

CONTROL OF A SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT FOR SYNCHRONOUS GENERATOR DAMPING ENHANCEMENT

*A Thesis submitted in partial fulfilment of the requirements for the award of
the degree of*

Master of Technology
in
Cryogenics and Vacuum Technology

Submitted by
VIDYA BHUSHAN KUMAR

(212ME5407)

Under the Guidance of

Prof. B. SUBUDHI



Department of Mechanical Engineering
National Institute of Technology
Rourkela-769008
2014

ACKNOWLEDGEMENT

It is indeed a big joy for me to show my profound gratitude towards my guide, **Prof. B. Subudhi**, Professor, Department of Electrical Engineering, NIT Rourkela. His constant enthusiasm in conducting my work was indeed a source of inspiration to me. I am full of gratitude towards him for his intellectual and moral support in all stages of my project so that it could be taken to this point of completion.

I have taken note of his critical review of the final edition of this thesis, and accommodated his valuable suggestions for betterment.

I would also like to thank Mr. Satyajee Das sir, Ph.D for his precious time and help towards completion of my project.

I would wish to get hold of this chance to convey my deep appreciation to the Department of Mechanical Engineering, NIT, Rourkela, for affording me the chance to go on this task.

I am likewise indebted to my family members for giving me necessary support and encouragement for completing this thesis. I am also beholden to all my friends for helping me in finishing this task.

Abstract

In power system, oscillations may occur due to load change or system fault which creates unsynchronized and undamped signals and creates instability in the system. So to enhance dynamic stability of the system, a control mechanism is constructed for Superconducting magnetic energy storage (SMES) unit to enhance the damping of the power system.

Proportional Integral (PI) controller is utilized to improve damping of oscillation of a synchronous generator connected to an infinite bus. Eigen values of system are found using matlab which helps in minimizing the oscillations caused by disturbances and enhances damping. PI controller parameters are found by using pole assignment technique

Response curves are generated in Matlab to compare the difference between the damping of oscillations for synchronous generators without PI controller and with PI controller with SMES.

DECLARATION

This end semester report project has been penned by me.

Signature of the Student

Certified that the student has performed the project work under my supervision.

Signature of the Supervisor

DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY,

ROURKELA - 769 008, ODISHA, INDIA





CERTIFICATE

This is to certify that the report titled “ Control of a Superconducting Magnetic Energy Storage unit for Synchronous Generator Damping Enhancement”, submitted to the National Institute of Technology, Rourkela by **Mr. Vidya Bhushan Kumar, Roll No. 212ME5407** for the award of Master of Technology in Cryogenics and Vacuum Technology, is a benefit record of research work carried out by him under my supervision and guidance.

The candidate has satisfied all the prescribed prerequisites.

This report, which is based on candidate’s own work, has not stated elsewhere for a degree/diploma.

In my opinion, the report is of standard required in fulfillment of the requirements for the degree of Master of Technology in Cryogenics and Vacuum Technology.

Prof. B. Subudhi

Supervisor

Department of Electrical Engineering

National Institute of Technology

Rourkela – 769 008 (ODISHA)

CONTENTS

| | |
|---|------------|
| ACKNOWLEDGEMENT | i |
| ABSTRACT | ii |
| DECLARATION | iii |
| CERTIFICATE | iv |
| LIST OF SYMBOLS | vii |
| LIST OF FIGURES | ix |
| | |
| 1. INTRODUCTION..... | 1 |
| 1.1 Superconducting Magnetic Energy Storage..... | 2 |
| 1.2 Thesis Objective..... | 4 |
| 1.3 Thesis Layout..... | 4 |
| | |
| 2. LITERATURE REVIEW | 5 |
| | |
| 3. SYSTEM ANALYSIS..... | 10 |
| 3.1 System Model..... | 10 |
| 3.2 Static Excitation System..... | 12 |
| 3.3 Governor and Turbine System..... | 12 |
| 3.4 SMES Unit..... | 13 |

| | |
|--|-----------|
| 4. MODELING OF SMES AND CONTROLLER. | 17 |
| 4.1 SMES Modeling..... | 17 |
| 4.2 Eigen Value Calculation..... | 18 |
| 4.3 Controller Design and Parameter Calculation..... | 19 |
| 5. SIMULATION AND RESPONSE CURVES..... | 20 |
| 5.1 Simulation of System with SMES but without PI controller..... | 23 |
| 5.2 Simulation of System with SMES and PI controller | 26 |
| 6. RESULT AND CONCLUSION..... | 29 |
| 7. BIBLIOGRAPHY..... | 30 |
| 8. APPENDIX: SYSTEM PARAMETERS | 33 |

