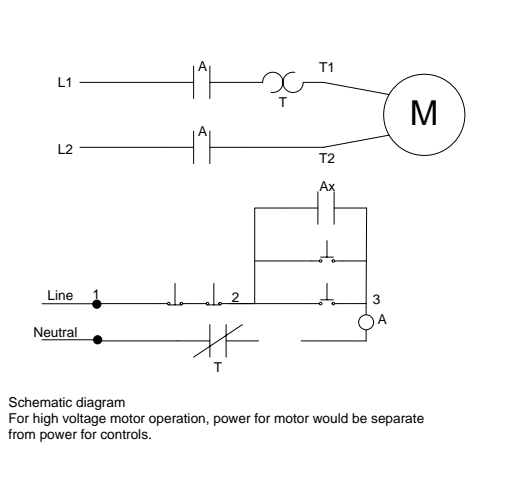
Schematics of a magnetic starter. Note that 'Ax' is in series with coil 'A'. As a result as long as 'A' is energized, 'Ax' is closed and as long as 'Ax' is closed the coil 'A' is energized. The coil 'A' is de-energized and 'Ax' is open when stop switch is pressed or thermal protection is open.

- Following the above schematic diagram, make the wiring diagram by connecting the wires in the following figure. Double check your connection and have your instructor inspect before you power the circuit for testing. Make the actual wire connections following the wiring diagram. Make sure that all connections are secure and there are no short circuits. Test the circuit.



The dotted lines inside the motor starter unit are to show the internal wiring only. They are not accessible, so do not make a connection to them. Make connections only to the terminals.

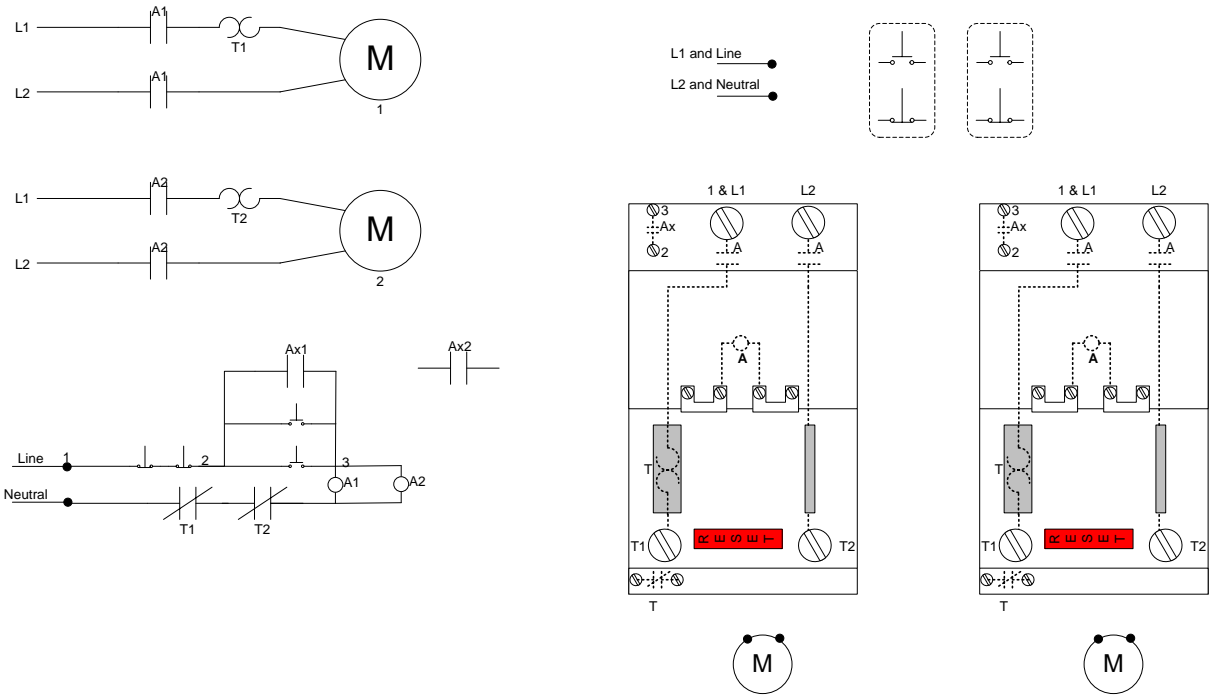
- Draw a circuit for one motor to be turned on and off by pressing either of two start/stop switches. Note that you will have to modify only the switching circuit. Connect the start switch in parallel and stop switches in series.



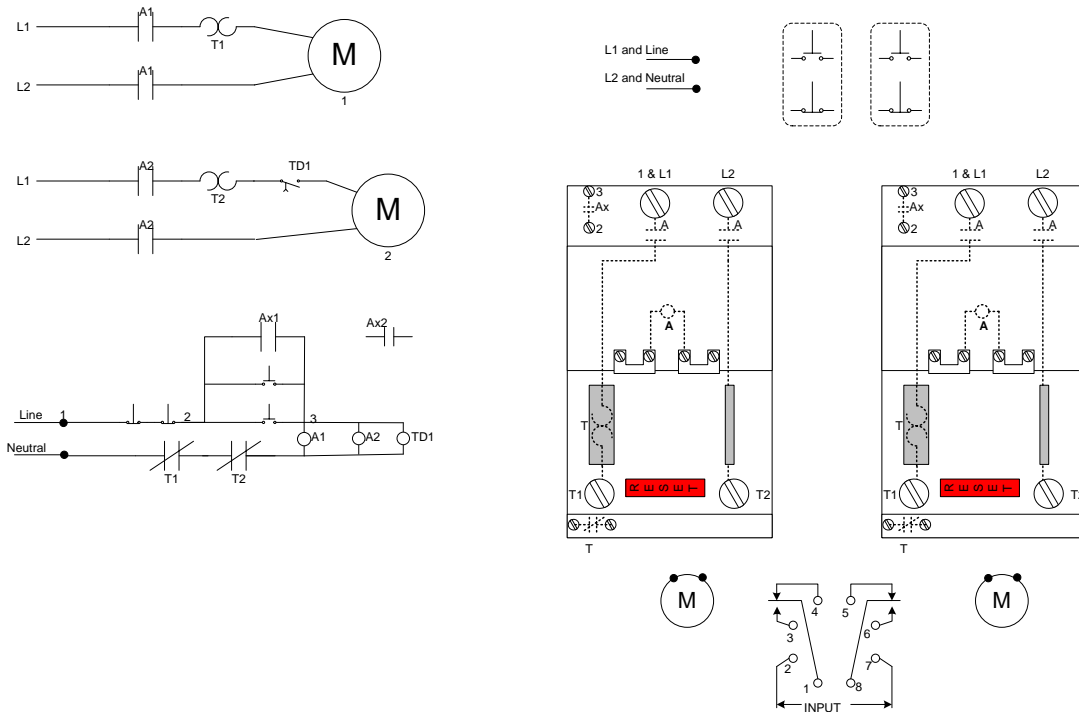
Modify your actual wire connections from previous connection. Double check your connection and have your instructor inspect before you power the circuit for testing.

- Develop a circuit for two motors to be turned on and off by a two start/stop switches. The circuit should have thermal overload protection connected in such a way that if either motor trips the overload, both motors turn off. Keep in mind that normally closed relays needs to be in series to trip

the motor if one of them trips.

