DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY (ISM) DHANBAD

Laboratory Manual

Course Name: Electrical Machine and Control Lab

Course Code: EEC376

for

V-Semester, B. Tech. (EE)

Location of the Lab: Room No. – 024 & 121, New Academic Building

EXPERIMENT NO.: 1

TITLE:

Study of matrix manipulation and graphs.

OBJECTIVE:

Acquaintance of MATLAB basics in terms of the following:

Number and matrix entry, Manipulation of matrices, Construction of matrices on various criteria and extraction of various terms/rows/column on some criteria and preparation of plot, data and graphs. Editing/arranging graphs.

OUTCOME:

Hands-on knowledge will be gained by the students about the MATLAB software. Students will learn basic MATLAB operations.

SAFETY PRACTICES AND DO's & DONT's:

- After completion of the work the data produced are to be saved in the folder as specified by the instructor.
- Power off of the computer with proper procedure to avoid software crushing or like.

APPARATUS REQUIRED:

S. No.	APPARATUS	SPECIFICATION
1.	Computer	Desktop / Laptop Processor __, OS __, Speed __, ROM __, Hard Disc size __.
2.	MATLAB Software	MATLAB ____ (version)

THEORY:

The following sample operations are to be carried out in MATLAB command window. The details may be found in the ‘help’ menu of the MATLAB software.

(i) Number and matrix entry:

Defining a scalar A, a matrix B, and an array C in MATLAB:

```
>>A = 3 ↵                                   % scalar variables require no special syntax

A =

    3

>>B = [1,2,3,4,5; 2,3,4,5,6; 3,4,5, 6,7; 4,5,6,7,8] ↵   % vectors are denoted by square brackets. Commas separate the elements within a row, and semicolons separate different rows.

B =

    1   2   3   4   5
    2   3   4   5   6
    3   4   5   6   7
    4   5   6   7   8

>>C= [1, 2, 3] ↵

C =

    1   2   3                               % an array is special case of a matrix that has only one row.
```

(ii) Manipulation of matrices:

```
>>D = [1, 2, 3; 3, 2, 5; 1, 6, 7] ↵

D =

    1   2   3
    3   2   5
    1   6   7

>>E = [2, 6, 8; 3, 4, 5; 7, 8, 9] ↵
```

```
E =

    2     6     8
    3     4     5
    7     8     9
```

>>D+E↵ % Matrix addition

```
ans =

    3     8    11
    6     6    10
    8    14    16
```

(a) >>D-E ↵ % Matrix subtraction

```
ans =

   -1    -4    -5
    0    -2     0
   -6    -2    -2
```

(b) Matrix multiplication (Two types of multiplication)

(1) >>D*E↵ % Nominal matrix multiplication

```
ans =

    29    38    45
    47    66    79
    69    86   101
```

(2) >>D.*E↵ % Element wise matrix multiplication

```
ans =

     2    12    24
     9     8    25
     7    48    63
```

(c) Matrix division (Four types of division)

(1) >>D/E↵ % Right matrix divide, D*inv(E)

% Command, F=mrdivide(D,E)

ans =

```
  0.0000    1.5000   -0.5000
 -2.0000   10.5000   -3.5000
  2.0000   -4.5000    1.5000
```

(2) >>D./E ↵ % Right array divide, dij*inv(eij)

% Command, F=rdivide(D,E)

% denotes element by element division

```
ans =
    0.5000    0.3333    0.3750
    1.0000    0.5000    1.0000
    0.1429    0.7500    0.7778
```

(3) >>D.\E ↵ % Left array divide, inv(dij)*eij

% Command, F=ldivide(D,E)

% denotes element by element division

```
ans =
    2.0000    3.0000    2.6667
    1.0000    2.0000    1.0000
    7.0000    1.3333    1.2857
```

(iii) Construction of matrices on various criteria and extraction of various terms/rows/column on some criteria:

a) >>B (2,5) ↵ % Extract an element in the 2nd row and 5th column of matrix B

ans = 6

b) >>B (:,4) ↵ % Extract all the elements of the 4th row of Matrix B

```
ans=   4
       5
       6
       7
```

c) >>B (:, 2:3) ↵ % Extracting 2nd and 3rd column

ans =

```
2 3
3 4
4 5
5 6
```

d) >>**S** = B (2:3,2:4) ↵ %Creating a sub-matrix S

S=

```
3 4 5
4 5 6
```

e) Deleting a Row or a Column in a Matrix

An entire row or column of a matrix can be deleted by assigning an empty set of square braces [] to that row or column. Basically, [] denotes an empty array.

>>B(4 , :) = []↵ % Deleting the 4th row of matrix B

B =

```
1 2 3 4 5
2 3 4 5 6
3 4 5 6 7
```

>>B (: , 5)=[] ↵ % Next, deleting the 5th column of matrix B

B =

```
1 2 3 4
2 3 4 5
3 4 5 6
4 5 6 7
```

Sample practice: Enter a 3×3 matrix, find its inverse and multiply it with the original matrix. Comment on the result.

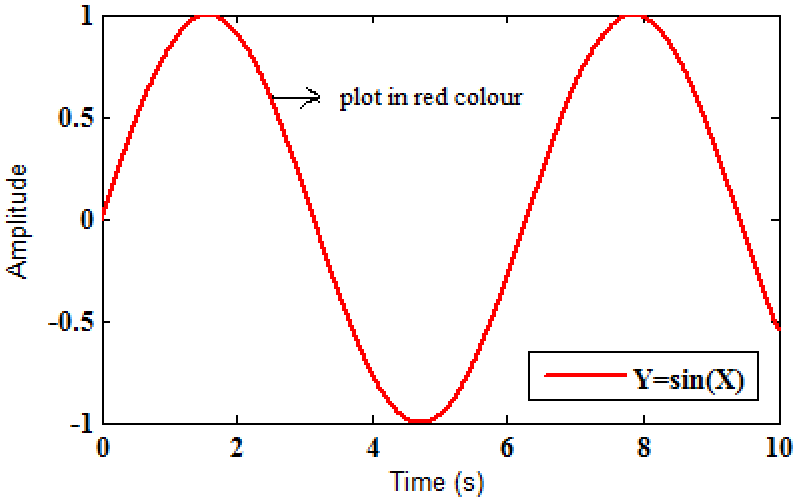
(iv) Graph Plotting and editing:

Define function

>>X=0:0.01:10; ↵

>>Y=sin(X) ↵

>>plot(X,Y) ↵



Further practice:

(i) Insert X-Label and Y-Label.

(ii) Insert Legend (Edit the font in Times New Roman with font size 12).

(iii) Change the plot color, line type and line width.

(iv) Plot sine and cosine curves in a single plot.

(v) Make line styles of sine and cosine curves different.

(vi) Draw sine and cosine curves in side by side plots.

EXPERIMENT NO.: 2

TITLE:

Control Systems study using MATLAB.

OBJECTIVE:

Transfer function models and control system configuration, time response (impulse response and step response), frequency response (Bode plot: magnitude and phase plot) and LTIVIEW.

OUTCOME:

In this experiment, the student will learn about finding various Time response and Frequency response curves of a control system.

SAFETY PRACTICES AND DO's & DONT's:

- After completion of the work the data produced are to be saved in the folder as specified by the instructor.
- Power off of the computer with proper procedure to avoid software crushing or like.

APPARATUS REQUIRED:

S. No.	APPARATUS	SPECIFICATION
1.	Computer	Desktop / Laptop Processor __, OS __, Speed __, ROM __, Hard Disc size __.
2.	MATLAB Software	MATLAB ____ (version)

THEORY:

The following sample operations are carried out in MATLAB command window. The details may be found in the 'help' menu of the MATLAB.

(i) Transfer function models and control system configuration

Entry of Transfer Functions of a linear model and to represent it in the form of:

(a) pole-zero model
(b) state-space model

Consider two transfer functions:

>>*sys1*=tf ([1, 0], [2, 3]) ↵ *% Entry of a transfer function*

sys1 =

$$\frac{s}{2s+3}$$

>>*sys2*=tf ([1, 2], [1, 4]) ↵

sys2 =

$$\frac{s+2}{s+4}$$

>>sys3= series (sys1, sys2) ↵ % connects the transfer functions sys1 and sys2 in series

sys3 =

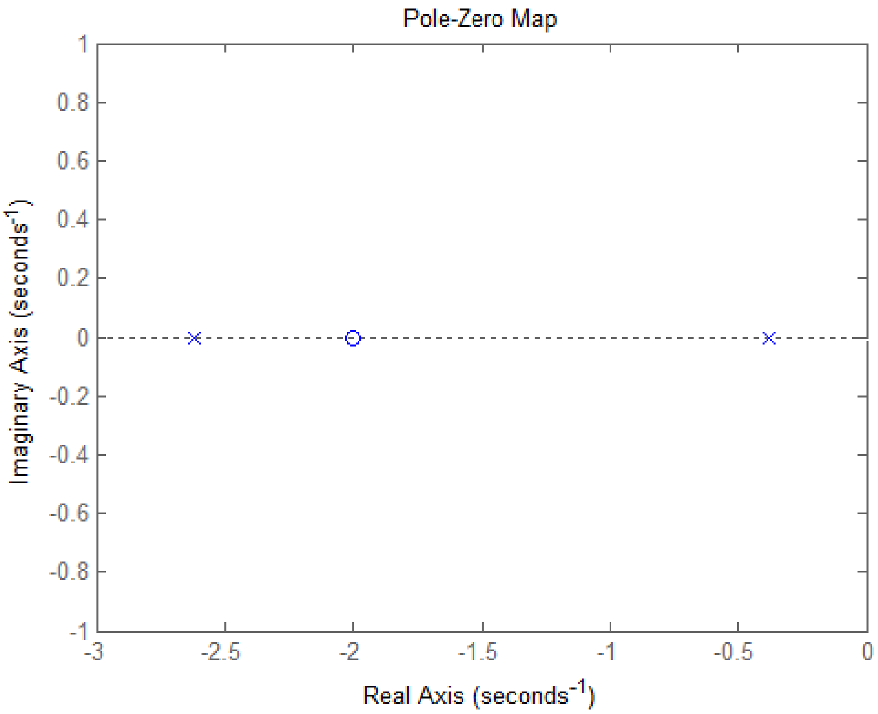
$$\frac{s^2+2s}{2s^2+11s+12}$$

>>sys4=zpk(sys3) ↵ % creates a continuous-time zero-pole-gain (zpk) model

sys4 =

$$\frac{0.5s(s+2)}{(s+4)(s+1.5)}$$

>> pzmap (sys4) ↵



>> sys5=ss(sys3) ↵ % converts the dynamic system sys to the state-space representation.

sys5 =

a =

	x_1	x_2
x_1	-5.5	-3
x_1	2	0

b =

	u_1
x_1	2
x_2	0

c =

	x_1	x_2
y_1	-0.875	-0.75

d =

	u_1
y_1	0.5

(ii) Time response and frequency response

>>*sys6*=tf ([1], [1, 1]); ↵ *% Defining a transfer function*

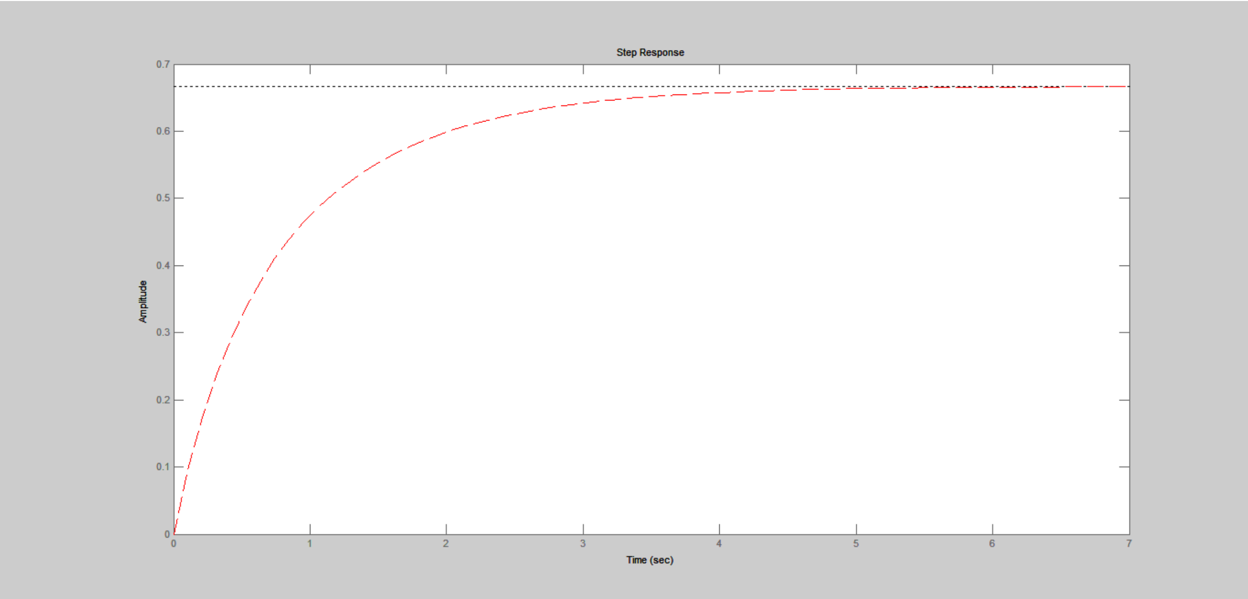
>>*sys7*=tf ([1, 1], [1, 2]) ; ↵

>> sys8 = feedback (sys6,sys7) ↵ %Feedback connection of two input/output systems

Transfer function:

s + 2
----
s^2 + 4 s + 3

>> step(sys8,'r--') ↵ % computes the step response of sys8



>> sys9=zpk (sys8) ↵

Zero/pole/gain:

(s+2)