List of Symbols

| | |
|-----------|--|
| e'_d | Armature transient voltage of d axis |
| e'_q | Armature transient voltage of q axis |
| V_t | Terminal voltage |
| P_o | Real output power |
| p.f | Power factor |
| ω | rotor angular speed |
| E_{FD} | field voltage |
| V_s | output voltage of stabilizing transformer |
| δ | torque angle |
| V_d | terminal voltage of d axis |
| V_q | terminal voltage of q axis |
| L_t | Line reactance |
| R_t | Line resistance |
| X'_d | d-axis stator winding transient reactance |
| X_d | d-axis stator winding synchronous reactance |
| X_q | q-axis stator winding synchronous reactance |
| T'_{do} | time constant of open circuit d-axis transient |
| T'_{qo} | time constant of open circuit q-axis transient |
| R_a | stator resistance |
| M | moment constant |
| D | damping constant |
| K_{ER} | regulator gain |

| | |
|------------|--|
| T_E | time constant of regulator |
| K_F | stabilizing transformer gain |
| T_F | time constant of stabilizing transformer |
| I_{SMES} | superconducting inductor current |
| V_{SMES} | superconducting inductor voltage |
| W_{SMES} | SMES energy stored |
| K_c | SMES control loop gain |
| P_{SMES} | power transferred to SMES |
| T_w | washout time constant |
| P_h | output power of steam chest |
| P_r | output power of speed relay |
| P_c | output power of servomotor |

List of Figures

| | |
|--|----|
| Fig.1 Component block diagram of SMES unit | 3 |
| Fig.2 Synchronous Machine connected to infinite bus | 10 |
| Fig.3 Block model of Static Excitation System | 12 |
| Fig 4 Block model of Governor and turbine | 12 |
| Fig 5 Block Model of fundamental SMES..... | 13 |
| Fig 6 SMES simulink model | 17 |
| Fig 7 PI controller | 19 |
| Fig 8 Graph between terminal voltage V_t (p.u) vs Time..... | 23 |
| Fig 9 Graph between rotor angular speed ω (p.u) and time..... | 24 |
| Fig 10 Graph between P_{SMES} (p.u) and Time..... | 24 |
| Fig 11 Simulink model of system with SMES but without PI controller..... | 25 |
| Fig 12 Graph between terminal voltage V_t (p.u) vs Time..... | 26 |
| Fig 13. Graph between Rotor angular speed ω (p.u) vs Time..... | 27 |
| Fig 14 Graph between P_{SMES} (p.u) and Time..... | 27 |
| Fig 15 Simulink model having both SMES and PI..... | 28 |

CHAPTER 1

1. INTRODUCTION

As we know that power system architecture made of system loads and generation centers distributed by long distances. If there is any disturbance like changing load or short circuiting or system fault in a power system in the grid or bus which carries the energy can experience undamped and bad synchronized power oscillations.

In the paper, we are designing a PI controller for SMES to effectively improve the damping of synchronous generator attached to an infinite bus. Parameters of PI controller are found first by calculating the Eigen values through matlab by linearizing the circuit. Using those Eigen values together with the knowledge of modal control theory we use pole assignment technique PI controller is designed.

This PI controller together with SMES unit is connected to the synchronous generator which is attached to an infinite bus and disturbance is added. It is then simulated in matlab and graphs were plotted, which compares the damping improvement of synchronous generator with SMES but without PI controller and with both SMES and PI controller.

Superconductivity is basically nothing but a process when a conductor or alloy shows zero resistance to the flow of current as well as there is an exclusion of magnetic field when its temperature is lowered below certain temperature called critical temperature.