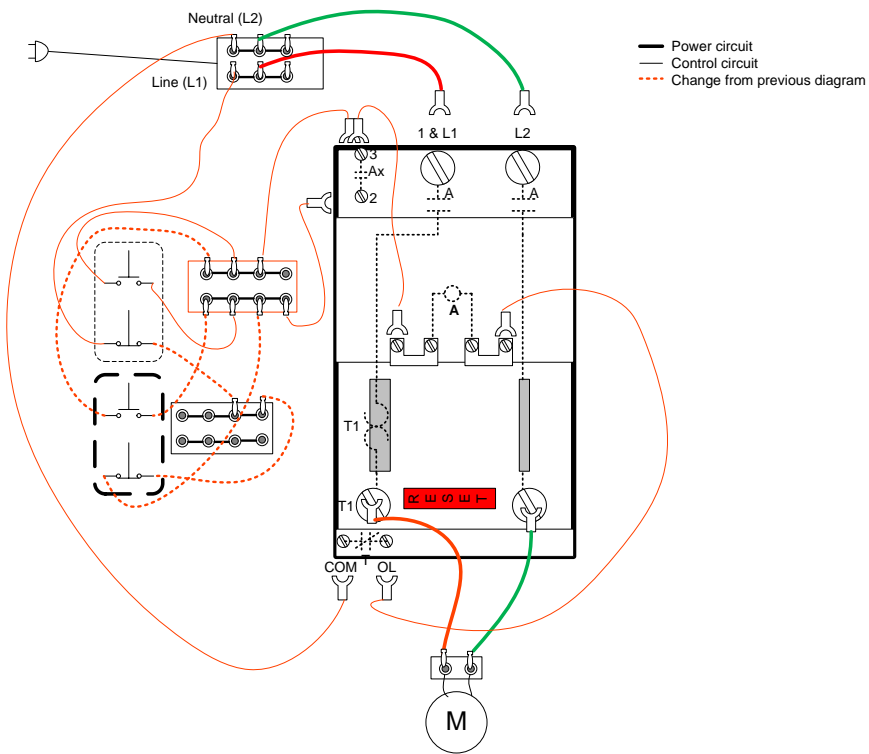
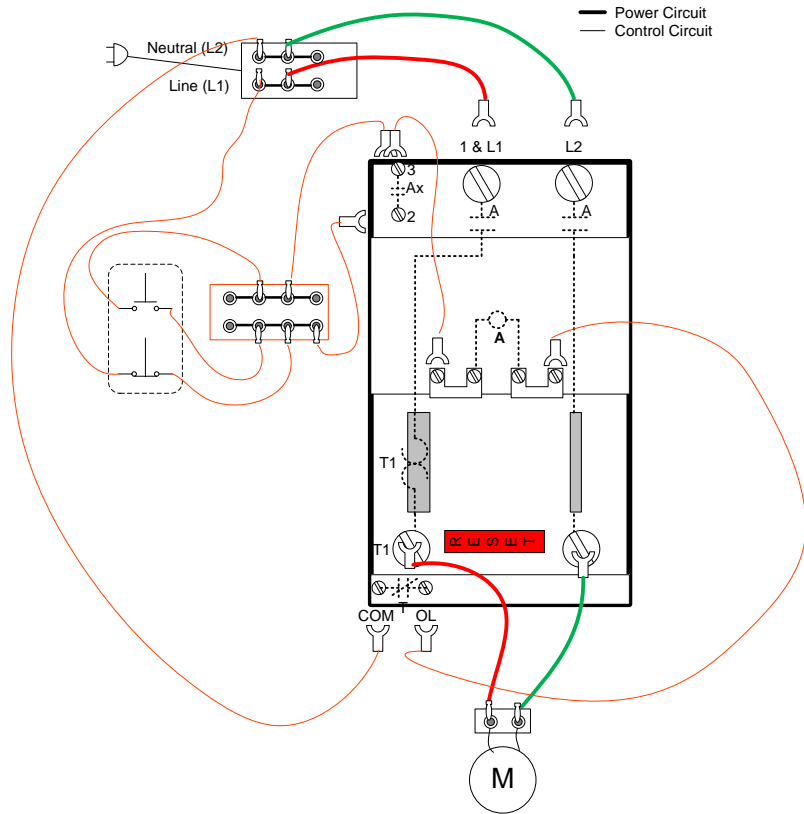


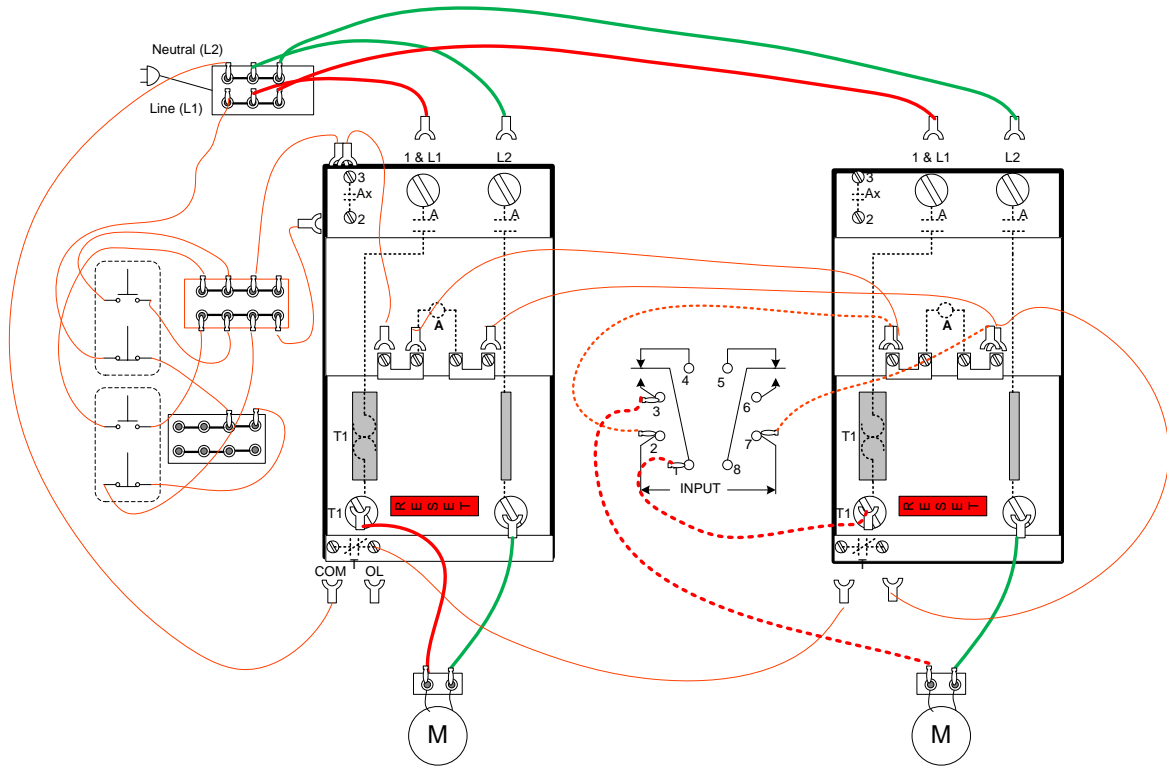
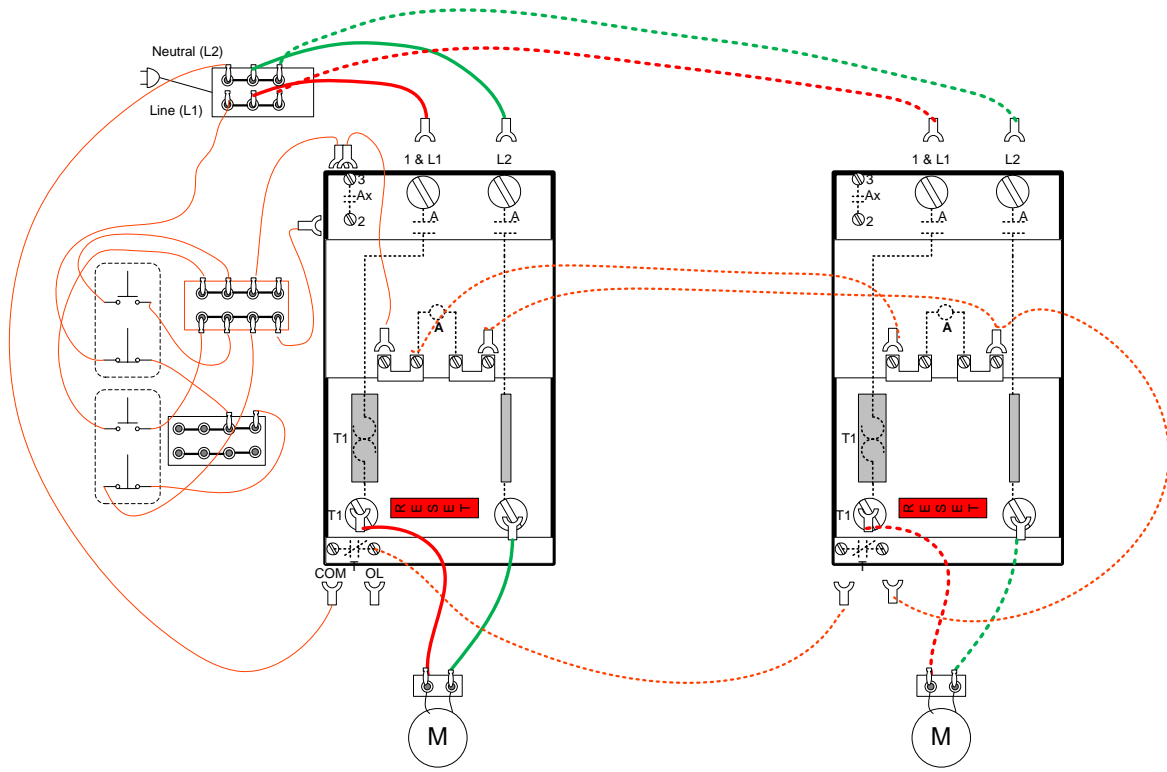
6. Develop a circuit for two motors to be turned on and off by two start/stop switch with the second motor turning on 5 seconds after the first (called stagger starting). This will require a time delay relay.



Time delay action shown in figure behaves like this: Pin 1 and 4 are normally closed and pin 1 and pin 3 are normally open. When the input power is energized, after the set time, Pin 1 will connect to pin 3 and pin 1 and pin 4 will be open until input power is off. There is no time delay when turning off. Same goes with pin 8, 5 and 6.