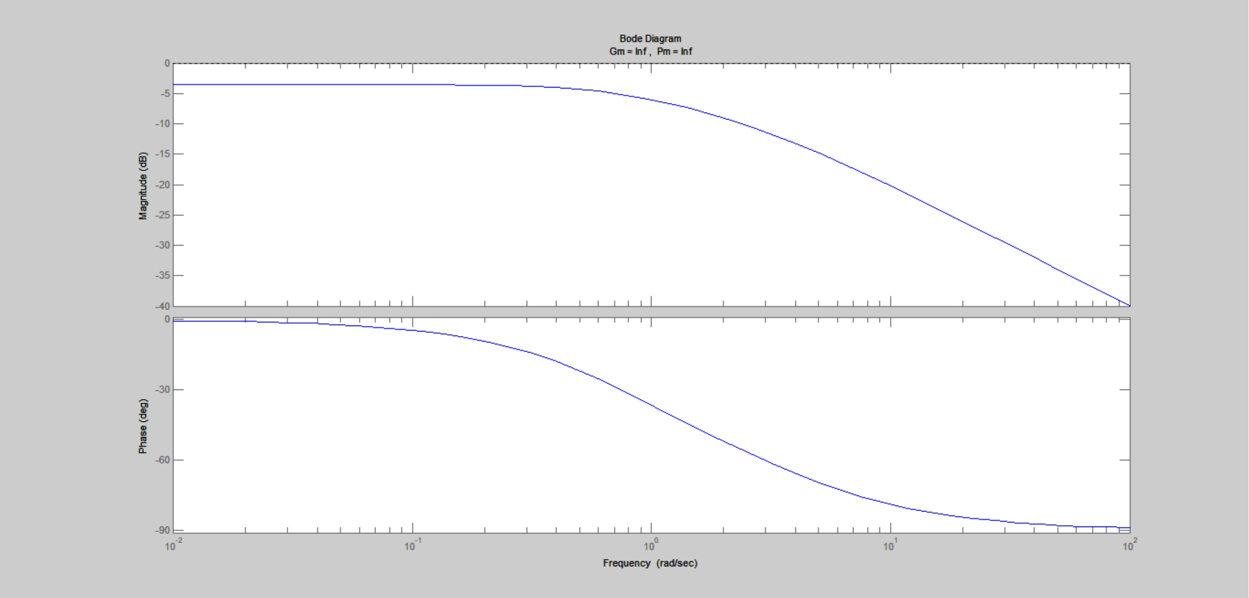
(s+3) (s+1)

>> margin(sys9); ↵ % shows bode plot with stability limits Check difference with “bode” command.

>> [Gm,Pm,Wcg,Wcp]= margin (sys_9) % computes the gain margin Gm, the phase margin Pm, and the associated frequencies Wcg and Wcp

(iii) ltiview

>>ltiview(sys7) ↵ %LTI Viewer is a graphical user interface (GUI) that can display several plot types (step, impulse, bode, Nyquist, Nichols, zero/pole and any number of models in a single viewer plot responses.



QUESTIONS FOR STUDENTS:

Plot all the above curves for the transfer function (unit step input)

$$(100) / (s^2 + 10s + 100)$$

EXPERIMENT NO.: 3

TITLE:

Study of time response and frequency response using MATLAB using M-file.

OBJECTIVE:

Pole-zero diagram, time response and bode diagram plotting from system function using M-file. Determining the locus of roots of a polynomial and learning to use LTIVIEW.

OUTCOME:

Hands-on knowledge will be gained by the students about stability of a system using pole zero plot, time response and bode diagram using M-file in MATLAB. Students will learn to determine the locus of roots of a polynomial by using LTIVIEW of MATLAB.

SAFETY PRACTICES AND DO's & DONT's:

- ➢ After completion of the work the data produced are to be saved in the folder as specified by the instructor.
- ➢ Power off of the computer with proper procedure to avoid software crushing or like.

APPARATUS REQUIRED:

S. No.	APPARATUS	SPECIFICATION
1.	Computer	Desktop / Laptop Processor __, OS __, Speed __, ROM __, Hard Disc size __.
2.	MATLAB Software	MATLAB ____ (version)

THEORY:

The following operations are carried out in MATLAB command window. The details may be found in the 'help' menu of the MATLAB.

Introduction: An m-file, or script file, is a simple text file where you can place MATLAB commands. MATLAB reads the commands and executes them exactly as it would if you had typed each command sequentially at the MATLAB prompt. All m-file names must end with the extension '.m' (e.g. test.m).

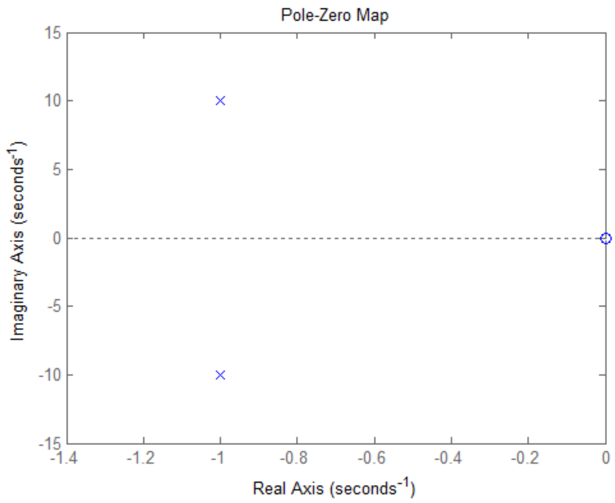
Opening an M-file: To create an m-file, choose **New** from the **File** menu and select **Script**. This procedure brings up a text editor window in which you can enter MATLAB commands. To open an existing m-file, go to the **File** menu and choose **Open**.

Saving an M-file: To save the m-file, simply go to the **File** menu and choose **Save** (remember to save it with the '.m' extension).

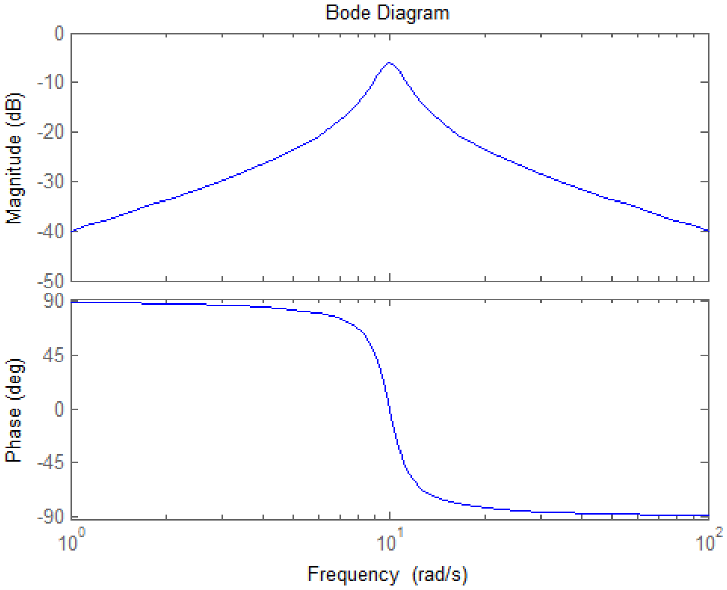
Executing an M-file: After the m-file is saved (with the name filename.m) in the current MATLAB folder or directory, you can execute the commands in the m-file by simply typing filename at the MATLAB command window prompt.

(i) To find pole-zero diagram, step response and bode diagram from system function using M-file

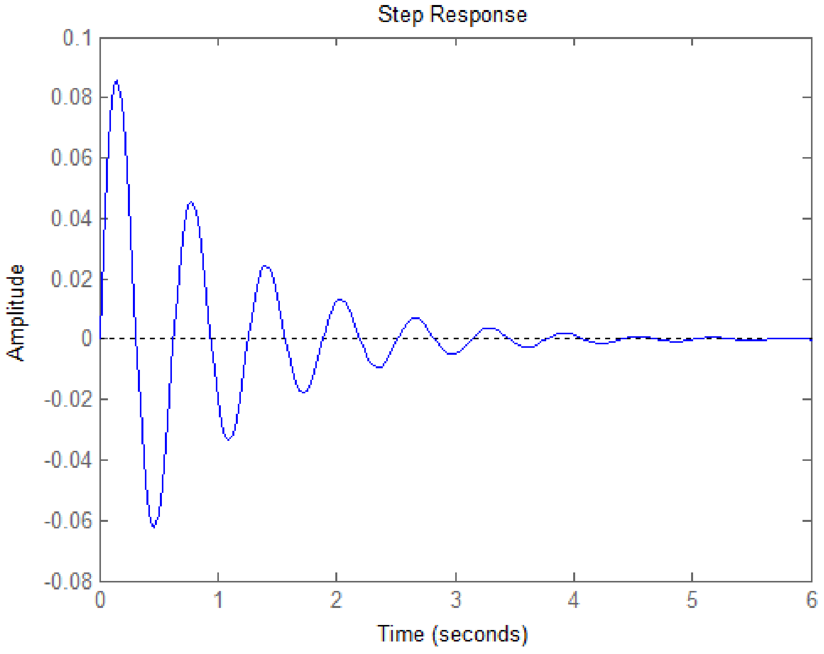
```
>> num=[1 0];            %Define numerator polynomial
>> den=[1 2 101];        %Define denominator polynomial
>> figure (1)            %Create figure 1
>> pzmap(num,den);       %Plot Pole-Zero diagram in figure 1
```



```
>> figure(2);                    %Create figure 2
>> bode(num,den);                %Plot the Bode Diagram in figure 2
```



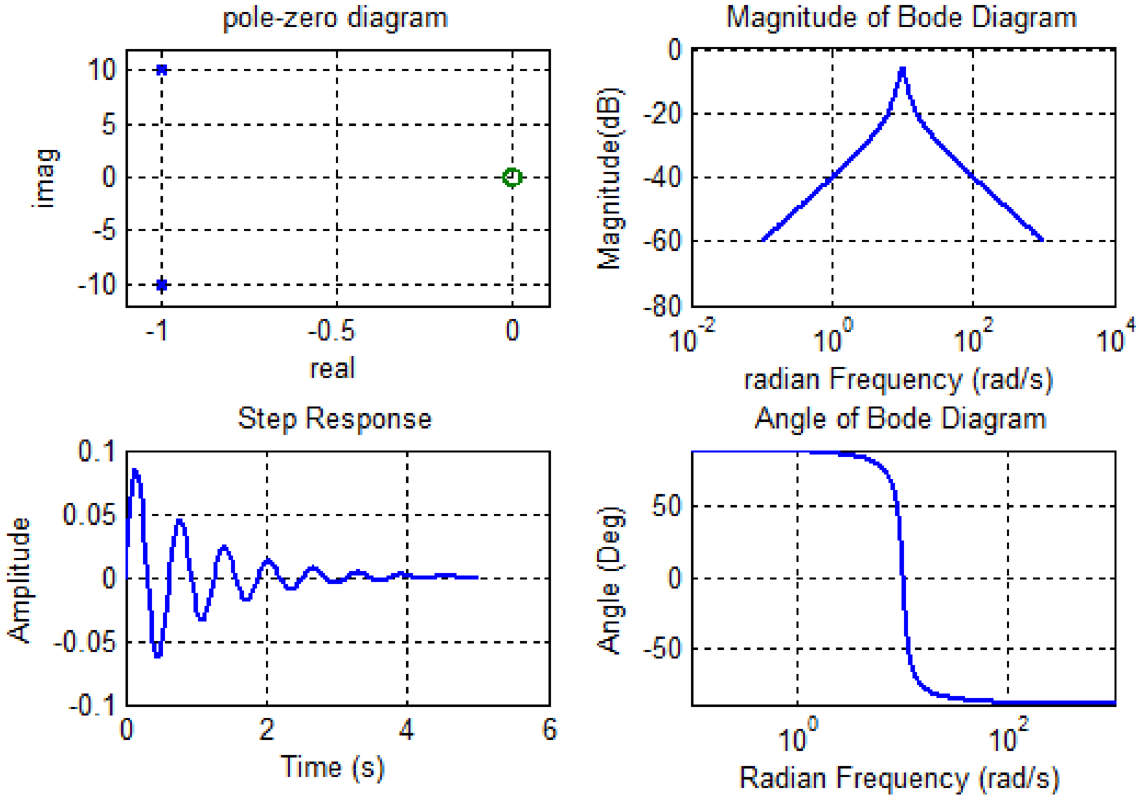

```
>> figure(3);                    %Create figure 3
>> step(num,den);                %Plot the step response in figure 3
```



The following script plots the same results but display the results with more control over the appearance of the plot.