Superconductivity in past was not much feasible because of the temperature on which it works. Low Temperature Superconductors needed temperature of around 4 K or less. Achieving such low temperature is not only costly but is a very complex technology as well. So superconductivity remained a subject for only theoretical work until the discovery of high temperature superconductors (HTS) in 1981. It was found that some materials have critical temperature above 90 K which is higher than the boiling point of Nitrogen (77 K) which made it possible for researchers to use superconductors easily in research work.

1.1 Superconducting Magnet Energy Storage (SMES):

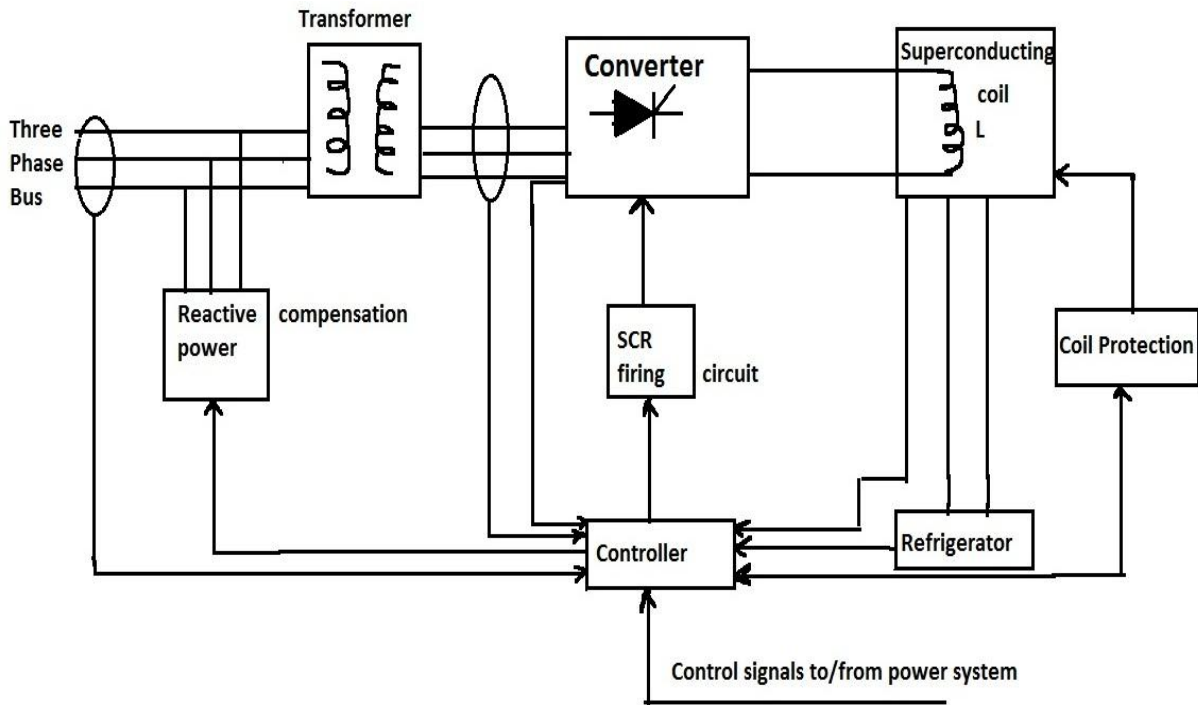


Fig 1. Component block diagram of SMES unit [10]

Complete SMES unit consists of a three phase bus connected to a transformer. GTO or other types of converter are attached to the transformer. There are normally 12 pulse converters connected to the SMES unit. SMES coil 'L' is basically inductor which is in superconducting state. A low temperature is maintained to keep coil in superconducting state through a refrigerator. Normally we use HTS type super conductors where liquid nitrogen is sufficient to lower the temperature below critical temperature.