7. Prepare a written report for this lab that includes a circuit diagram for each configuration from above. Explain clearly in your report
 1. What is the advantage of using separate start and stop switches for motor control instead of a normal switch for light?
 2. How do you connect two start switches if you want to turn the motor on by pressing any of the switches?
 3. How do you connect two stop switches if you want to turn the motor off by pressing any of the switches?
 4. How does thermal overcurrent protection work? Explain clearly with schematics.
 5. Why it is important to stagger start electric motors?
 6. Change the final circuit so that motor is in 240V supply and control circuit is in 120V supply.





Lab 8: PLC programming with ladder logic

Name: _____

Programmable Logic Controller (PLC) is an indispensable part of modern control systems. PLC is similar to a computer or a micro controller except that they are ruggedized for operation in harsher environment. In this exercise we will learn logic (ON or OFF) controls of motors and for self-repeating tasks.

Some terminologies:

Micrologix 1500: is a model of PLC hardware from Allen Bradley (AB).

RS LOGIX 500: is software also from Allen Bradley to program Micrologix.

Start Switch: Normally Open (NO) switch used to start something.

Stop Switch: Normally Closed (NC) switch used to stop something.

OBJECTIVE

- To get acquainted with PLC microprocessor and its essential components.
- Understand ladder logic programming style and basic rules.
- Practice program for a motor control and a traffic light control.

Open the RS LOGIX program

1. To start RS LOGIX 500 from: Start >> Programs >> Rockwell Software >> RS LOGIX 500 English >> RS Logix 500 English.
2. Create a new file (CTRL+N) or File >> New.
3. The program will ask for a processor type (PLC TYPE), select **Bul 1764 Micrologix 1500 LSP Series B**
If this is not an available option, select any processor, we will fix that when downloading the program to PLC. Click OK
4. Now you should see the **ladder view** pane with a single rung labeled --(END)--. This is the window where you will write your ladder logic program later.

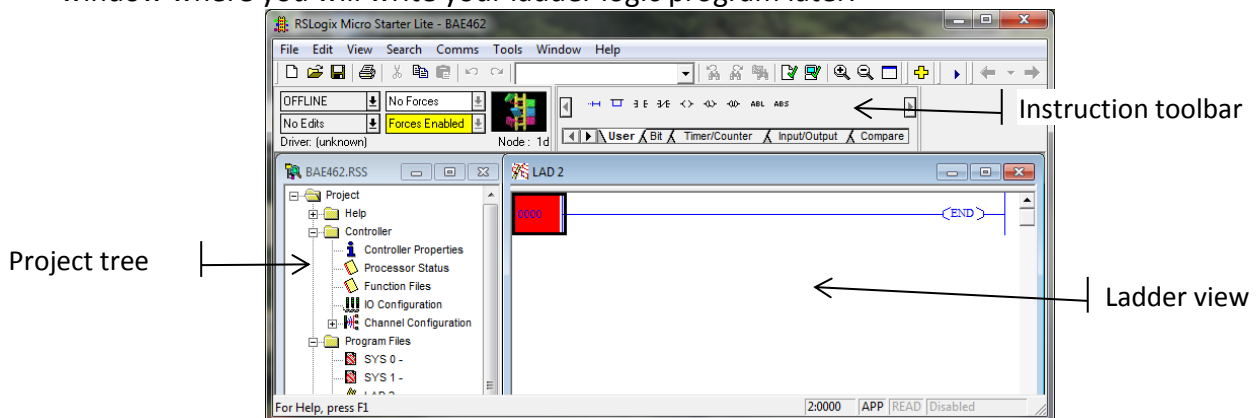


Figure 1: RS LOGIX 500 initial screen.

Example 1: Program a motor ON-OFF using a start and a stop switch.

Desired operation: The motor is off when program starts. The motor turns on when the start switch is pressed. The motor turns off when the stop switch is pressed.

Solution:

The logic: If STOP switch is closed and START switch is closed, then energized the coil. Once the coil is energized, auxiliary switch will bypass the START switch.

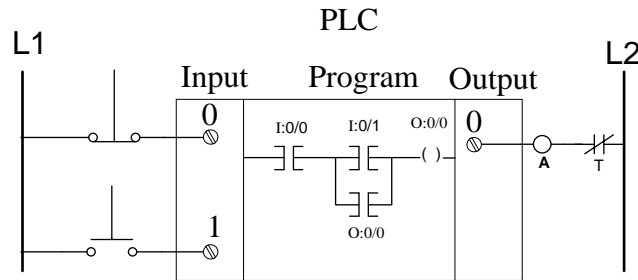


Figure 2: Schematic diagram for a motor control circuit. The ladder logic program uses two XIC (examine if closed) logics (I:0/0 and I:0/1) to test the input states. The branch auxiliary switch is linked to output file at O:0/0.

Making the real connection: Connect the motor as shown in the figure below which is equivalent to the one shown in schematics diagram above.

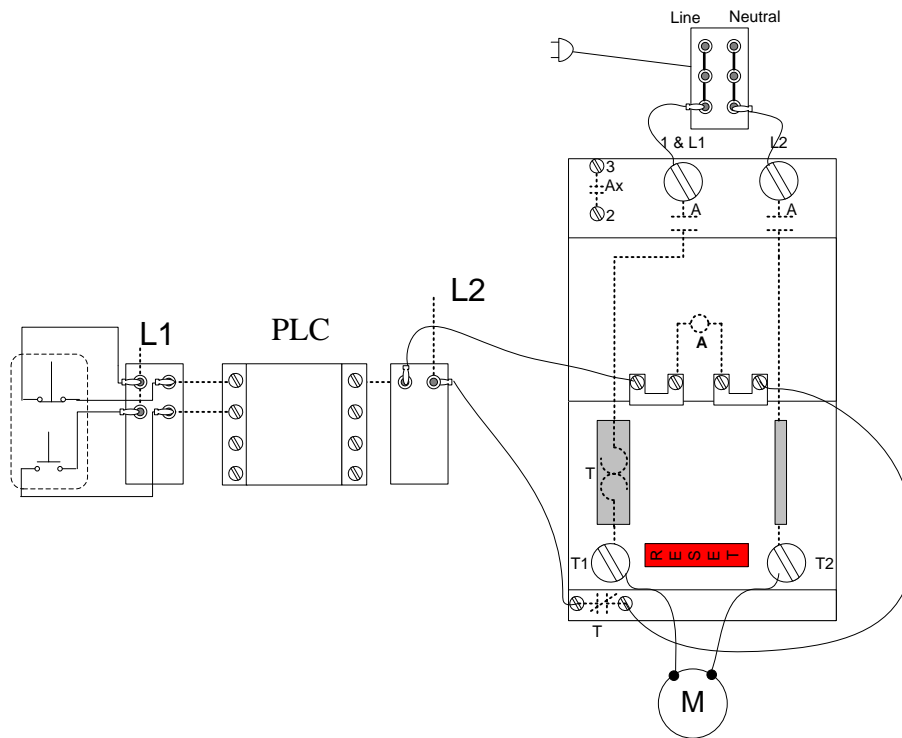


Figure 3: Actual connection of the switches and motor to PLC

Programming the logic: Click on the left side of the rung (marked 0000) that has **–(end)–** on it.

- From the instructions toolbar under user tab, click on the Examine If Closed (**XIC**) icon (\overline{E}) to examine the state of the STOP switch.

- b. Double click on the '?' mark and enter the switch address I:0/0. [Means the switch is connected to first input (#0) at first position (#0). The counting starts from 0.]
- c. Press enter and enter description of this address as 'STOP'. Click OK.
- d. Add one for XIC instruction to check the START switch state. [The program inserts new component after highlighted point, if the program inserts a component in a wrong place, you can drag to the place you want it to be]
- e. Type in the switch location - I:0/1.
- f. Add Turn on a bit (ON) to turn on the output.
- g. Type in the address of the output O:0/0 for the first external output and name it Motor1.
- h. Add an auxiliary relay similar to XIC switch and name it the same as O:0/0 so that this relay is linked to output O:0/0.
- i. Test you program for effort from Edit >> Verify file. Fix any error if displayed. Your program should look like similar to figure 4.

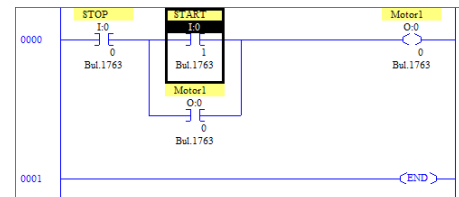


Figure 4: Motor control ladder logic

Downloading the program:

- a. Save your program as "YourTeamName_motor1.RSS" in a thumb drive and bring to the computer connected to PLC.
- b. Open the program in the computer connected to PLC.
- c. Double click on Controller Properties in Project tree view and make sure the controller selected is **Bul 1764 Micrologix 1500 LSP Series B**. If not select this from the list.
- d. To test your program, find the Online/Offline Toolbar and select **Download**. During the download process you will be go through following dialogue boxes:
 - a. Revision Note - press OK
 - b. RS LOGIX 500 - Are you sure you want to proceed - press OK
 - c. RSLOGIX 500 - SLC is in remote run mode... Continue? - press yes
 - d. Change back to run mode - press yes
 - e. Do you want to go online - press yes
- e. If everything goes well, your program has been successfully downloaded, the processor is running, the computer is connected to the PLC and is monitoring the operation.
- f. Start your program by pressing the START switch (physical switch).
- g. Notice that when the computer is connected and is monitoring, the relays that are activated are highlighted. If monitoring of process aren't needed, you can disconnect the serial cable used to program the PLC.