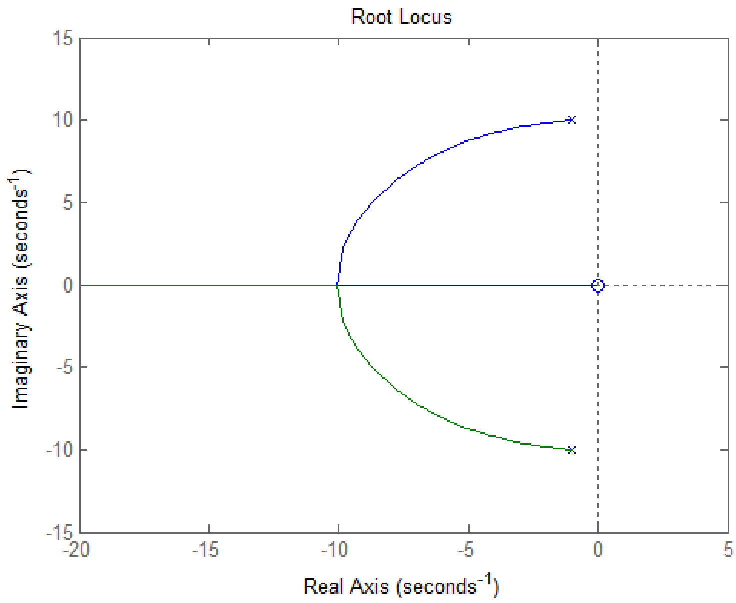
```
>> t=linspace(0,5,201);                 % Define a time vector with 201 equally-spaced points
                                        from 0 to 5s.
>> w=logspace (-1,3,201);               % Define a radian frequency vector with 201
                                        logarithmically- spaced points from 10^-1 to 10^3 rad/s
>> num=[1 0];                           % Define numerator polynomial
>> den=[1 2 101];                       % Define denominator polynomial
>> [poles,zeros]=pzmap(num,den);        % Define poles to be a vector of the poles and zeros to be
                                        a vector of zeros of the system function
>> [mag,angle]=bode(num,den,w);         % Define mag and angle to be the magnitude and angle
                                        of the frequency response at w
>> [y,x]=step(num,den,t);               % Define y to be the step response of the system function
at t
>> figure(1)                            %Create figure 1
>> subplot(2,2,1)                       % Define figure 1 to be a 2 x 2 matrix of plots and the
                                        next plot is at position (1,1)
>> plot(real(poles),imag(poles),'x',real(zeros),imag(zeros),'o');
                                        %Plot pole-zero diagram with x for poles and 0 for zeros
>> title('Pole-Zero Diagram');          %Add title to the plot
>> xlabel('Real');                      %Label x axis
>> ylabel('Imaginary');                 %Label y axis
>> axis([-1.1 0.1 -12 12]);             %Define axis for x and y
>> grid;                                % add grid to the plot
>> subplot(2, 2, 2);                    %Next plot goes in position(1,2)
>> semilogx(w,20*log10(mag));           % Plot magnitude logarithmically in w and decibels in
                                        magnitude
>> title('Magnitude of Bode Diagram');
>> ylabel('Magnitude(dB)');
>> xlabel('radian Frequency (rad/s)');
>> grid;
>> subplot(2, 2, 4);                    %Next plot goes in position (2,2)
>> semilogx(w,angle);                   %Plot angle logarithmically in w and linearly in angle
>> title('Angle of Bode Diagram');
>> ylabel('Angle (Deg)');
```

```
>> xlabel('Radian Frequency (rad/s)');
>> axis([0.1 1000 -90 90]);
>> grid;
>> subplot(2, 2, 3);
>> plot(t,y);                    %Plot step response linearly in t and y
>> title('Step Response');
>> xlabel('Time (s)');
>> ylabel('Amplitude');
>> grid;
```

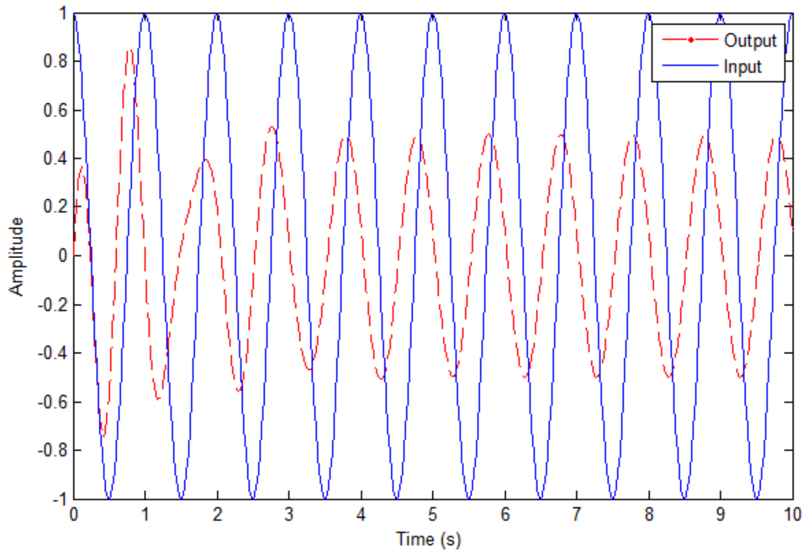


(ii) To determine the locus of roots of a polynomial

```
>> num=[1 0];                    %Define numerator polynomial
>> den=[1 2 101];                %Define Denominator polynomial
>> rlocus(num,den)               % Plot root locus
```




```
>> num=[5 0];                       %Define Numerator polynomial
>> den=[1 2 101];                   %Define Denominator Polynomial
 >> t=linspace(0, 10, 401);         %Define a time Vector
>> u=cos(2*pi*t);                   %compute the cosine input function
>> [y,x]=lsim(num,den,u,t);         %compute the response to the input u at time t
>> plot(t,y,'r',t,u,'b');           %Plot the output in red and input in blue
>> xlabel('Time (s)');
>> ylabel('Amplitude');
```



EXPERIMENT NO.: 4

TITLE:

Introduction to SIMULINK for control system study.

OBJECTIVE:

Study of library blocks of Simulink and develop control system configuration in Simulink. Find response at different node of the control system configuration and analyse the response characteristics in command window.

OUTCOME:

In this experiment, the student will learn about Simulink modelling in MATLAB using its Library browser and compare the corresponding results in command window.

SAFETY PRACTICES AND DO's & DONT's:

- After completion of the work the data produced are to be saved in the folder as specified by the instructor.
- Power off of the computer with proper procedure to avoid software crushing or like.

APPARATUS REQUIRED:

S. No.	APPARATUS	SPECIFICATION
1.	Computer	Desktop / Laptop Processor __, OS __, Speed __, ROM __, Hard Disc size __.
2.	MATLAB Software	MATLAB ____ (version)

(i) STUDY OF LIBRARY BLOCKS OF SIMULINK

Simulink (Simulation and link) is an extension of MATLAB that offers modelling, simulation and analysis of dynamical system under a Graphical User Interface (GUI) environment. Simulink is based on block diagrams of dynamic systems. The Simulink library has blocks which are organized as functional groups. Some of the groups are:

a) **Sources**: In this group the blocks for the generation of input signals (Step, sinusoid) are present.
b) **Sinks**: This group contains blocks for the graphical visualization of signals.

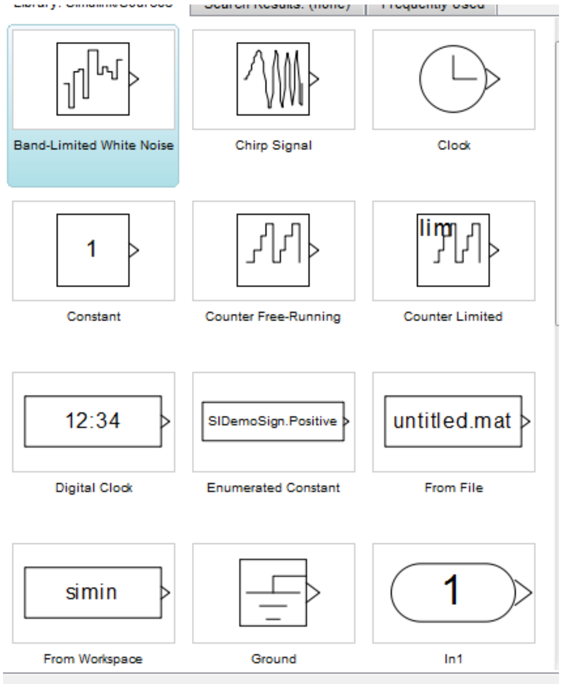


Fig. 1: Sources

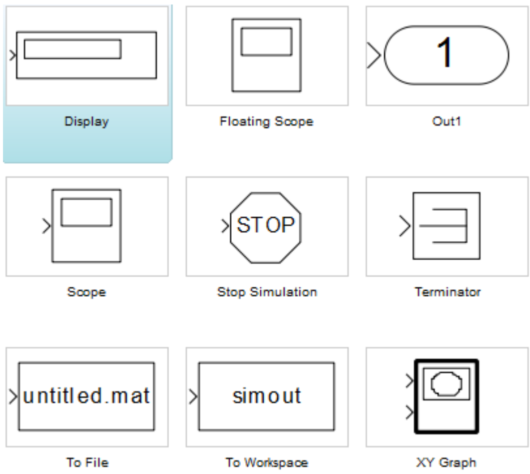
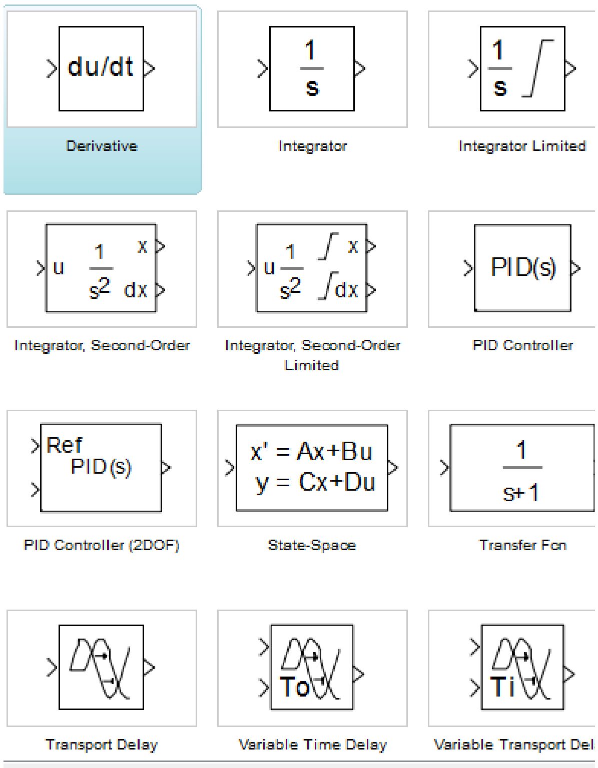


Fig. 2: Sinks

c) **Math**: This group has the blocks for the mathematical elaboration of signals.
d) **Continuous**: Blocks of this group define (continuous) transfer functions.



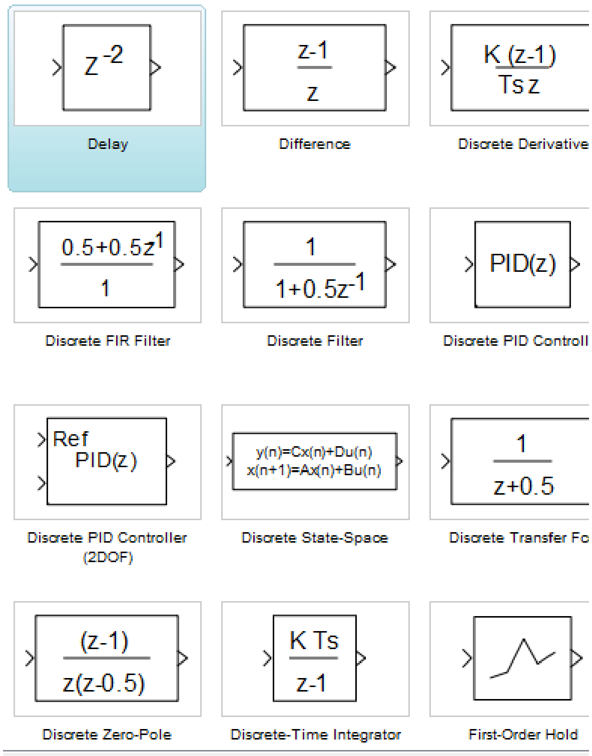


Fig. 3: Continuous. Fig. 4: Discrete.

The most commonly used blocks are

- Clock: - It outputs the current simulation time at each simulation step.
- Constant: - For generating a constant value.
- Step: - For generating a step function.
- Ramp: - For generating a ramp function.
- Sine wave: - For generating a sinusoidal function.
- Scope: - It displays the input signal as a function of time.
- XY Graph: - It produces the graphics of a signal y (on the second input) as a function of the signal x (On the first input).
- To Workspace: - It saves the samples of the input signal in a MATLAB variable.
- Transfer Function – It allows to specify a transfer function by specifying the vectors containing the co-efficient of numerator and denominator.
- Zero-Pole: - It defines the transfer function by specifying the vectors containing poles and zeros of the transfer function.

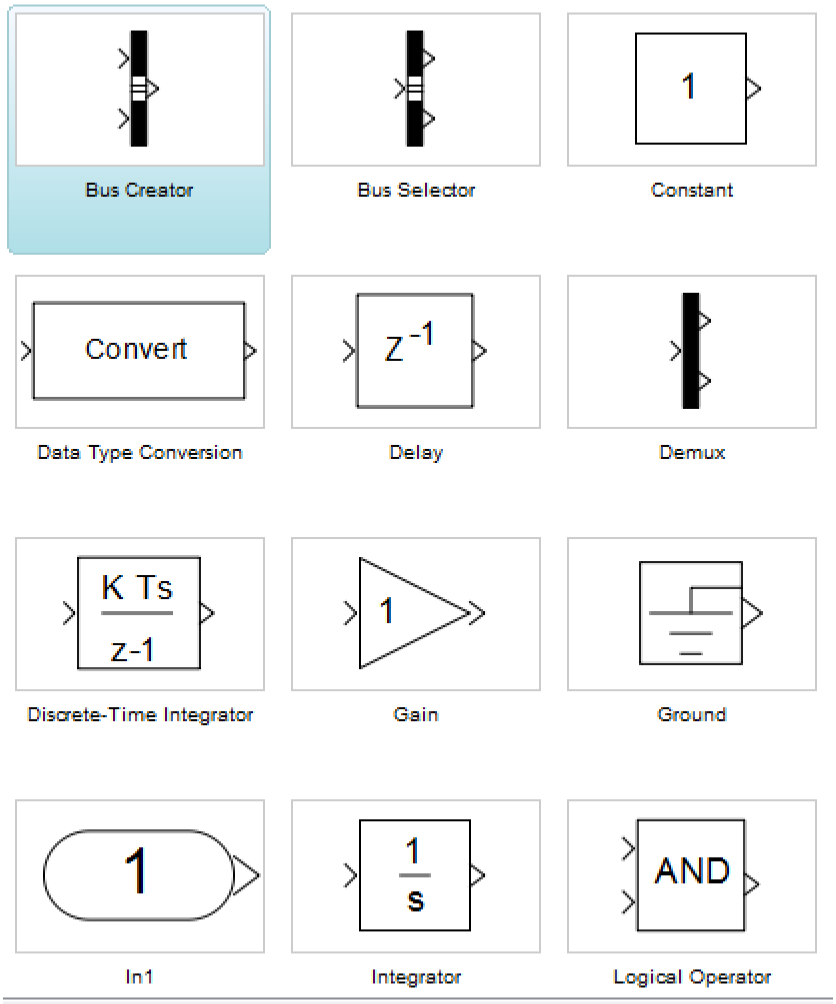


Fig. 5: Commonly used blocks.