A coil protection is also used that saves the coil in case of large current or magnetic stress. Controllers are used to set firing angle of converters which will tell SMES when to charge and when to discharge. A reactive power compensation unit is also there that will compensate the unwanted reactive power from the system

1.2 Thesis Objective

The objectives to be achieved in this subject area:

- To Design a PI controller for a SMES unit connected to a synchronous generator.
- To simulate the controller model with synchronous generator attached to an infinite bus using Matlab.
- To obtain response after adding fault and disturbances to the infinite bus to compare the effect of damping on synchronous generator system between SMES system without PI controller and SMES and PI controller

1.3 Thesis Layout

Chapter 1 Introduction to the objective, details about SMES system including thesis objective and thesis layout.

Chapter 2 is Literature Review on Superconductivity Magnetic Storage system and system dynamic stability

Chapter 3 contains system model and equations related to the system parts and SMES.

Chapter 4 presents the Modeling of SMES and PI controller and determining the Eigen values of the system.

Chapter 5 presents the simulation and results of the models system with SMES and PI controller and without PI controller and comparing the damping enhancement through graph.

Chapter 6 contains result and conclusion.

CHAPTER 2

2. LITERATURE REVIEW

The path in the field of research and its application of Superconducting Magnetic Energy storage Unit (SMES) only started after the discovery of HTS superconductors as it made it cheaper and less complicated to handle. Since then a lot of research and development took place in SMES and its vast applications including the dynamic stability of the power systems.

Williams (1989) in his paper described the changing shape of superconducting magnets with time, and its development in 30 years. He also enlightened us with the vast application of superconducting magnets in fields of medical, nuclear research and in power conditioning. He also explained different superconducting magnets based on their application. Magnets used to energy application, high field magnets used in higher application, AC magnets etc. Also the superconducting materials used in these magnets were explained by him. In the end he explained the future applications and prospects on High temperature superconducting magnets (HTS).

Lee (1999) proposed a model for control of simultaneous active and reactive power of SMES which in turn is used to stabilize the dynamic and transient states. He also designed a PI controller for SMES using modal control theory to stabilize the disturbances and oscillations produced in the system. He used both static and dynamic loads in this system and improved the stability of the system.

Masuda and Shintomi (1979) reported to test the technical problems related to SMES in which one of major problem is AC loss of SC coil that happens because of pulsed operations. Other problems like hysteresis loss, eddy current loss and coupling loss are much higher in superconductors compared to normal conductors. To test these, they developed a system having 100 KJ to test a superconducting switch that is used in the superconducting energy storage systems. In this they measured the energy transfer between superconducting coils with a power line. They did a detailed study of ac losses that occurs during pulse operations in superconducting magnetic energy storage (SMES).

Boenig and Hauer (1985) described the first conduction cooled (HTS) high temperature superconducting magnetic energy storage system which was built in China. The capacity of the SMES capacity is 380V, this system is made of high temperature superconducting magnet confined inside a dewar. System consists of a cryogenic unit, convertor, the monitoring unit and control unit etc. Laboratory as well as field test was done to investigate the operational characteristics of SMES and so it demonstrates the SMES effectiveness when improvements are made on system voltage stability and on the oscillation damping.

Hojo et al. (1999) proposed method that can help in achieving robust stabilization in power systems by using Superconducting magnetic energy storage (SMES). In this they first linearized the property of power deviation by using active control of SMES. They called it robust system because stability of system doesn't depend on operating conditions, configuration of the system and so on which enhanced the transient stability and steady state stability and they compared the proposed control method with the conventional feedback control method with uses generator speed deviation in SMES to control the transient stability.

Boom and Peterson (1972) proposed a model using Superconducting Energy storage that can be used as an alternative to pumped hydro storage which will cost less than 200\$/kW and also the losses that used to occur in hydro storage will be minimized by more than 50 percent. System will have to potential of damping overall oscillation generated because of disturbances. Also he described the importance of stress consideration in magnet core windings and optimization of superconducting materials and analysis was made for 400 MW-10000MW units.

Rogers et al. (1983) designed a Superconducting Magnetic storage system (SMES) for damping the power oscillations that occurs on western U.S. In this a 30-MJ capacity Superconducting inductor was used to store energy and was contained in a non-conducting dewar and a helium refrigerator was used to maintain the temperature of Superconducting coil below critical temperature with a gas handling system installed as well.