Example 2: Program a motor ON -OFF with delay

In this exercise we will assume that people around the motor must be warned with red light before the motor turns on (as in airport luggage conveyor belt). A red light should turn on 3 seconds before the motor starts. Change the ladder logic to as shown in figure 5.

The timer used in this exercise is on delay (TON). TON reset itself when the rung goes off then back to on again. When using a relay linked to a timer you enter it as T:0/DN. The DN (DONE) mean the relay will be activated when time is done.

The TON instruction begins to count timebase intervals when rung conditions become true. As long as rung conditions remain true, the timer adjusts its accumulated value (ACCUM) each evaluation until it reaches the 'Preset' value. The accumulated value is reset when rung conditions go false, regardless of whether the timer has timed out.

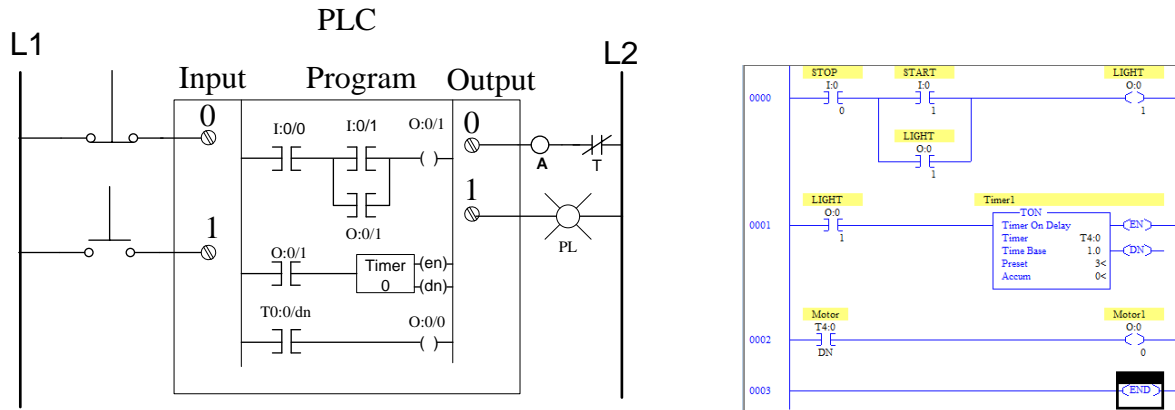


Figure 5: Modified PLC program to add a delay. Figure on right shows the actual ladder logic program

In most cases, you can use the following address format: X:y/z (X = file type letter, y = slot number, z = bit number if applicable)

- | | | | |
|--------------------|--------------|----|---------------|
| a. Outputs | O:0/0-O:0/11 | or | O0:0/0-O:0/11 |
| b. Inputs | I:0/0-I:0/9 | or | I1:0/0-I:0/9 |
| c. Internal Timers | T:0-T:255 | or | T4:0-T4:255 |

5. Save the previous program as MOTOR2.RSS.
6. Wire output 1 from PLC to red light.
7. Change the output and associated bit address to O:0/1 and name it 'Light'.
8. Change the auxiliary relay to address O:0/1.
9. Add an ON timer (TON). Timers are on the timer/counter tab on Instruction toolbar. Name the timer as T:0 [Program may change the timer to T4:0 automatically for default timer].
10. Add an XIC instruction on timer rung and link it to Light.
11. Add another rung, add an XIC and link it to T:0/DN and finally add a motor control output at address O:0/0 which is the same as in example 1.
12. Your diagram should look similar to the one shown in figure 5.
13. Check for errors and test your program by downloading into PLC.

Example Program for repetitive task:

In this exercise you will learn how to use ladder logic to build a traffic light as an example for repetitive task. The purpose of this example is to demonstrate how a repetitive task is programmed using ladder logic instead of starting and running manually. This example uses linked timers that one task after another and the last timer in the sequence resets the first timer to repeat the task.

Solution:

We will breakdown the problem into North-South side traffic (NS SIDE) and East-West (EW) side traffic. Let's first program the NS side to work. After that you will add the EW side to finish the solution.

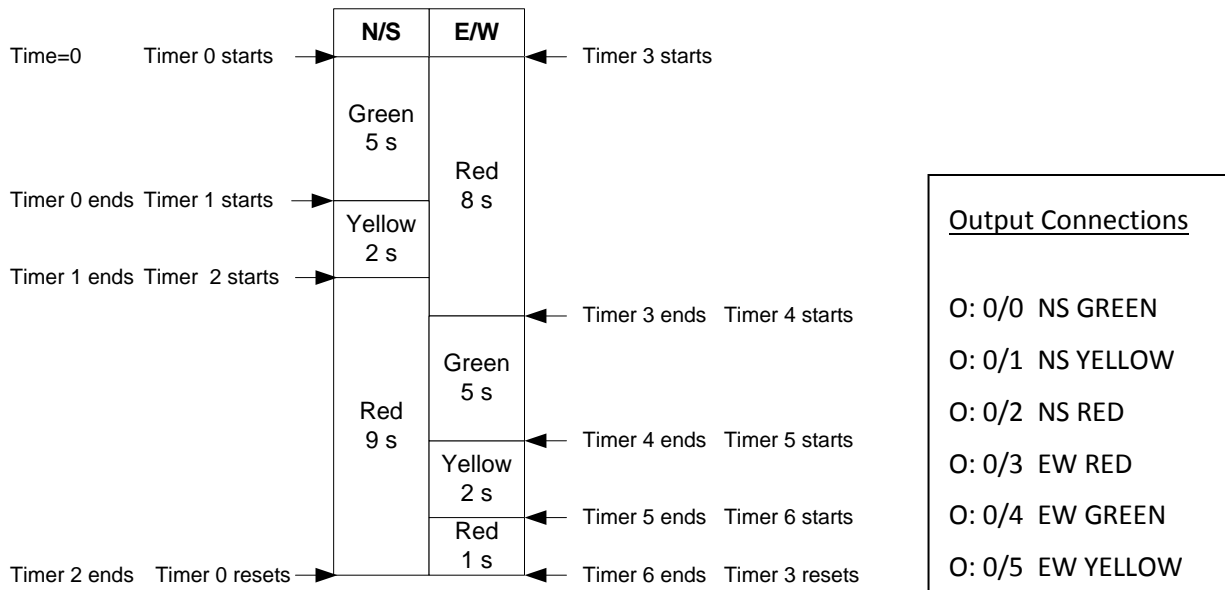


Figure 6: The traffic light problem. This figure shows one way to set the timers to do a repetitive task.

Programming the NS Side

14. NS GREEN is on, timer 0 starts, after 9 seconds, NS GREEN is OFF, NS YELLOW is on. Ladder logic for this is made as shown in figure 7.
15. Timer 0 should turn off NS RED after 9 seconds and Turn on NS GREEN. This logic can be implemented with a timer as shown in the figure 7.

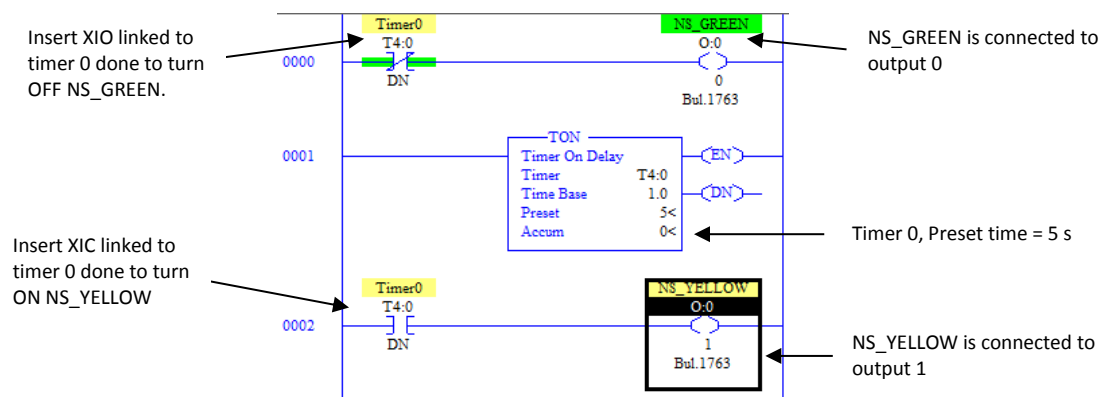


Figure 7: Timer 0 action. After 5 seconds Timer 0 will turn off the NS_GREEN output and Turn on the NS_YELLOW output.