(ii) Developing control system configuration in Simulink

At the MATLAB prompt type >> SIMULINK. This command displays a new window containing icons for the subsystem blocks that make up the standard library. These subsystems can be opened (by double clocking) to produce the windows containing the prototype blocks to be copied into your models. Click on File and New, then move the window to a comfortable positions.

Open Sources, Sinks, Linear, and Connections by double clicking on the icon with the left mouse button. Move the windows to a comfortable position. Blocks can be copied from one window to another by dragging them from the original location to the new location by holding down the left mouse button. Assemble the following diagram in your working window

[Step input->Sources; Sum & Transfer Fun-> Linear; Auto-Scale Graph->Sinks]

1) Open-loop configuration:

a) Enlarge the blocks, arrange into order, and wire them together as shown. Block are expanded by dragging the corner indicators outward with the mouse; To wire a block, drag the block's output arrow to the input arrow of the next icon using the left mouse button.

b) Double click on the transfer function block and change the coefficient.

c) Click on the file, then save and name your model tf_sim

d) Click on the simulation, then parameters and set stop time to 6 and max step size to 0.1

e) Click on simulation, then start and observe the trace on the auto scale graph.

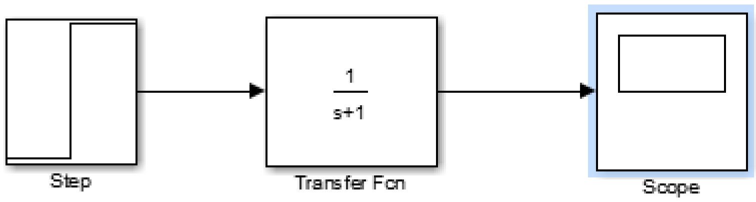


Fig. 6: Simulink model for open – loop configuration.

2) Closed-loop configuration:

a) Consider a transfer function, $G(\boldsymbol{s}) = \frac{3S+9}{(S^2+4S+16)}$, the step response of a unity feedback system in Simulink having forward path transfer function is to be obtained.

b) The model consists of blocks: step, transfer function, sum and scope.

c) Double click on the transfer function block and change the coefficient. Now modify the model to the closed loop feedback control system shown below.

d) Double click on the sum block and set the second symbol to – (minus sign).

e) Wire the feedback: Get a tap off the transfer function wire with a right click hold drag and pull it down below the icon. Point towards the left click hold drag to add a new wire to the head of the feedback arrow and move left under the sum block. Repeat this procedure to go up then right into the – input of the sum.

f) Click on simulation, then start and observe the trace on the graph window.

*Notice that with feedback we have increased the speed of the response.

g) Save the model.

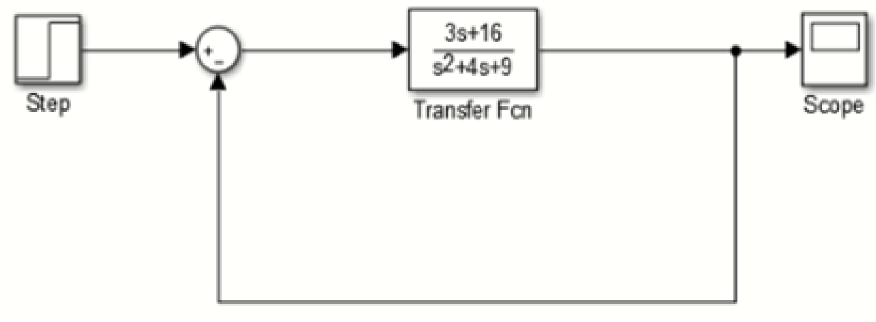


Fig. 7: Simulink model for closed – loop configuration.

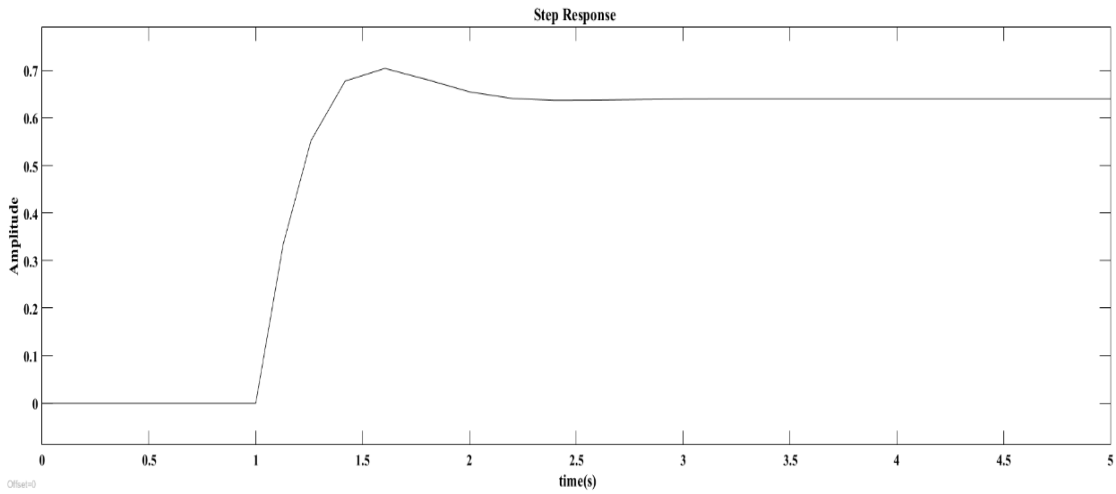


Fig. 8: Step response of unity feedback system for closed-loop configuration.

(iii) Finding response at different node of the control system configuration

Obtain step response of the unity feedback transfer function with a PI controller and also check the response at different nodes whose transfer function is given by: $\boldsymbol{G(S)} = \frac{S+1}{(S^2+4S+9)}$

In some cases, parameters, such as gain, may be calculated in MATLAB to be used in a Simulink model. If this is the case, it is not necessary to enter the result of the MATLAB calculation directly into Simulink. Enter the following command at the MATLAB command prompt.

K = 5

This variable can now be used in the Simulink Gain block by entering variable K in the Gain block.

Now, if any calculations are done in MATLAB to change any of the variables used in the Simulink model, the simulation will use the new values the next time it is run. To try this, in MATLAB, change the gain, K, by entering the following at the command prompt.

K = 3

Responses at different nodes can be obtained by connecting a scope at each node. For exact steady state value Display block can be connected at the nodes.

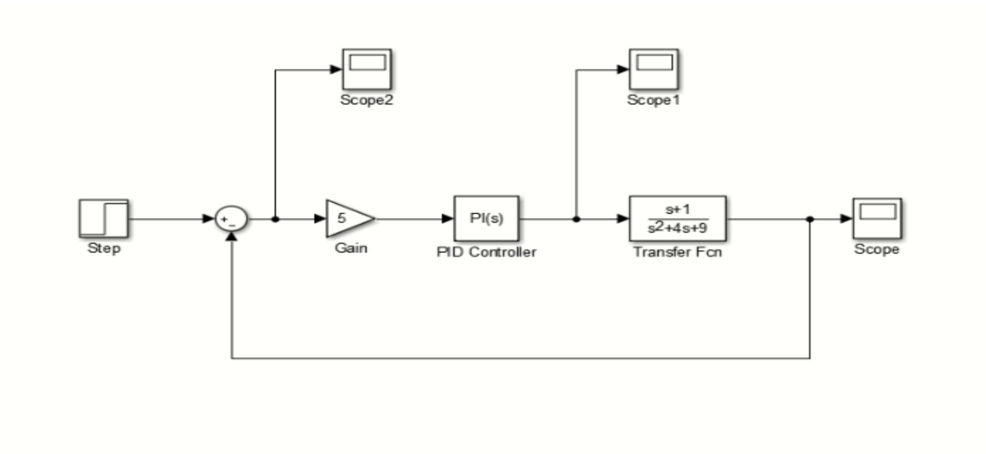


Fig. 9: Simulink model for closed-loop configuration with PI controller.

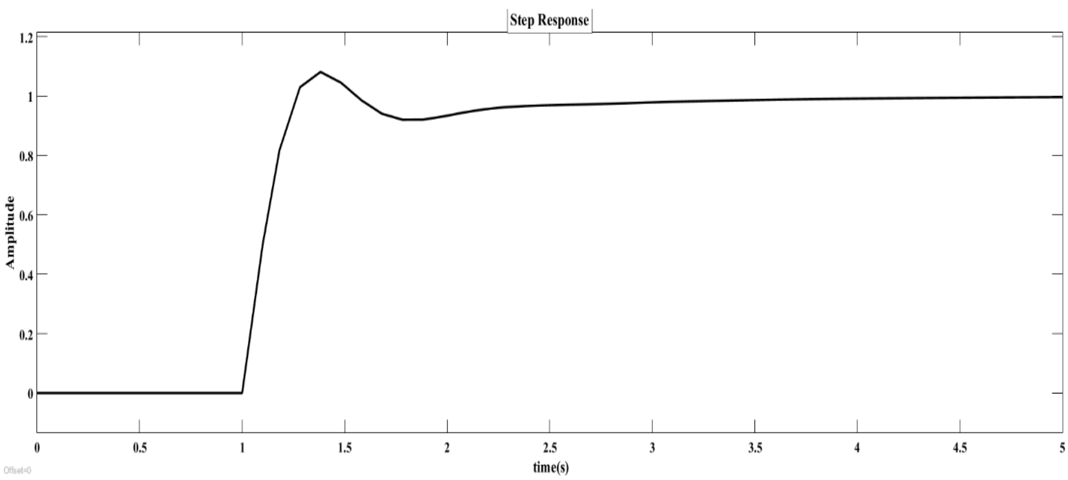


Fig. 10: Simulink model for closed-loop configuration with PI controller.

EXPERIMENT NO.: 5

TITLE:

Simulation, design and analysis of an AVR system using MATLAB Simulink.

OBJECTIVE:

Simulation and analysis (bode and time responses) of an AVR system in open-loop and closed-loop configuration and design of a PID controller by means of Zeigler-Nichols method.

OUTCOME:

In this experiment, the student will learn about AVR system and Zeigler-Nichols method of PID controller design.

SAFETY PRACTICES AND DO's & DONT's:

- After completion of the work the data produced are to be saved in the folder as specified by the instructor.
- Power off of the computer with proper procedure to avoid software crushing or like.

APPARATUS REQUIRED:

S. No.	APPARATUS	SPECIFICATION
1.	Computer	Desktop / Laptop Processor __, OS __, Speed __, ROM __, Hard Disc size __.
2.	MATLAB Software	MATLAB ____ (version)

THEORY:

A proportional-integral-derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable.

Generator Model: The synchronous machine generated EMF is a function of the machine magnetization curve, and its terminal voltage is dependent on the generator load. In the linearized model, the transfer function relating the generator terminal voltage to its field voltage can be represented by a gain K_G and a time constant Γ_G, and the transfer function is:

$$\frac{V_t(s)}{V_F(s)} = \frac{K_G}{1+\Gamma_G S}$$

These constant are load dependent, K_G may vary between 0.7 to 1, and Γ_G between 1.0 to 2.0 seconds from full load to no load.

Sensor Model: The voltage is sensed through a potential transformer and, in one form, it is rectified through a bridge rectifier. The sensor is modeled by a simple first order transfer function, given by

$$\frac{V_s(s)}{V_t(s)} = \frac{K_R}{1+\Gamma_R S}$$

Γ_R is very small, and we may assume a range of 0.01 to 0.06 second. Utilizing the above models results in the AVR block diagram shown in Figure

The open-loop transfer function of the block diagram in Figure

$$KG(s)H(s) = \frac{K_A K_E K_G K_R}{(1+\Gamma_A S)(1+\Gamma_E S)(1+\Gamma_G S)(1+\Gamma_R S)}$$

And the closed-loop transfer function relating the generator terminal voltage $V_t(s)$ to the reference voltage $V_{ref}(s)$ is

$$\frac{V_t(s)}{V_{ref}(s)} = \frac{K_A K_E K_G K_R (1+\Gamma_R S)}{(1+\Gamma_A S)(1+\Gamma_E S)(1+\Gamma_G S)(1+\Gamma_R S) + K_A K_E K_G K_R}$$

Or $V_t(s) = T(s) V_{ref}(s)$

For step input $V_{ref}(s) = \frac{1}{S}$, using the final value theorem, steady-state response is

$$V_{tss} = \lim_{s \to 0} S V_t(s) = \frac{K_A}{1+K_A}$$

(i) Simulation and analysis (bode and time response) of an AVR system in open loop and closed loop

An automatic voltage regulator (AVR) is an electronic device for automatically maintaining generator output terminal voltage at a set value under varying load and operating temperature. It controls output by sensing the voltage V_{out} at a power-generating coil and comparing it to a stable reference. The error signal is then used to adjust an average value of the field current. Most cheap portable generators have fixed excitation. In such machines, when an alternator is loaded, its terminal voltage drops due to its internal impedance. This impedance is formed of leakage reactance, armature reactance and armature resistance. The V_{out} also depends on the power factor of the load. That's why to maintain V_{out} within tighter limits; more expensive models use an AVR. The AVR system of a generator has the following parameters:

Item	Gain	Time Constant
Amplifier	K_A	$\Gamma_A = 0.1$
Exciter	$K_E = 1$	$\Gamma_E = 0.4$
Generator	$K_G = 1$	$\Gamma_G = 1.0$
Sensor	$K_R = 1$	$\Gamma_R = 0.05$

(ii) Design of a PID controller by means of Zeigler-Nichols method

Use the Ziegler-Nichols open-loop tuning method, by performing the following steps:

1. Make an open loop step test
2. From the process reaction curve determine the transportation lag or dead time, td, the time constant or time for the response to change, τm, and the ultimate value that the response reaches at steady-state, Km, for a step change of Xo.
3. Determine the loop tuning constants. Plug in the reaction rate and lag time values to the Ziegler-Nichols open-loop tuning equations for the appropriate controller (P, PI, or PID) to calculate the controller constants by using the table given below-

	K_p	T_i	T_d
P- Controller	$\frac{X_o}{K_m}\frac{\tau_m}{t_d}$	∞	0
PI- Controller	$0.9\,\frac{X_o}{K_m}\frac{\tau_m}{t_d}$	$3.3\,t_d$	0
PID- Controller	$1.2\,\frac{X_o}{K_m}\frac{\tau_m}{t_d}$	$2\,t_d$	$0.5\,t_d$

Table 1: Open loop calculations

Use the Routh-Hurwitz array to find the range of K_A for control system stability.
(b) Use MATLAB rlocus function to obtain the root locus plot.
(c) The amplifier gain is set to K_A=10
(i) Find the steady-state step response.