16. End of timer 0 should start timer 1. At the end of timer 1, NS YELLOW is turned OFF and NS_RED is turned ON. Since timer 1 starts after timer 0 is done, a XIC switch inked to timer 0 to start timer 1 as in figure 8.
17. Timer 2 should turn off the NS_RED and Turn on the NS_GREEN after 9 seconds. In order to turn NS_GREEN, all we need to do is reset timer 0, which will close the rung connected to NS_GREEN. Resetting timer 0 in rung 1 opens the contact in rung 3 and resets timer 1 which in turn will reset timer 2. So the logic repeats itself. Complete your ladder logic as shown in figure 9.

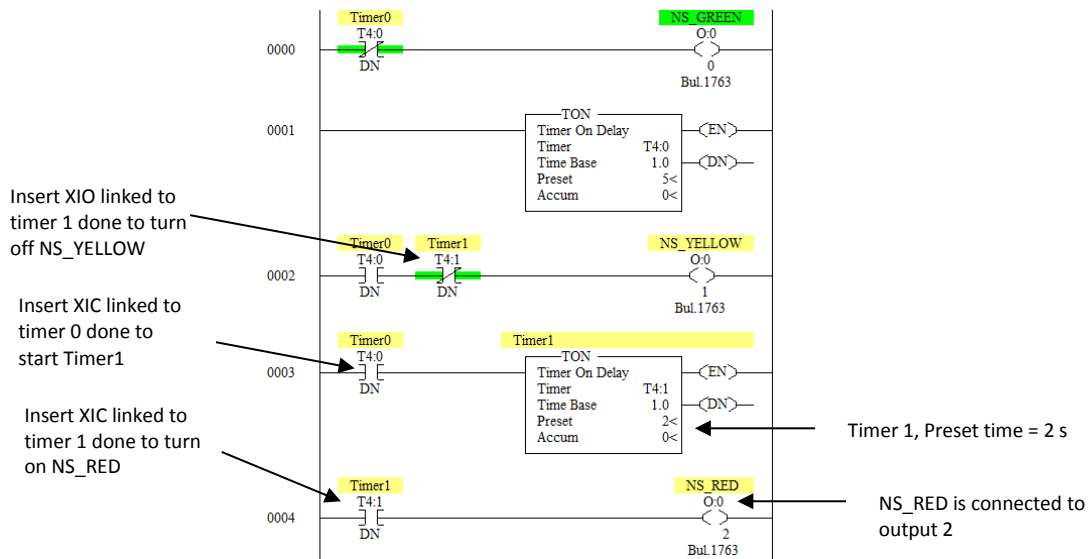


Figure 8: Timer 1 is started after timer 0 is done. After timer 1 is done it turns off the NS YELLOW and turns on NS_RED

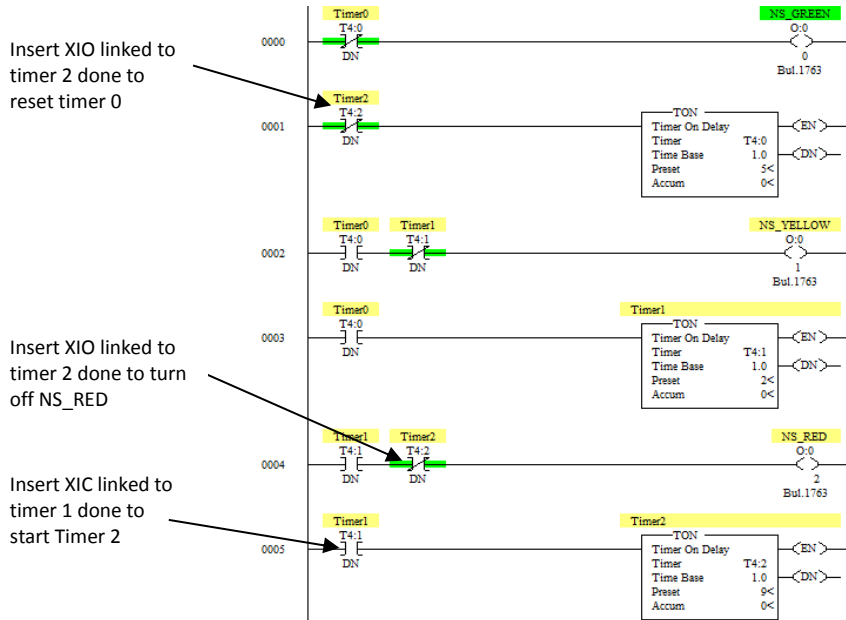


Figure 9: Timer 2 should turn off the NS_RED and reset the Timer 0

18. Check for errors, if no error then download and test your program.

Lab Work and Report

Develop complete ladder logic to control both NS and EW stop lights. Transfer your file into the computer attached to PLC. Download the program to the Micrologix 1500 PLC. Connect the lights and external switches (if not already connected), and test (debug, if necessary) the program. Demonstrate the program to one of the course instructor and turn in a copy of the ladder logic with your comments on the programming logic for credit.

Lab 9: SCADA system field trip

Name(s) _____

Feel free to ask questions that you may have other than basic questions listed below for recording.


1. What does the SCADA control system actually monitors and controls and what data are logged?
2. What is the supply voltage system for the plant and how much the electricity cost per kWh and how much utility bill is paid for electricity?
3. What is the biggest size of electric motor they have in the plant and what it is used for?
4. How the motors are started up (all at once or stagger start)?
5. What programming language is used to program the SCADA system?
6. How the operator is notified if there is a problem in the process line?
7. Write down the general sequence of main operation when the system is turned on and when turned off.

Lab 10: System modeling and controller design with Simulink

Name: _____

This lab introduces Simulink concepts necessary to model dynamic systems. Simulink is an extension of MATLAB for modeling, simulating, and analyzing dynamical systems. For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations.

Concept 1: Getting to Know Simulink

Step 1: Open up MATLAB and click on the Simulink icon  to open up the Simulink Library Browser (or type `simulink` in the matlab command line). Create a new block diagram by clicking File => New => Model.

Step 2: Create the model shown below by dragging the appropriate blocks from the library browser into the workspace (*Step* is contained in the *Sources* library; *Scope* is located in the *Sinks* library, and the *Gain* block can be found under *Math Operations*).

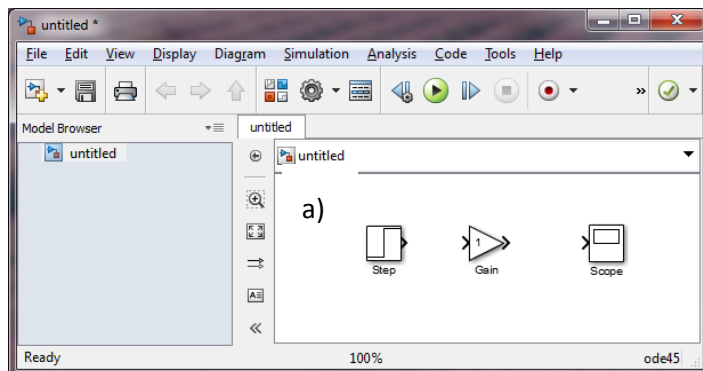


Figure 10: a) Simulink environment, b) Connected block

Step 3: Signals enable you to pass data between blocks. To connect the workspace above with signals, place your cursor over the output port of *Step* (notice that the pointer will change to a crosshair) and drag to the input port of the *Gain* block. Similarly connect the *Gain* block to *Scope*. **Note:** Simulink has an auto-connect feature. To see how this works, erase the newly added signal from the above step. Click on the *Gain* block to highlight it, hold down the control key and click on the *Scope* block.

The *Step* block has a default step time of 1 which denotes at what time in the simulation the step occurs. Change this value to 5 by double-clicking on it. The *Gain* block has a default value of 1 which has no effect on the signal. To change the value, double-click on it and type in 2 for the gain. Run the simulation by clicking the Play button. Double-click on the scope to view the signal. Once you are done viewing the signal, reset the step time back to 1.

Step 4: Labels can increase the readability and usefulness of a model. This may not be evident for small models like the one created thus far. However, when dealing with larger models containing several input, output, and gain blocks, it will help the user if the blocks are labeled. Simulink has default names for every block. To rename a block, simply click on the label.

A block label which is unnecessary can also be hidden. For example, the *Gain* block is easily recognized and, thus, does not need to be labeled. To remove the label, right-click on the block and then go to Format => Hide Name.

Another feature to make a model more readable is signal labeling. To label a signal, double-click on it to bring up a text box. Label the signal coming out of the *Gain* block as *y1*. Your workspace should now look like as shown in figure 1 (b).