(ii) Use MATLAB to obtain the step response and time-domain performance specifications.

(iii) Simulation study of the designed system

1. Make a new model file in MATLAB.
2. Use Sim Power System Toolbox and Mathematical Operations Toolbox for inserting the models of different mathematical operations such as add, subtract, limiters etc. and different electrical displays such as scope and Displays.
3. Insert the blocks from respective toolboxes into new model by dragging it and connect that blocks.
4. Give proper input to the model and check the output at the output port/display/scope.
5. In this simulation, Step load change is given to the alternator system with AVR. By selecting suitable parameters of Error amplifier, SCR power Amplifier and Stabilizer, V_t deviations can be reduced to zero.

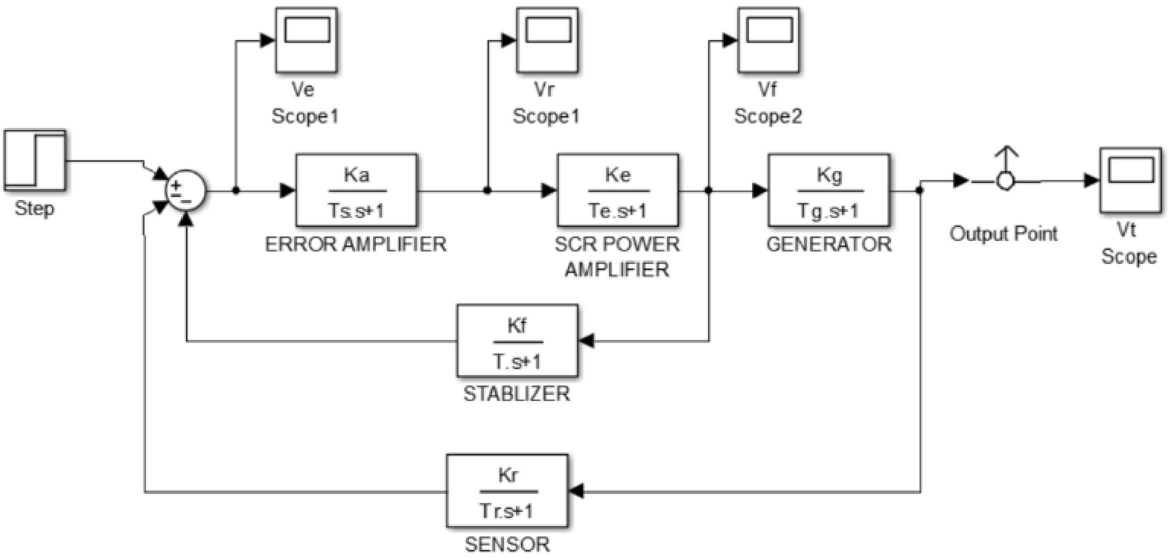


Fig1: MATLAB Simulink block diagram of an AVR

Conclusion: The automatic voltage regulator controls the terminal voltage of the alternator by controlling excitation voltage. PID controller was designed using the Ziegler Nichols open loop and the closed loop method.

EXPERIMENT NO.: 6

TITLE:

Simulation and Analysis of a discrete-time control system, comprising of continuous-time plant.

OBJECTIVE:

Find the performance indices Mp, Tp, Ts, GM, PM for unity negative feedback control system, find z-domain transfer function (open and closed loop) for sampling period, T= 0.1 sec, 1 sec and 10 secs and find performance indices Mp, Tp, Ts, GM, PM, root locus for unity negative feedback control system.

OUTCOME:

In this experiment, the student will learn about performance indices of continuous time plant and analysis of a discrete time control system for different sampling period.

SAFETY PRACTICES AND DO's & DONT's:

- After completion of the work the data produced are to be saved in the folder as specified by the instructor.
- Power off of the computer with proper procedure to avoid software crushing or like.

APPARATUS REQUIRED:

S. No.	APPARATUS	SPECIFICATION
1.	Computer	Desktop / Laptop Processor __, OS __, Speed __, ROM __, Hard Disc size __.
2.	MATLAB Software	MATLAB ____ (version)

PROBLEM:

For a plant $\frac{6(s+1)}{(s+2)(s+3)}$

(i) Find the performance indices Mp, Tp, Ts, GM, PM for unity negative feedback control system

(ii) Find z-domain transfer function (open and closed loop) for sampling period, T= 0.1 sec, 1 sec and 10 secs.

(iii) Find performance indices Mp, Tp, Ts, GM, PM, root locus for unity negative feedback control system.

Procedure:

(i) Find the performance indices Mp, Tp, Ts, GM, PM for unity negative feedback control system

```
>>    clc

>> num= [6 6];

>> den = [1 5 6];

>> h=tf([num],[den])

h =

% enter the numerator

% enter the denominator

%calculation of transfer function


6 s + 6
-------------
s^2 + 5 s + 6

>>[Gm,Pm,Wcg,Wcp] = margin(h);          % computes the gain margin Gm, the phase
                                        margin Pm, and the associated frequencies Wcg and
Wcp

Gm =
Inf

Pm =

  132.8873
```

Wgm =

NaN

Wpm =

4.7958

>> margin (h)

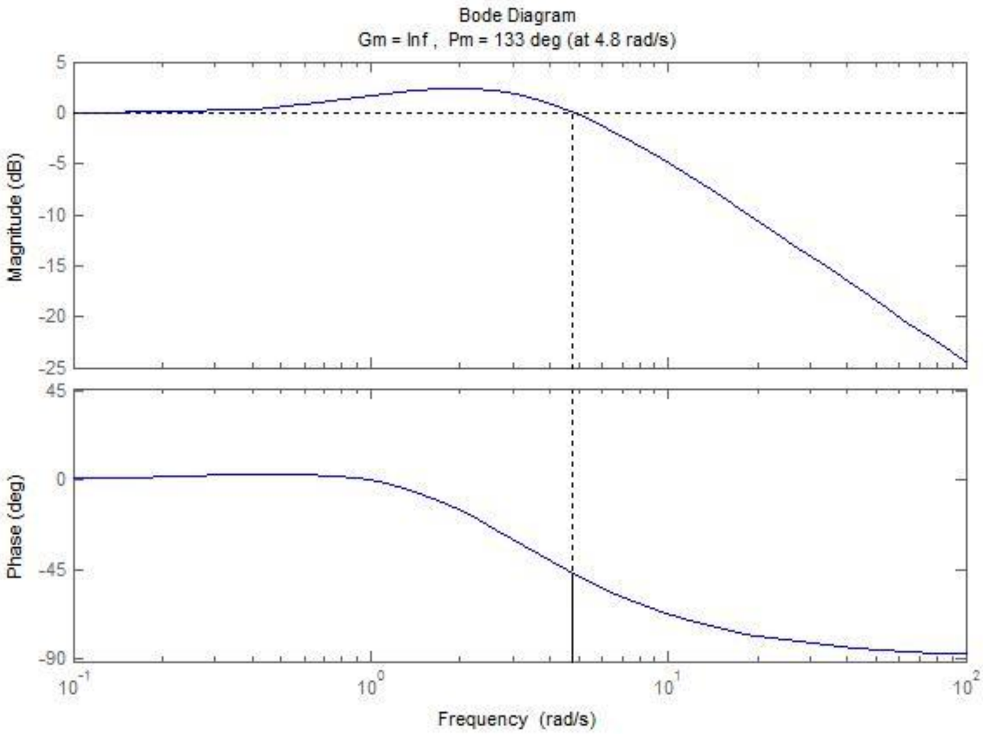


Fig. 1: Bode plot

(ii) Find z-domain transfer function (open and closed loop) for sampling period, T= 0.1 s, 1 s and 10 s.

ts = 1;

% Taking sampling time = 1 sD = c2d(h,ts)

% Converts continuous-time dynamic system to discrete time

D =

1.207 z - 0.3852

----

z^2 - 0.1851 z + 0.006738

Sample time: 1 seconds
Discrete-time transfer function.
Repeat the same procedure for sampling time = 0.1 s and 10 s

(iii) Find performance indices Mp, Tp, Ts for unity negative feedback control system.

```
>> cl_tf = feedback(h,1)

cl_tf =

     6 s + 6
  ---------------
  s^2 + 11 s + 12

>> step (cl_tf)
```

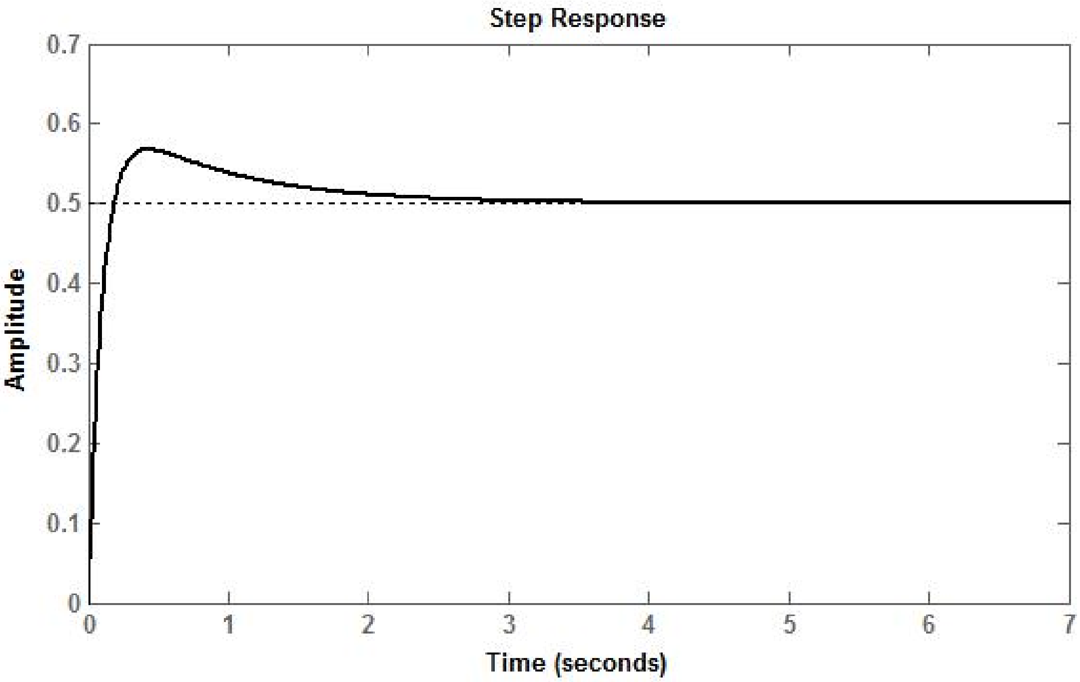


Fig. 2: Step response for unity feedback control system.

EXPERIMENT NO.: 7

TITLE:

Study of voltage regulation of a 3-Φ alternator by synchronous impedance method (EMF method).

OBJECTIVE:

To determine the voltage regulation of 3-Φ alternator by synchronous impedance method (EMF method).

OUTCOME:

Hands-on knowledge will be gained by the students and also the following performance characteristics/parameters of the 3-Φ alternator can be determined:

1. Open circuit characteristic curve (Generated voltage per phase vs Field current).
2. Short circuit characteristics curve (Short circuit current vs Field current)
3. Open circuit voltage per phase (V_{oc}) for the rated short circuit current (I_{sc})
4. The values of Z_s, X_s, E_o and percentage voltage regulation

SAFETY PRACTICES AND DO's & DONT's:

1. Wear cover shoes. All connections should be tight, neat and clean. Avoid connecting loose wires/connectors, cables etc.
2. Initially all switches are to be kept in open position.
3. The circuit connection should be checked by the respective Instructor carefully before switching on.
4. All the applied voltages should be maintained correctly to avoid unhealthy operation.
5. The motor input current should not exceed its rated value.
6. Care should be taken to read the readings of all the measuring instruments used.
7. Turn off all the equipment and supply before leaving the laboratory once an experiment concludes.

MACHINE UNDER TEST:

Sl. No.	Machine	Specification	Make
1	3-Φ Alternator		
2	DC Motor		

APPARATUS REQUIRED:

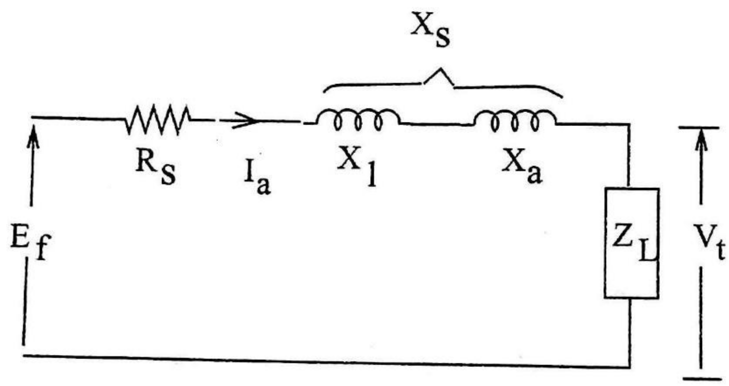
Sl. No.	Instruments/ Apparatus	Range	Quantity	Make
1	Ammeter – 1			
2	Ammeter – 2			
3	Voltmeter – 1			
4	Voltmeter – 2			
5	Rheostat – 1			
6	Rheostat – 2			
7	Tachometer			

THEORY:

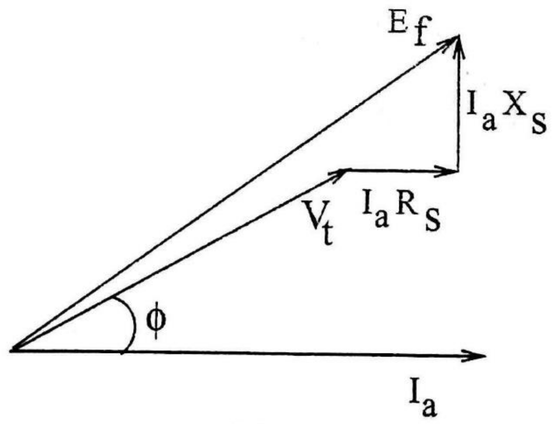
The voltage regulation of an alternator is defined as the increase in voltage from full-load to no-load (field excitation and prime mover speed remain same) expressed as a fraction of the rated terminal voltage.

The regulation of a 3-Φ alternator may be predetermined by conducting the Open Circuit (OC) and the Sort Circuit (SC) tests. The methods employed for determination of regulation are EMF or synchronous impedance method, MMF or Ampere Turns method and the ZPF or Potier triangle method. In this experiment, the EMF method is used. The OC and SC graphs are plotted from the two tests. The synchronous impedance is found from the OC test. The regulation is then determined at different power factors by calculations using vector diagrams. The EMF method is also called pessimistic method as the value of regulation obtained is much more than the actual value.

As shown in the Fig 1. (a), a fictitious reactance X_a represents the armature reaction effect. It is considered to be of such value that it produces flux and emf as those produced by armature reaction mmf. acting alone. In the circuit model, E_f stands for open circuit phase terminal voltage, also known as excitation emf also x_l and R_s are the leakage reactance and armature resistance respectively. X_s is called synchronous reactance.



(a)



(b)

Fig 1. (a) Equivalent circuit with synchronous impedance and (b) phasor diagram

$E_f = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$ where, ϕ should be treated as negative for leading load.

Open Circuit Characteristics (OCC) It depicts the magnetization characteristics of the machine. It is the plot of open circuit voltage (line-to-line or phase voltage) against field current at a given speed. The straight-line portion of the line is called air- gap line.

Short Circuit Characteristics (SCC) It is the plot of armature current against field current when the machine is driven at its speed with the terminal short circuited.

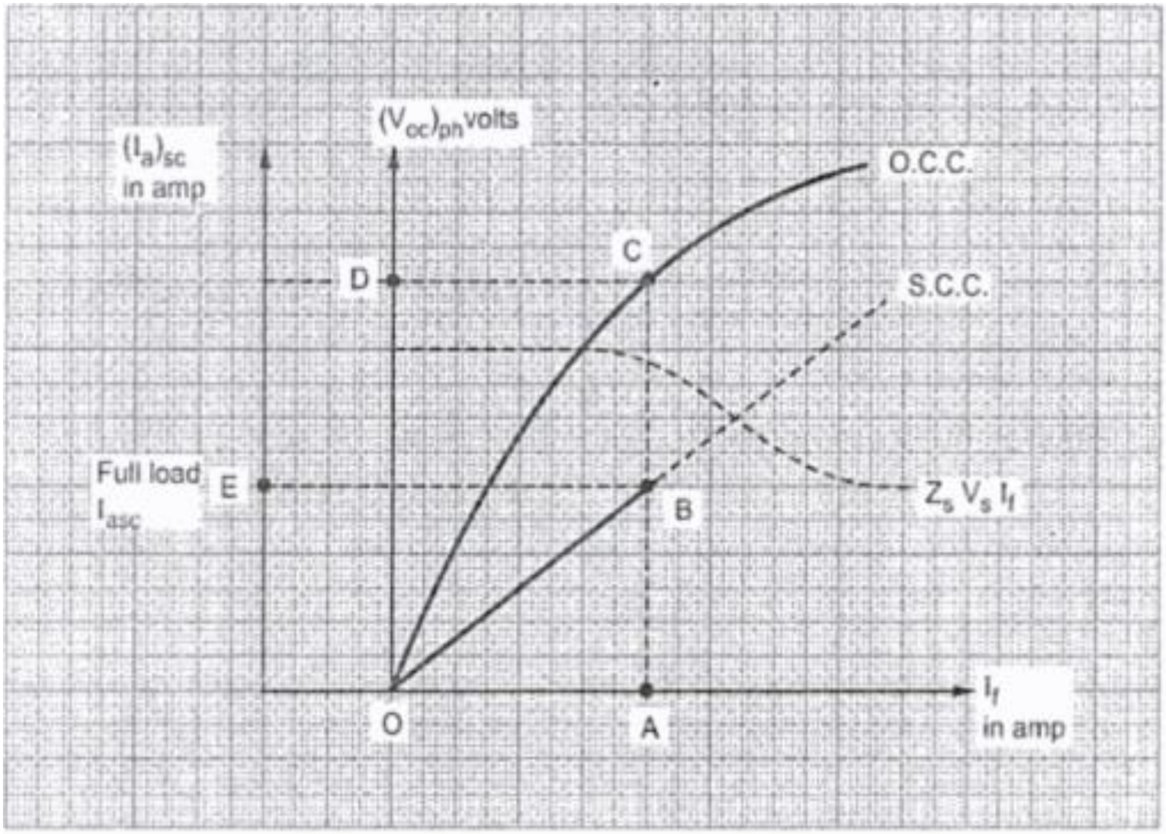


Fig 2. O.C.C. and S.C.C. of an alternator

CIRCUIT DIAGRAM:

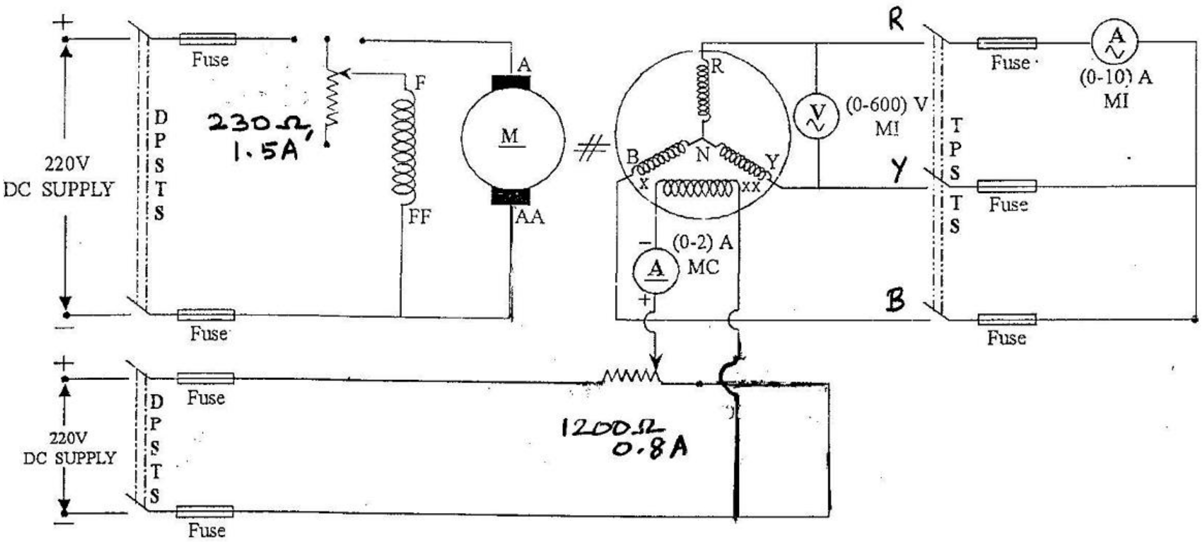


Fig 3. Circuit diagram for determination of voltage regulation of 3-Φ alternator by synchronous impedance method (open circuit and short circuit tests)

OBSERVATION:

1. OPEN CIRCUIT TEST:

Sl. No.	Field Current (I_f) in Amp	Open Circuit Line Voltage (V_l) in Volts	Open Circuit Phase Voltage (V_P) in Volts

2. SHORT CIRCUIT TEST:

Sl. No.	Field Current (I_f) in Amp	Short Circuit Current (I_{sc}) in Amp

CALCULATIONS:

1. Armature resistance, Rs = ... Ω
2. Synchronous impedance, Zs = $\frac{O.C.Voltage}{S.C.Current}$
3. Synchronous reactance, $X_S = \sqrt{Z_S^2 - R_s^2}$
4. Open circuit voltage with lagging power factor = $\sqrt{(V\cos\phi + I_a R_s)^2 + (V\sin\phi + I_a X_s)^2}$
5. Open circuit voltage with leading power factor = $\sqrt{(V\cos\phi + I_a R_s)^2 + (V\sin\phi - I_a X_s)^2}$
6. Open circuit voltage with unity power factor = $\sqrt{(V + I_a R_s)^2 + (I_a X_s)^2}$
7. Percentage voltage regulation = $\frac{E_O - V}{V} * 100$

RESULT:

Thus, the voltage regulation of 3-Φ alternator has been predetermined by the synchronous impedance method as follow:

Sl. No.	Power Factor	% Voltage Regulation
1.	0.8 lagging	
2.	0.8 leading	
3.	Unity	

SAMPLE QUESTIONS:

1. What is meant by voltage regulation?
2. What is meant by Synchronous Impedance?
3. What is OC test?
4. What is SC test?

EXPERIMENT NO.: 8

TITLE:

Determination of direct axis reactance (X_d) and quadrature axis reactance (X_q) of a Synchronous Machine (Slip test).

OBJECTIVE:

To determine the direct axis reactance (X_d) and quadrature axis reactance (X_q) of a salient pole synchronous machine.

OUTCOME:

In this experiment, the student will learn about finding the values of direct axis reactance (X_d) and quadrature axis reactance (X_q) of a salient pole 3-Φ alternator / synchronous generator.

SAFETY PRACTICES AND DO's & DONT's:

1. Wear cover shoes. All connections should be tight, neat and clean. Avoid connecting loose wires/connectors, cables etc.
2. Initially all switches are to be kept in open position.
3. The circuit connection should be checked by the respective Instructor carefully before switching on.
4. All the applied voltages should be maintained correctly to avoid unhealthy operation.
5. The motor input current should not exceed its rated value.
6. Care should be taken to read the readings of all the measuring instruments used.
7. Turn off all the equipment and supply before leaving the laboratory once an experiment concludes.

MACHINE UNDER TEST:

Sl. No.	Machine	Specification	Make
1	3-Φ Alternator		
2	DC Motor		

APPARATUS REQUIRED:

Sl. No.	Instruments/ Apparatus	Range	Quantity	Make
1	Ammeter			
2	Voltmeter – 1			
3	Voltmeter – 2			
4	Tachometer			
5	3-Φ auto-transformer			
6	3-Φ M.C.B.			

THEORY:

The salient-pole type synchronous machines have the non-uniform air-gap. The air-gap is smaller along the polar axis which is coinciding with the main field pole axis (direct axis or *d*-axis) than that of the inter-polar axis (quadrature axis or *q*-axis). Therefore, the reluctance of the air-gap must not be the same. Along the *d*-axis, the reluctance of the magnetic circuit is somewhat less than that of along the q–axis. Hence, the effect of magnetomotive force (mmf), when acting along the *d*-axis, will be different than that when it is acting along the *q*-axis. Thus, the effect of armature reaction in the case of a salient pole synchronous machine also must be taken as two components viz.one acting along the *d*-axis and the other acting along the q-axis.

"*Blondel's two-reaction theory*" considers the effects of these armature reactions separately. Neglecting saturation, their different effects are considered by assigning to each, an appropriate value of armature-reaction "reactance": the direct axis synchronous reactance $\left(X_d\right)$ and the quadrature axis synchronous reactance $\left(X_q\right)$. They are the steady state reactance of the salient-pole type synchronous machine. The values of X_d and X_q can be measured by the slip test on a synchronous machine.

Basic circuit diagram for conducting this test is shown in Fig. 1. Here the armature terminals are supplied with a subnormal voltage of rated frequency with field circuit left open. The generator is driven by a prime mover at a slip speed which is slightly more or less than the synchronous speed. This is equivalent to the condition in which the armature mmf remains stationery and rotor rotates at a slip speed with respect to the armature mmf. As the rotor poles slip through the armature mmf, the armature mmf will be in line with *d*-axis and *q*-axis, alternately. When it is in line with the *d*-axis, the armature mmf directly acts on the magnetic circuit and at this instant the voltage applied on the machine divided by armature current gives the value of X_d. At this instant, the armature current per-phase is minimum and the terminal voltage per-phase is maximum.

$$X_d = \frac{\text{Maximum value of armature voltage / phase}}{\text{Minimum value of armature current / phase}}$$

When the armature mmf coincides with the *q*-axis, then the voltage impressed divided by armature current gives the value of X_q. At this instant, the armature current per-phase is maximum and the terminal voltage per-phase is minimum.

$$X_q = \frac{\text{Minimum value of armature voltage / phase}}{\text{Maximum value of armature current / phase}}$$

Since, $X_d > X_q$, the armature current, hence the pointer of the ammeter will oscillate from a minimum to a maximum value. Similarly, the terminal voltage will also oscillate between the minimum and maximum.