Studying the behavior of a dynamic model

In this exercise we will study the heat exchanger problem we have discussed in the class. The system is in figure 2. The valve position can be varied from 0 to 100% and the coil output temperature also changes from 0 to 100% steady state value for corresponding change in valve position. Note that we are dealing with percentage to get rid of initial condition and to linearize the system. In reality the temperature may be changing from 40°F at 0% valve open to 90° at 100% valve open. We then treat 40° as 0% increase and 90° as 100% increase. Percent temperature change for set value *x* can be calculated as:

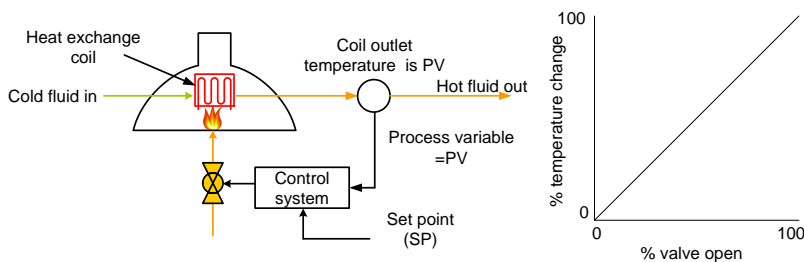
$$\frac{x-40}{90-40} * 100\%$$


Figure 11: Furnace system on left. Percent valve open and its corresponding steady state temperature is shown on the right. Pay attention to the word steady state as transient temperature may be different than steady state temperature. Changing to percentage linearizes the system.

Assuming the furnace can be modeled by a first order system with a time constant of 5 second, we can write the temperature-time equation as:

$$5 \frac{dT}{dt} + T = f(t)$$

where $f(t)$ is the percent valve open which may vary over time and T is the percent temperature change. If the Laplace transform of output variable is $O(s)$ and Laplace transform of forcing function is $F(s)$, then the ratio of $F(s)/O(s)$ is called transfer function.

$$5sO(s) + O(s) = F(s)$$

$$\text{Transfer function } G(s) = \frac{F(s)}{O(s)} = \frac{1}{5s+1}$$

The transfer function is determined with zero initial condition, assuming that the system was at rest at $t = 0$. The reason we assumed zero initial condition is that transfer function is a model of the system BEFORE you apply initial conditions.

Representation of system model in Simulink

Once you have the transform function, you can determine T for any valve position changing over time. We will study the system behavior with step input using Simulink.

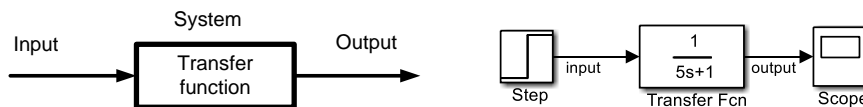


Figure 12: The system model on left and its representation in Simulink

Replace the gain block in figure 1(b) with transfer function. Transfer function can be found under continuous blocks. Double click on the transfer function block. Under **Numerator coefficients:** type [1] and under **Denominator coefficients:** type in [5 1]. In general an equation like $5s^2 + 3s + 1$ is entered as [5 3 1]. Click OK. Now double click on step block and change **Final Value:** to 100. Run the simulation and look at how T changed over time when the valve was completely opened. Include this plot in your lab report with proper explanations.

System response for any input

One of the advantages of having a transfer function is that the output from a system can be determined for any type of type varying input. For example say the fuel valve was open like in the figure shown in figure 4, how would the COT vary with time?

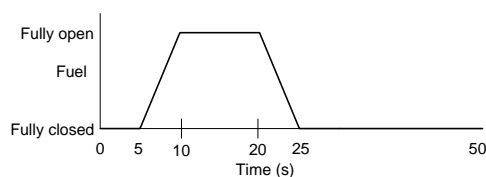



Figure 13: The valve opening over time. Fully open = 100, fully closed = 0

Delete the step function and replace with the system input from a step input to repeating sequence



under Sources. Double click on the block. Under Time values enter [0, 5, 10, 20, 25, 50] and for Output values enter [0, 0, 100, 100, 0, 0]. This defines the signal value at defined time points. The output at any other time is interpolated. Change the simulation stop time to 50s. To do this from **Simulation menu**, select **Model Configuration Parameters**. Then change the stop time to 50s.

Plotting in two axes

Say we want to plot both input and output signal. In order to do that, double click on scope icon to view the plot. Find the setting icon  on the plot toolbar. Change the number of axes to 2. You will now see

two inputs to the scope. Connect the input signal to the scope. Your diagram should look like the one shown in figure 5(b)

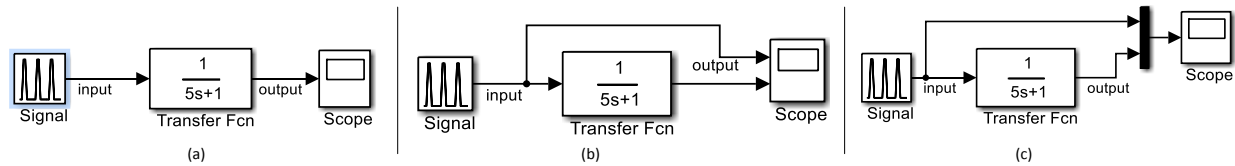


Figure 14: Representation of the input a. only output is plotted b & c, both input and output are plotted.

Alternatively you can plot both input and output in the same plot using multiplex box. Under signal routing library find 'Mux' block. Drag and drop mux block to modeling window and connect the signal as shown in figure 5(c).

Adding delay to the system response

One of the typical characteristics of the real life system is that there is some time delay in system output and input. The delay may be coming from several factors. Most of the real world higher order systems can be modeled using a dead time (also known as 'transport delay' or simply 'delay') and process lag. Process lag is the rate which output changes for step input after dead time to the input signal. Add



transport delay Transport Delay block from continuous library and insert between transfer function and the scope. To insert a block, just drag the block over the line between transfer function and scope and drop it. Double click on the transport delay and select 1s.

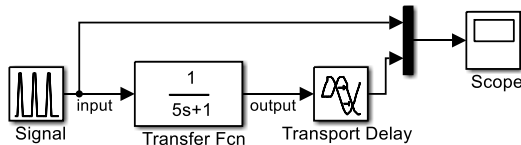


Figure 15: Transport delay is also known as 'dead time' or simply 'delay'. Transport delay is under 'Continuous' library.

Changing the simulation parameters

In the background, the Simulink calculates the output value iteratively at certain time intervals. When we have a transport delay of 1s, we want to make sure that the iteration time interval is less than 1s. To change the iteration step size (value of Δt) to 0.1s, select from Simulation menu >> Model Configuration Parameters. Change the solver type to Variable-Step and maximum step size to 0.1. Click OK and run the simulation.

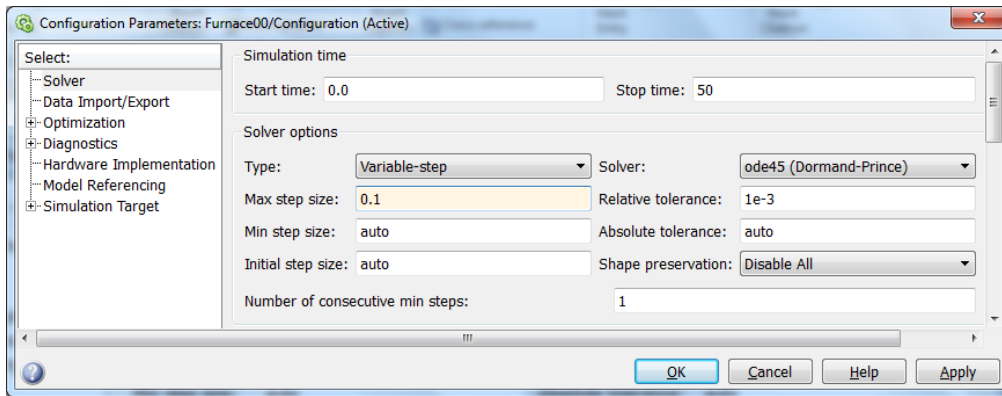


Figure 16: Solver configuration dialog box. Change the solver type to Variable-Step and maximum step size to 0.1.

System controls

One of the major objectives of system modeling is to be able to control the system effectively. In this section we will see how a PID controller is tuned for the system we have just discussed. A schematic diagram of a PID controller is shown below.

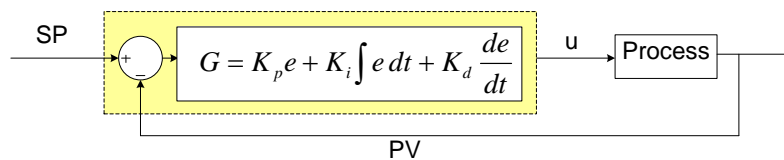


Figure 17: A feedback control system with a PID controller.

A PID control has only three gain terms K_p , K_i , and K_d to adjust to achieve a desired system behavior. K_p is called proportional gain, K_i is called integral gain and K_d is called differential gain. For a proportional control, K_i and K_d are set to zero. So the controller gain (G) for a proportional gain control is $= K_d$. Also for our furnace example, the value of u has to be between 0 and 100. Therefore we modify our system to include proportional controls as shown

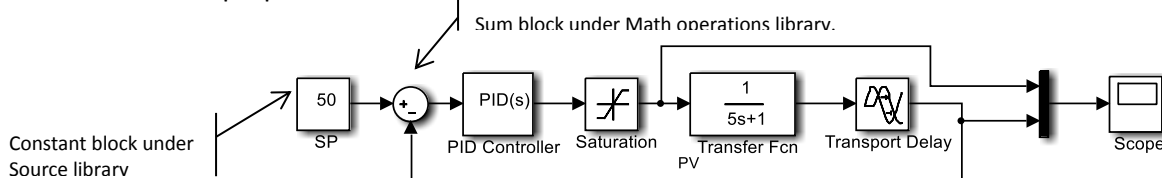


Figure 18: A Simulink PID controller with saturation and delay

Let's assume that transport delay is 1 seconds. Double click on the transport delay block and set Time delay: to 1. Click OK. Now double click on saturation. Set upper limit to 100 and lower limit to 0. Click OK. Now double click on Proportional gain and set P value to 1 (this is K_p), Set Integral (I): to 0 and Derivative (D): to 0. Click OK. Double click on Sum block and change the signs to +-. Name Constant block as SP and change value to 50.