CIRCUIT DIAGRAM:

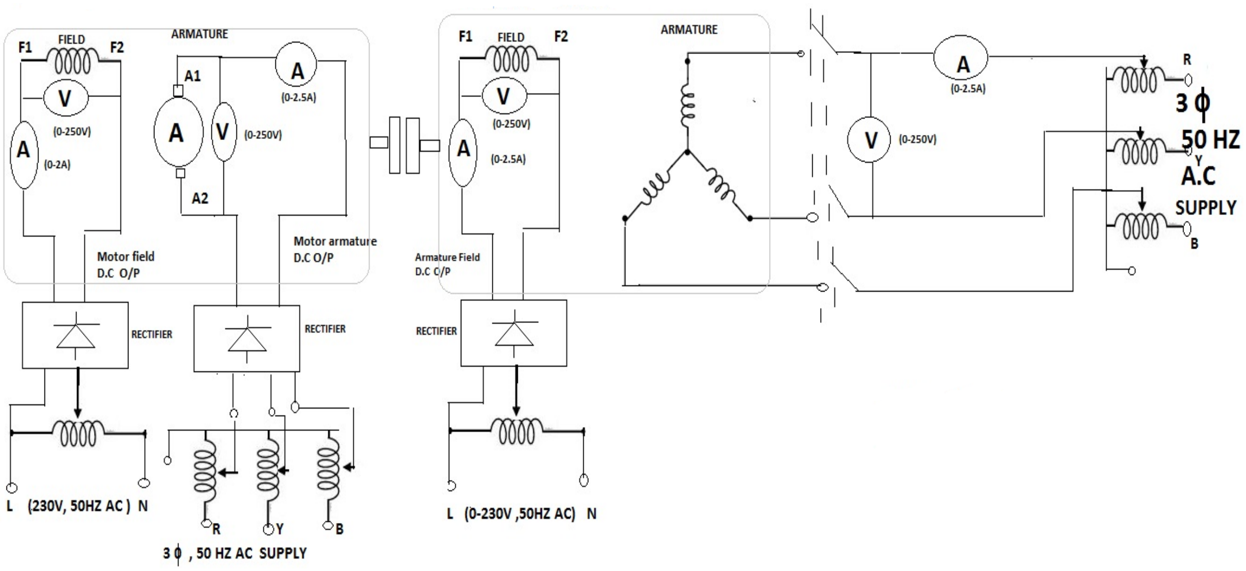


Fig. 1. Connection diagram for the measurement of X_d & X_q of the synchronous machine

OBSERVATION:

Sl. no.	Speed (rpm)	Armature voltage		Armature current		$X_d = \frac{V_{max}}{I_{min}}$	$X_d = \frac{V_{min}}{I_{max}}$	$\frac{X_d}{X_q}$
		Maximum	Minimum	Maximum	Minimum			
		V_{max}	V_{min}	I_{max}	I_{min}			
		(Volt)	(Volt)	(Amp)	(Amp)	(Ohm)	(Ohm)	

RESULTS:

The values of X_d and X_q of a three-phase salient-pole alternator have been found which are:

$X_d =$ ohm.

$X_q =$ ohm.

SAMPLE QUESTIONS:

1) When the synchronous motor is running at synchronous speed, how much torque produces in the damper winding?
2) What do you mean by d-axis and q-axis reactance?
3) Why alternator filed winding is opened during the test?
4) What do you mean by slip test?

EXPERIMENT NO.: 9

TITLE:

Study of speed control of a 3-Φ squirrel-cage induction motor by V/f control method.

OBJECTIVE:

To determine V/f ratio for the speed control of 3-Φ squirrel-cage induction motor.

OUTCOME:

Hands-on knowledge will be gained by the students regarding the speed regulation by V/f control technique of a 3-Φ squirrel-cage induction motor.

SAFETY PRACTICES AND DO's & DONT's:

1. Wear cover shoes. All connections should be tight, neat and clean. Avoid connecting loose wires/connectors, cables etc.
2. Initially all switches are to be kept in open position.
3. The circuit connection should be checked by the respective Instructor carefully before switching on.
4. The applied voltage should be maintained correctly to avoid unhealthy operation.
5. The motor input current should not exceed its rated value.
6. Care should be taken to read the readings of all the measuring instruments used.
7. Make sure to turn off the motor while switching direction to forward to backward or vice versa.
8. Turn off all the equipment and supply before leaving the laboratory once an experiment concludes.

MACHINE UNDER TEST:

Sl. No.	Machine	Specification	Make
1	3-Φ squirrel-cage induction motor		

APPARATUS REQUIRED:

Sl. No.	Instruments/ Apparatus	Range	Quantity	Make
1	Frequency meter			
2	Power factor meter			
3	Voltmeter -1			
4	Voltmeter -2			
5	Ammeter			
6	Tachometer			
7	V/f controller			

CIRCUIT DIAGRAM:

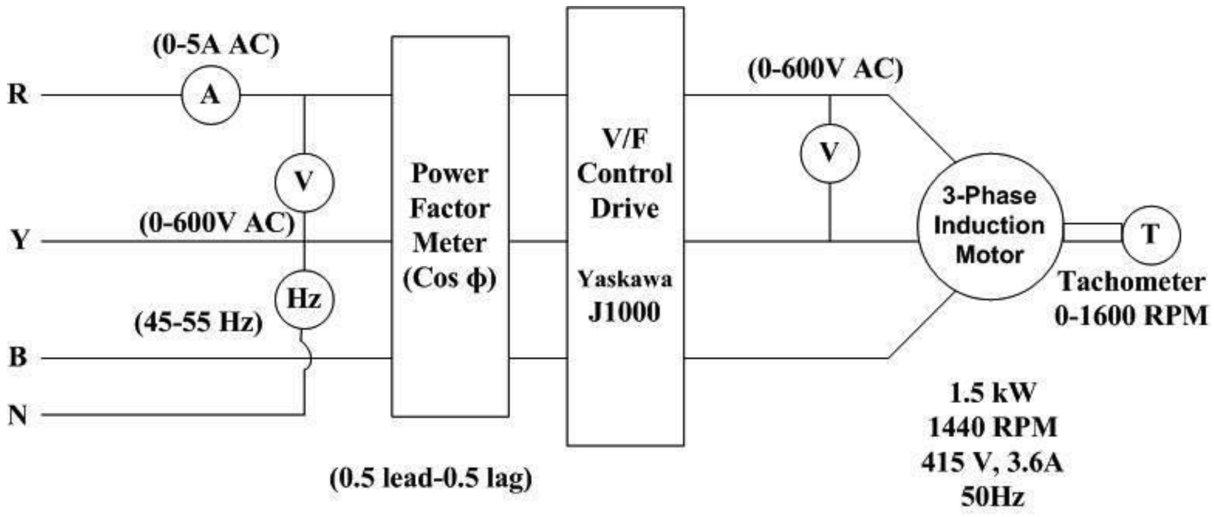


Fig. 1 Circuit diagram of V/f control technique of a 3-Φ squirrel-cage induction motor

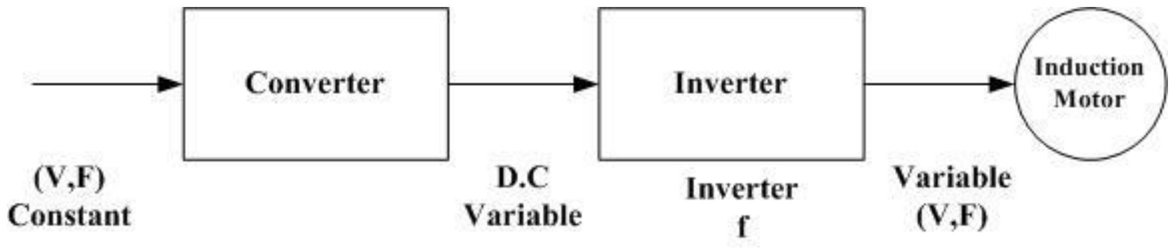


Fig. 2 Block diagram of V/f control drive

THEORY:

By changing the supply frequency, the synchronous speed of induction motor can be controlled over a wide range according to eqns. (1) and (2). The synchronous speed (N_S) and air gap flux are given by

$$N_S = \frac{120f}{P} \quad (1)$$

$$N = N_S(1 - S) \quad (2)$$

$$\Phi g = \frac{1}{4.44K_1T_{Ph1}}\left(\frac{V}{f}\right) \quad (3)$$

where, K_1 = stator winding constant, $\boldsymbol{T_{Ph1}}$ =stator turns per phase, *V* = supply voltage, *f* = Supply frequency. It may be seen that from the eqn. (3) that if the supply frequency (*f)* is changed, the value of air gap flux also gets affected. Induction motors are normally designed to operate near the saturation point on their magnetization curves, So the increase in flux due to a decrease in frequency will cause excessive magnetization currents to flow in the motor. Hence, it is necessary to maintain air gap flux constant when supply frequency is changed. This can be achieved when the *V/f remains* constant. That means when frequency varies then voltage must be varied in same proportion so that net ratio remains same or constant. This can be achieved V/f control drive as shown in Fig. 2. In this arrangement, variable (V, f) supply can be obtained from constant (V, f) supply using converter-inverter arrangement as shown in Fig. 2. When supply frequency to the stator terminal varies, the supply voltage to the stator also varies automatically in same proportion. As a result of which V/f ratio remains constant.

OBSERVATION TABLE:

1) Forward direction

Sl. No.	Frequency (Hz)	Voltage (V)	V/f ratio	Rotor speed (rpm)

2) Backward direction

Sl. No	Frequency (Hz)	Voltage (V)	V/f ratio	Rotor speed (rpm)

SAMPLE QUESTIONS:

1. What are the advantages and disadvantages of V/f speed control technique of an induction motor?
2. Why is the speed of the induction motor controlled with a constant V/f?
3. How many types of method are used for the speed control of induction motor from the stator side?
4. Is it possible to control multiple motors using a single controller?
5. What is the effect of frequency on motor efficiency?

EXPERIMENT NO.: 10

TITLE:

Study of rotor resistance starting and the effect of load variation of a 3-Φ slip-ring induction motor.

OBJECTIVE:

To observe rotor resistance starting and also to determine load vs speed characteristics of a 3-Φ slip-ring induction motor.

OUTCOME:

In this experiment, the student will learn about the starting and the effect of load variation a of 3-Φ slip-ring induction motor with the help of external rotor resistance. Moreover, the students can gather a knowledge of torque vs speed characteristics.

SAFETY PRACTICES AND DO's & DONT's:

1. Wear cover shoes. All connections should be tight, neat and clean. Avoid connecting loose wires/connectors, cables etc.
2. Initially all switches are to be kept in open position.
3. The circuit connection should be checked by the respective Instructor carefully before switching on.
4. The applied voltage should be maintained correctly to avoid unhealthy operation.
5. The motor input current should not exceed its rated value.
6. Care should be taken to read the readings of all the measuring instruments used.
7. Make sure to turn off the motor while switching direction to forward to backward or vice versa.
8. Turn off all the equipment and supply before leaving the laboratory once an experiment concludes.

MACHINE UNDER TEST:

Sl. No.	**Machine**	**Specification**	**Make**
1	3- Φ slip-ring induction motor		
2	DC shunt generator		

APPARATUS REQUIRED:

Sl. No.	Instruments/ Apparatus	Range	Quantity	Make
1	Ammeter			
2	Voltmeter			
3	Rotor resistance starter			
4	Tachometer			
5	Load box			

THEORY:

The starting current of an induction motor needs to be controlled in regard to have a smooth startup. It is done either by reducing the supply voltage or by increasing the motor impedance at starting. Slip ring induction motor (SRIM) use a method, known as 'rotor resistance starter' for starting where the advantage of 'slip ring' rotor can be fully utilized.
For starting of SRIM, whereas full voltage is applied to the stator terminals, the effective motor resistance is increased by adding extra resistance to the rotor winding during starting. These external resistances are connected to the rotor windings through brushes and slip rings. At starting, values of these external resistances are set to maximum so that rotor impedance, and hence the total motor impedance is maximum and the motor starting current is restricted. As the motor speeds up, these variable resistances are gradually reduced. When the motor reaches speed near its full value, these starting resistances are completely cut-off and the rotor windings are externally shorted at the brushes.
Rotor resistance starters are preferred over auto-transformer starters for a SRIM because of the fact that it not only reduces the starting current, but also provides higher starting torque and better power factor starting.

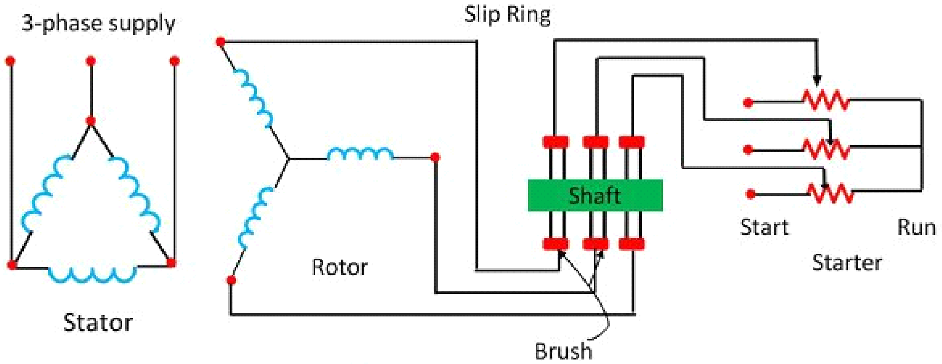


Fig. 1 Rotor resistance starter for SRIM

Adding external resistance on rotor side –

Starting torque, $T_{st} = \dfrac{3}{\omega_s} \dfrac{V_1^2 r_2'}{(r_1 + r_2')^2 + (x_1 + x_2')^2} \approx \dfrac{3}{\omega_s} \dfrac{V_1^2 r_2'}{(x_1 + x_2')^2}$ [neglecting $(r_1 + r_2')$ with respect to $(x_1 + x_2')$].

Maximum torque, $T_m = \dfrac{3V_1^2}{2\omega_s} \dfrac{1}{r_1 + \sqrt{r_1^2 + (x_1 + x_2')^2}}$

Slip for maximum torque, $s_{mt} = \frac{r_2'}{\sqrt{r_1^2 + (x_1 + x_2')^2}}$

It can be estimated that with increasing rotor circuit resistance r_2:

1) The starting torque T_{st} increases slightly.
2) There is no change in the maximum torque T_m since it is independent of the rotor circuit resistance r_2.
3) The slip for maximum torque s_{mt} increases since it is directly proportional to r_2.

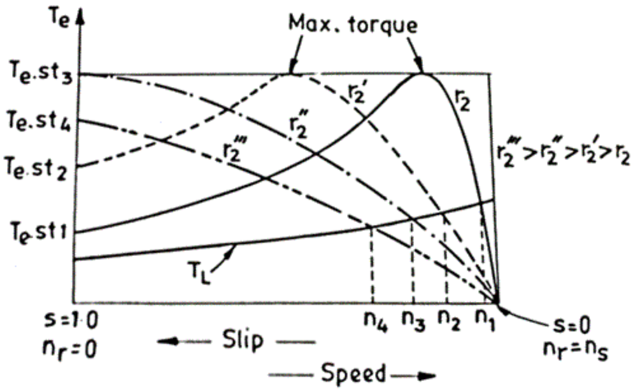


Fig. 2 Speed control of induction motor by varying rotor circuit resistance.

The main advantage of this method is that with addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

1) The speed above the normal value is not possible.
2) Large speed change requires large value of resistance and if such large value of resistance is added in the circuit it will cause large copper loss and hence reduction in efficiency.
3) Presence of resistance causes more losses.
4) This method cannot be used for squirrel cage induction motor.

CIRCUIT DIAGRAM:

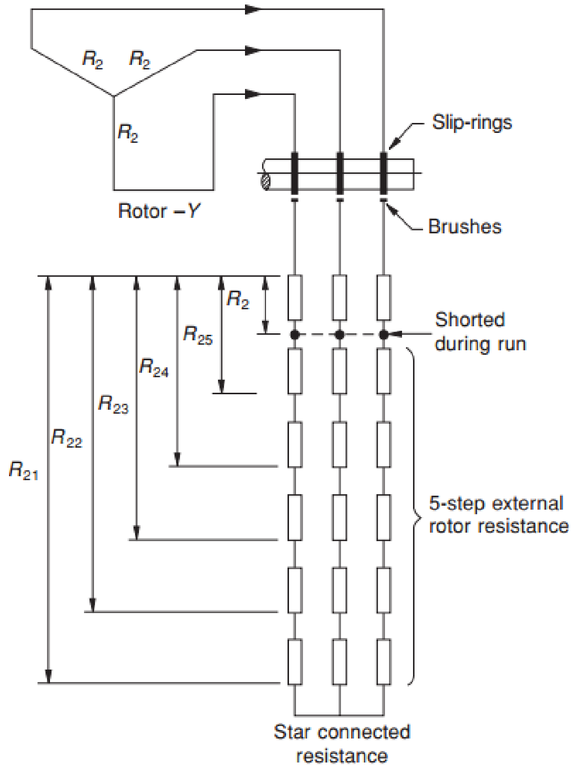


Fig. 3. Circuit diagram for speed control of 3-Φ slip-ring induction motor by rotor resistance method

OBSERVATION:

Sl. No.	External load	IM Supply voltage (V)	IM Supply current (I)	Generator armature		Generator field		Speed of induction motor (RPM)
				Voltage (V)	Current (I)	Voltage (V)	Current (I)	

CALCULATIONS:

Necessary calculations are to be worked out.

SAMPLE QUESTIONS:

1) What are the constructional differences between 3-Φ slip-ring and squirrel-cage induction motors?
2) Why is the rotor resistance starter not used for 3-Φ squirrel-cage induction motor?
3) Draw and explain the torque-speed characteristic of a 3-Φ slip-ring induction motor for different values of rotor resistances.

EXPERIMENT NO.: 11

TITLE:

Measurement of negative sequence reactance of a 3-Φ alternator.

OBJECTIVE:

To obtain the value of the negative sequence reactance of a 3-Φ alternator.

OUTCOME:

Hands-on knowledge will be gained by the students regarding the evaluation of the negative sequence reactance of a 3-Φ alternator.

SAFETY PRACTICES AND DO's & DONT's:

1. Wear cover shoes. All connections should be tight, neat and clean. Avoid connecting loose wires/connectors, cables etc.
2. Initially all switches are to be kept in open position.
3. The circuit connection should be checked by the respective Instructor carefully before switching on.
4. All the applied voltages should be maintained correctly to avoid unhealthy operation.
5. The motor input current should not exceed its rated value.
6. Care should be taken to read the readings of all the measuring instruments used.
7. Turn off all the equipment and supply before leaving the laboratory once an experiment concludes.

MACHINE UNDER TEST:

Sl. No.	Machine	Specification	Make
1	3-Φ alternator		
2	DC motor		

APPARATUS REQUIRED:

Sl. No.	Instruments/ Apparatus	Range	Quantity	Make
1	Ammeter – 1			
2	Ammeter – 2			

3	Voltmeter – 1			
4	Voltmeter – 2			
5	Rheostat – 1			
6	Rheostat – 2			
7	Tachometer			

THEORY:

The negative sequence reactance may be found by applying balanced negative sequence voltage to the armature terminals.The machine is driven by the prime mover at its rated synchronous speed with the field winding short circuited. The ratio of voltage per-phase and armature current per-phase gives the negative sequence reactance per-phase. Another method of measuring negative sequence reactance is found from the armature terminals. The machine is driven at synchronous speed and the field current is so adjusted until the rated terminal current flows in the phases shorted through armature and current coil of wattmeter, respectively. The value of negetive sequence reactance (X_{neg}) is given by

$$X_{neg} = \frac{V}{\sqrt{3}I_{sc}}$$

CIRCUIT DIAGRAM:

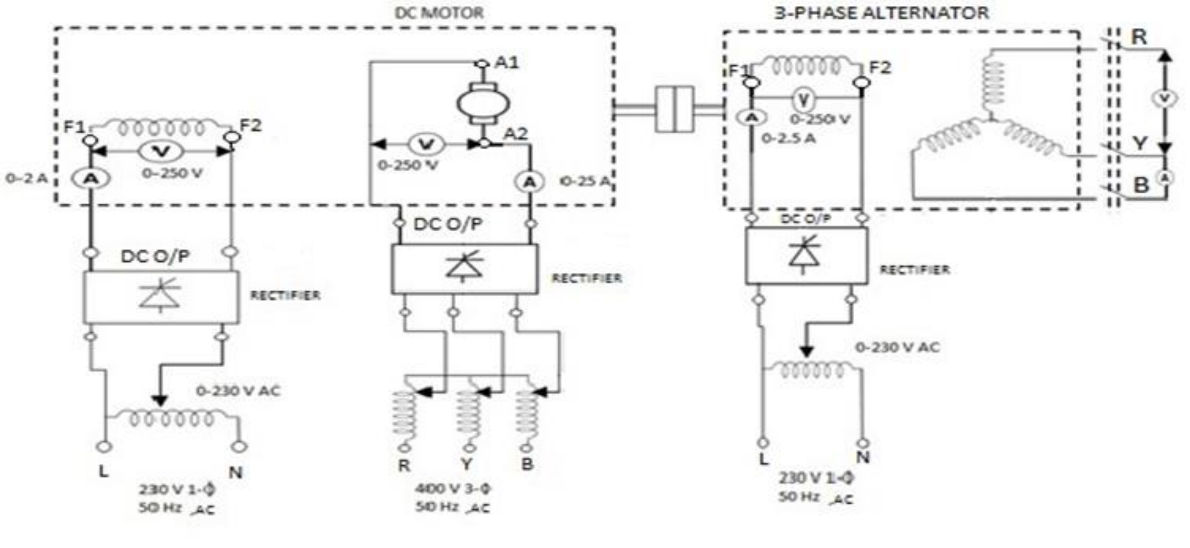


Fig. 1. Circuit diagram for the determination of negative sequence reactance of a 3-Φ alternator

OBSERVATION:

Sl. No.	V **(Line-Line) (Volt)**	I_{sc} **(Amp)**	X_{neg} **(Ohm)**	**Avg.** X_{neg} **(Ohm)**

SAMPLE QUESTIONS:

1) What is the significance of the negative sequence reactance of a 3-Φ alternator?
2) Why are damper windings used in a 3-Φ synchronous machine?
3) What is synchronous reactance?
4) What do you mean by sub-transient reactance?

EXPERIMENT NO.: 12

TITLE:

Study of direct-on-line (DOL) starter for the starting of 3-Φ squirrel-cage induction motor.

OBJECTIVE:

To find the torque ratio using DOL starter during starting of 3-Φ squirrel-cage induction motor.

OUTCOME:

In this experiment, the student will learn about the use of the DOL starter and also the starting mechanism with the help of it.

SAFETY PRACTICES AND DO's & DONT's:

1. Wear cover shoes. All connections should be tight, neat and clean. Avoid connecting loose wires/connectors, cables etc.
2. Initially all switches are to be kept in open position.
3. The circuit connection should be checked by the respective Instructor carefully before switching on.
4. The applied voltage should be maintained correctly to avoid unhealthy operation.
5. The motor input current should not exceed its rated value.
6. Care should be taken to read the readings of all the measuring instruments used.
7. Stop the motor by pressing STOP button, switch off the power supply and remove all the connections properly
8. Turn off all the equipment and supply before leaving the laboratory once an experiment concludes.

MACHINE UNDER TEST:

Sl. No.	Machine	Specification	Make
1	3-Φ squirrel-cage induction motor		
2.	DOL starter		

APPARATUS REQUIRED:

Sl. No.	Instruments/ Apparatus	Range	Quantity	Make
1.	Voltmeter			

2.	Ammeter			
3.	Auto-transformer			
4	Tachometer			

THEORY:

In a 3-Φ induction motor, the magnitude of an induced e.m.f. in the rotor circuit depends on the slip of induction motor. This induced e.m.f. effectively decides the magnitude of the rotor current. The rotor current/phase in the running condition is given by,

$$I_{2r} = \frac{sE_{20}}{\sqrt{R_2^2 + (sX_{20})^2}}$$

Where 'E_{20}' is rotor induced voltage/phase at standstill, 'R_2' is rotor resistance/phase, 'X_{20}' is rotor reactance/phase at standstill and 's' is the slip. But at start, the speed of the motor is zero and slip is at its maximum i.e. unity. So, magnitude of rotor induced e.m.f. is very large at start. As rotor conductors are short circuited, the large induced e.m.f. circulates very high current through rotor at start. This excessive current results in a large voltage drop in the distribution network and stop other machine which are already running on the supply mains.To avoid such effects, it is necessary to limit the current drawn by the motor at start.

Small induction motor (up to 2 kW capacity) may be connected directly to the supply mains whereas higher capacity motor are strictly prohibited to connect directly due to their high starting current which is 5 to 7 times the full-load current.

The starter is a device which is basically used to limit high starting current by supplying reduced voltage to the motor at the time of starting. Not only the starter limits the starting current but also provides the protection to the induction motor against overt loading, single phasing and low voltage situations. Torque produced by the induction motor is given by,

$$T = \frac{3}{2\Pi n_s}\frac{sE_{20}{}^2 R_2}{R_2{}^2 + (sX_{20})^2} = \frac{3}{2\Pi n_s} R_2\left(\frac{I_{2r}{}^2}{s}\right),$$

where 'n_s' = 120f/p is the synchronous speed (rps), 'f' is supply frequency (Hz) and 'p' is the number of poles in the motor. Three types of starting method is used generally for squirrel cage induction motor-

Direct-on-line (DOL) starting– This is the most common starting method available in the market. Fig. 1 shows the DOL starter, consist of main contactor and thermal or electronic overload relay. The motor is directly switch on to the supply mains. This method is restricted to small motor up to 5 kW rating for which starting torque is about twice the full load torque. The ratio of starting to no load torque is given by :

$$\frac{T_{st}}{T_{nl}} = \left(\frac{I_{2st}}{I_{2nl}}\right)^2 s_{nl},$$

where, 'T_{st}' is starting torque, 'T_{nl} is no-load torque, I_{2st} is starting current, I_{2nl} is no-load current, s_{nl} is full load slip.

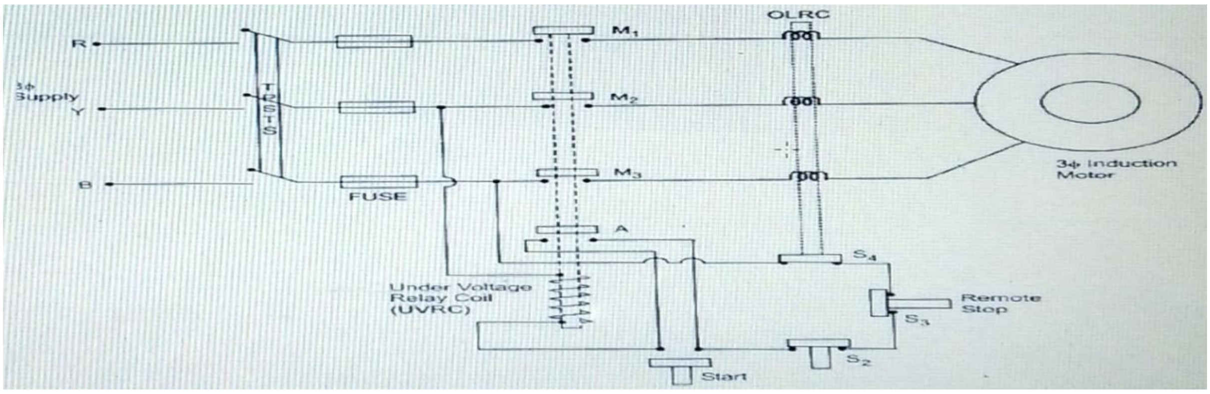


Fig. 1. Circuit diagram of direct-on-line (DOL) starter used in induction motor

RESULTS:

Sl. No.	Voltage (V)	Stator connection	I_{2st} (A)	I_{2nl} (A)	n_s	n_r	s_{nl}	$\frac{T_{st}}{T_{nl}}$

SAMPLE QUESTIONS:

1. How many starters are used for starting of an induction motor?
2. What are the advantages and disadvantages of a star-delta starter?
3. Which type of induction motor requires DOL starter?
4. Why do you use a rotor resistance starter?