Now run the simulation and see how the temperature increases with time. Also note the steady state temperature. Increase the gain and run the simulations. Write down your observation in the following table:

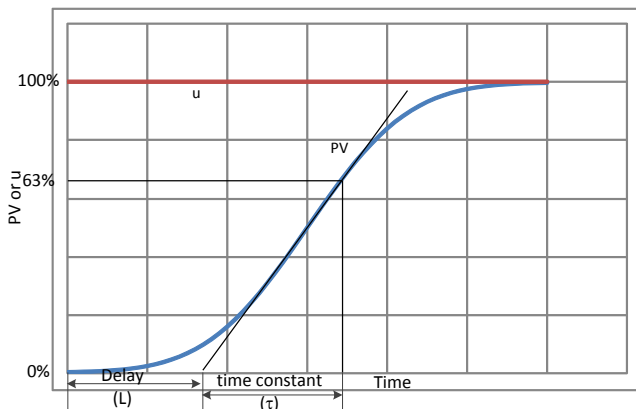
Gain	Steady state error $e_{SS} = SP - PV$ at steady state	System behavior
1		
10		
—		The PV never exceeds 10% of SP value and settles (not oscillate more than 2% of steady state value) within 10 seconds.

If the system should not have more than 10% overshoot of SP value and should settle (not oscillate more than 2% of steady state value) within 10 seconds what is the approximate maximum gain you can have with this system? What happens to allowable gain if the propagation delay is increased to 2 s? Write down your answers in the space provided below:

PID Controller Tuning

Although tuning a PID controller may look easy, for a real world system it may be quite complicated.

That trial and error manipulation of controller gains until you satisfy with system performance is called



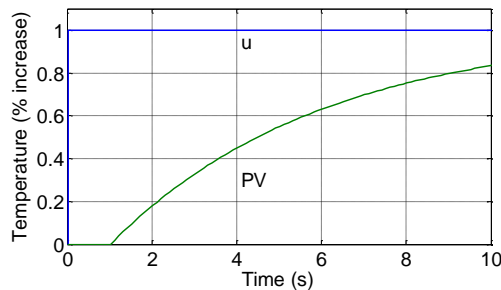
manual tuning. There are several methods of PID tuning; however, one widely used approach that helps you estimate the initial values of K_p , K_i and K_d is Ziegler–Nichols method. The method had a major influence on the practice of PID control for over half a century. The methods are based on characterization of process dynamics and simple equations. There are two methods proposed by Ziegler–Nichols. However we will use only one of them in this lab called step-response method.

This is method; feedback-loop of the controller is turned off. The system is given a unit step input and the response is measured. The response is then plotted and two dynamic parameters are derived as shown in figure 10 using PV response. The controller gains are then calculated using the following table.

PID type	K_p	K_i	K_d
P	$\frac{\tau}{L}$	0	0
PI	$0.9 * \frac{\tau}{L}$	$0.27 * \frac{\tau}{L^2}$	0
PID	$1.2 * \frac{\tau}{L}$	$0.6 * \frac{\tau}{L^2}$	$0.6 * \tau$

Figure 19: PID tuning using Ziegler-Nichols method

For our furnace problem, the furnace valve was opened 1% at $t = 0$ s. The following response was observed. Find the delay and time constant for this curve.



Of course you will find that delay = 1s and time constant is 5s, because that is what we started with. Now according to the Zeigler-Nichols method, there is the constant for our P control: $K_p = \frac{\tau}{L} = 5$, which is pretty close to what you may have though is a good number. If delay was 2s, then $K_p = \frac{\tau}{L} = 2.5$, any higher value will tend to have a higher overshoot.

Now let's change our controller to PI controller system:

For PI control, set the gain $K_p = 0.9 * \frac{\tau}{L} = 4.5$ and $K_i = 0.27 * \frac{\tau}{L^2} = 1.35$. Reset Transport delay to 1s.

Set these parameters to your PID controller and run the model. Look at your overshoot and see if that is acceptable. Now fine tune your gains using the following table which shows the effect of increasing each of the gain parameters.

	CL RESPONSE	RISE TIME	OVERSHOOT	SETTLING TIME	S-S ERROR
K_p		Decrease	Increase	Increase	Decrease
K_i		Decrease	Increase	Increase	Eliminate

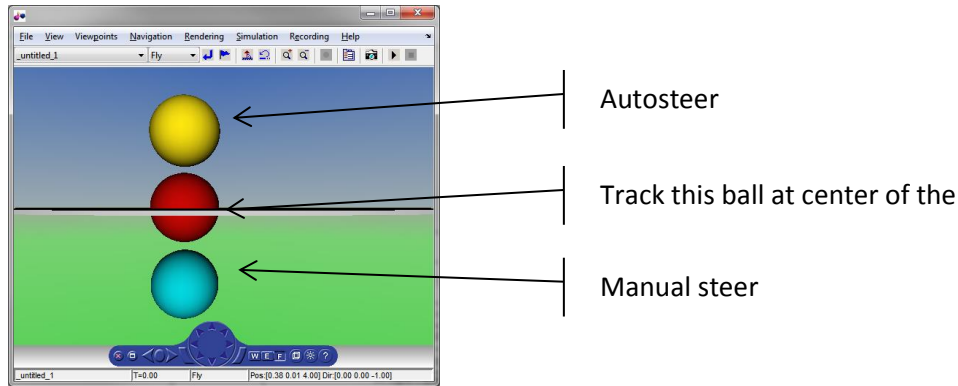
Write down your final parameters for your PI controller. Also include a plot showing your system response.

$$K_p = \underline{\hspace{2cm}} \quad K_i = \underline{\hspace{2cm}}$$

Steering wheel control

Let's assume that the above system represents a vehicle dynamics instead of a furnace system. The road is sinusoidally windy. You have though an auto steer system that will do the steering for you. The

objective is to follow the road as closely as possible. There are two vehicles, one in auto guidance and one you will drive. Let's see who will be able to track the road more closely. For this exercise, switch to one of the available steering wheel stations. Change the value of K_p and K_i from your previous exercise. Include a plot with SP (middle ball), PV from PID control (Top ball) and PV from manual control (bottom ball) positions over time. Compare tracking performance from the PID controller and the manual controller of the ball.



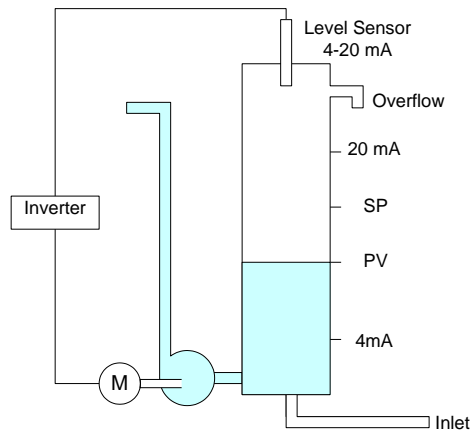
Turn in an individual lab report with your plots and explanations showcasing your understanding of a PID controller.

Lab 11: PID control with a Variable Frequency Drive

Name _____

The problem

Level control problem is usually encountered in several agricultural, environmental, industrial and other



operations. The problem is to maintain the water in a tank at a constant level by varying the inlet or outlet pump speed (outlet in this example). We are filling the tank from a garden hose and a vane pump is being used to pump the water out. The objective of this problem is to maintain the preset water level by controlling the pump speed. The pump is driven by a three phase induction motor being driven by a variable frequency drive.

The level sensor sends the signal between 4 and 20 mA to indicate the current water level. The sensor outputs 4 mA when the tank is empty and 20mA when the tank is full

Figure 20. The water level control problem. The pump needs to start only when error is negative i.e. when $SP < PV$

(Fig.1). Since error $e = sp - pv$, the error is positive when actual water level (PV) is below SP. Since frequency output from the VFD is proportional to error, the pump will run. In this problem we do not want the pump to run when PV is below SP and we want the pump to run when error is negative ($PV > SP$). **To fix the problem we will have to invert the sign of the error value.** When the error is negative, since VFD cannot produce negative frequency the frequency output will be zero. So pump will not run when PV is below SP and it will start running when water level gets above SP. We will learn how to achieve this in the following sections.

Introduction to a Variable Frequency Drive

A variable frequency drive (VFD, also known as inverter) is used for controlling the speed of an induction motor by controlling the frequency of the electrical power supplied to the motor.

In addition to controlling the motor at the set speed, VFD also helps to reduce starting current. When an induction motor is connected to a full voltage supply, it draws several times its rated current. By contrast, when a VFD starts a motor, it initially applies a low frequency and low voltage to the motor. Starting at a low frequency and voltage avoids the high inrush current. VFD drives such as one used in this lab are also capable of controlling feedback loop (PID control) and can be programmed to adjust the speed automatically.

Programming a Variable Frequency Drive

In this lab we are going to use HITACHI L100 model (**L100-007MFU2**) inverter. This particular inverter can run up to 1 HP, 3 phase motor from a single phase power supply. The inverter can be programmed either from the key pad or using a serial communication to the computer. Programming using key pad is cumbersome, so we will use a computer to program this unit.

Setting up the unit

1. Connect power to the inverter
2. Connect the serial cable from inverter to the computer.
3. Open the **Pro-Drive** software (The software comes with inverter).
4. Pro-Drive is simple software to change the various parameters of the controller. Take some time to make yourself familiar with the interface.
5. Create a new project in ProDrive.
6. Click on **Add Inverter** button and from the dialog box that appears, click **Detect and Read** button. This will read the current parameters stored into the drive.

There are several parameters you can change in this VDF. The parameters are grouped into A, B, C, D and F. Only the parameters used in this exercise are briefly described below.

Group 'A' Parameters: Standard settings

1. A_01: Output frequency source setting (00: Keypad potentiometer ;01: control terminal; 02: F1 setting)
2. A_02: Run command source (01: Control terminal; 02: Run Key on Keypad)
3. A_11 and A_12: Range of frequency output for input voltage or current range defined by parameter A_13 and A_14. Notice that the sign of error can be reverses by switching between A_11 and A_12 values in the right side of the figure.

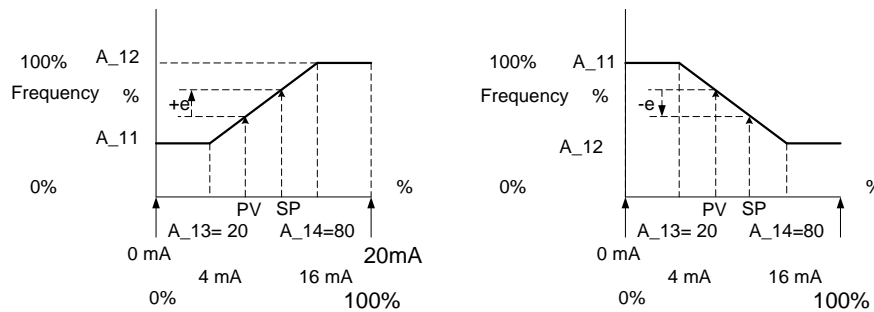


Figure 21. By interchanging the value of A_11 and A_12 parameters, we can reverse the sign of the error

4. A_20: PID setpoint.
5. A_71: PID enable (00:Disable, 01:Enable)
6. A_72: PID proportional gain($K_p = 0.2$ to 5)
7. A_73:PID Integral time constant ($T_i = 0$ to 150s)
8. A_74:PID Derivative time constant($T_d = 0$ to 100s)
9. A_75: PV scale conversion(frequency at PV multiplier from 0.01 to 99.99)
10. A_76: PV source setting (00: Current source; 01: Voltage source)

Group 'D' Parameters: Monitoring functions

11. D_01: Output frequency display
12. D_02: Output current monitor
13. D_03: Rotation direction
14. D_04: PID feedback display

Exercise: PID control

In standard operation, the inverter uses a reference source selected by parameter A_01 for the output frequency, which may be a fixed value (F_01), a variable set by the front panel potentiometer, or value from an analog input (voltage or current). To enable PID operation, set A_71=01. This causes the inverter to calculate the target frequency based on setpoint and the feedback signal from water level sensor. The water level sensor uses radio frequency to detect the travel time from sensor to the water level.

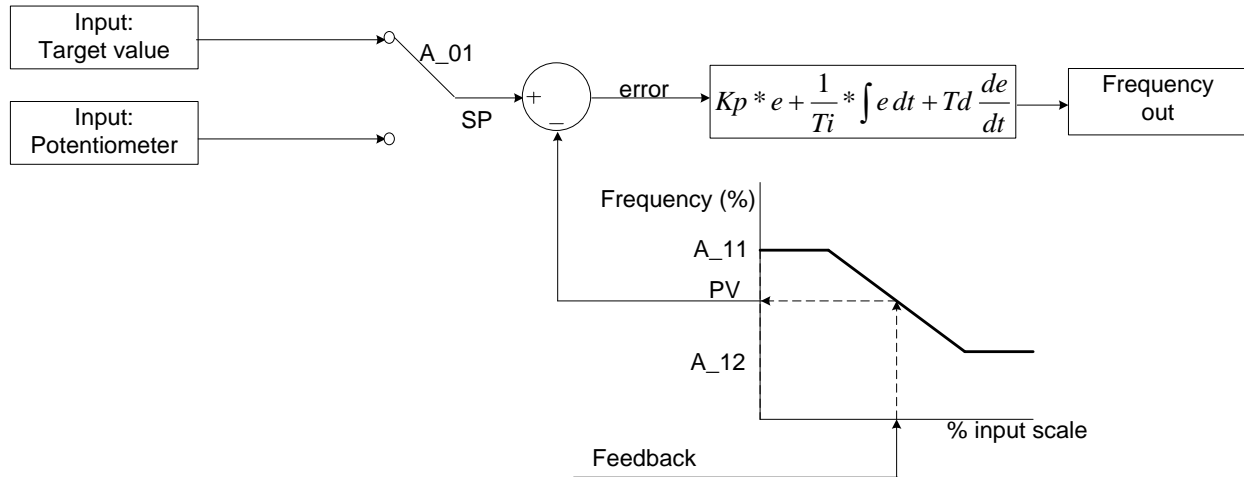


Figure 22. The feedback control loop. The feedback signal is converted to corresponding percentage of frequency output.

Calibration for water depth to percentage

Determine the 0% and 100% water level in terms of inches, so that the user can actually specify the desired water level in inches. Set the following parameter:

1. A_71 (=1): Turn on the PID control mode.
2. A_11 (=0): Output level corresponding to A_13.
3. A_12 (=100): Output level corresponding to A_14.
4. A_13 (=20): Starting point (% offset from 0 in 0-20 mA range).
5. A_14 (=100): End point (% offset from 0 in 0-20 mA range).
6. A_72 = 0.5, A_73 and A_74 to 0.
7. A_75 (=1) to display the water level from 0 to 100 (%)
8. A_76 = 00 for current input
9. Download your parameters to the controller

Empty the tank and start filling in slowly. Monitor the parameter d_4 which display the feedback value in percentage. Mark the water depth in inches when feedback value starts to increase from 0. Keep filling the water in until it reads 100 and record the water level. If you messed up with reading, drain the tank.

D_04 = 0 until water depth of _____ inches

D_04 = 100 at water depth of _____ inches

Finding control parameters

Tune the system using all three PID values using Ziegler Nichols method to control the water level at 50% of the level scale.

10. Set the setpoint water level to 50% ($A_{20} = 50$).
11. Set both integral (A_{73}) and differential gain (A_{74}) to 0
12. Set the proportional gain A_{72} (starting at 0.5 would be a reasonable start).
13. A_{11} (=100): Output level corresponding to A_{13} .
14. A_{12} (=0): Output level corresponding to A_{14} .
15. Download your parameters to the controller
16. Hit the Run button.
17. Open the water
18. Record the following:
Water level corresponding to 50% = _____ inch

Note that we set $A_{11}=100$ so that the error is reversed as discussed in previous section.

Record the steady state (or average of oscillating value) water level. Before you change to a new value of K_p , stop the controller, go off line, change the value and upload to the new values.

Kp	Water level (inch)			Steady state error (inch)
	Min	Max	Average	

19. Record the critical gain (K_c) when you get a steady oscillation in water level
Critical gain (K_c) = _____ Time between Peaks (P_c) = _____
Time between peaks is approximately the time between pump starts. Save the D4 curve as text file from **Monitor** icon on tool bar and providing the file name to save the values. Set sampling rate to every 1 second.
20. Use the following table to calculate of K_i and K_d .

Control Type	K_p	K_i	K_d
P	$0.50K_c$	-	-
PI	$0.45K_c$	$1.2K_p / P_c$	-
PID	$0.60K_c$	$2K_p / P_c$	$K_p P_c / 8$

21. Calculate the parameter value T_i (A_{73}) = $1/K_i$ and T_d (A_{74}) = K_d .

22. Try all P, PI and PID controller and record the d4 value in text file corresponding to Ziegler Nichols suggested parameters for each controller mode.
23. Change the parameters slightly (you may drop off the derivative term) from Ziegler Nichols's suggested values to get the best control system you can achieve. Write down the parameters and record the associated d4 curve.
24. Write your lab report with charts and explanations.