Ise and Murakami (1986) designed GTO converter in their laboratory using which they controlled active and reactive power of superconducting magnetic energy storage unit (SMES) over wide range of lag n lead. They used two sets of GTO converters to control reactive power

for wide range over lag and lead phases. And hence this system can be used for power system stabilizer.

Giese and Sheahen (1992) described the applications of superconducting magnets in different fields like electric utility sector. He also summarized about recent status in development and also about the influence of High temperature magnets (HTS) is discussed. Its application is also discussed which include, transmission lines, large scale generators, magnetic storage, motors, power electronics and current fault limiters.

Jiang and Conlon (1996) described the power regulation of a PWM type superconducting magnetic energy storage unit. In this they illustrated a power limit strategy to keep power flows of superconducting magnetic energy storage (SMES) unit under a controlled range. They detailed the design selection for controller. Power limit strategy used with PWM type SMES unit allows some absolute non- zero low power operating limit.

Observations from Literature Review

- High temperature Superconductors (HTS) has critical temperature above 90 K and nitrogen boiling point is 77K which makes HTS superconductors to be used in research and other applications.
- SMES units can hold large amount of energy that makes it very useful as energy storage device that can be used during power failure
- SMES has very fast response time and high efficiency which can be used in dynamic system stability.
- GTO converters are used to control the firing angle of the SMES which helps in controlling active and reactive power of the system.

CHAPTER 3

3. System Analysis

3.1 System model

We have a synchronous generator connected to an infinite bus through a transmission line having inductance (L_t) and resistance (R_t).

An infinite bus is a network in which voltage and frequency remains constant always.

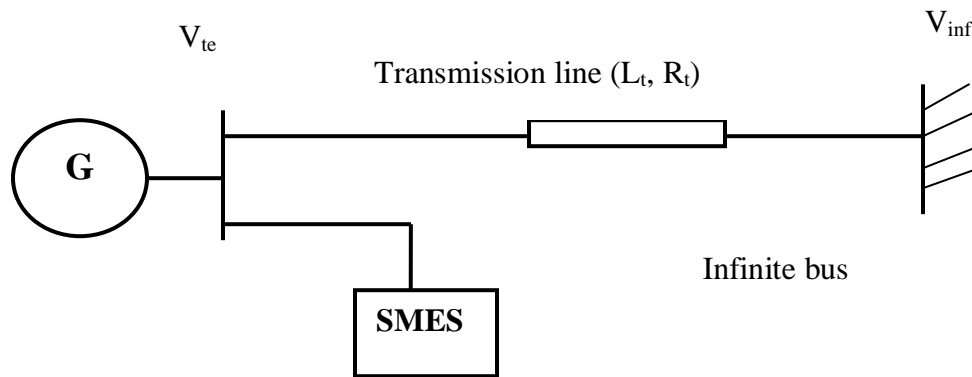


Fig 2. Synchronous Machine connected to infinite bus [5]

Synchronous Generator can be modeled by fourth order dynamic equations as follows:-

Equation (1) and (2) are armature dynamic voltage of direct (d) axis and q (quadrature) axis [5]

$$(\dot{e}'_d) = \frac{-e' - (X_q - X'_d)i_q}{T'_{qo}} \quad (1)$$

$$(e'_q) = \frac{[E_{FD} - e'_q - (X_d - X'_d)T_d]}{T'_{do}} \quad (2)$$

Angular rotor position δ and angular speed of rotor ω , equations can be written as [8]

$$\dot{\omega} = \frac{(P_m - D_g \omega - P_e - P_{SMES})}{M_g} \quad (3)$$

$$\delta = \omega_o (\omega - 1) \quad (4)$$

Dynamic (transient) output power is associated to dynamic voltage and current by [5]

$$P_e = e_d i_d + e_q i_q \quad (5)$$

Terminal voltage V_t is associated with the rotor d-axis and rotor q-axis voltages by [5]

$$V_t = (V_d^2 + V_q^2)^{1/2} \quad (6)$$

3.2 Static Excitation System

Static excitation part of the synchronous generator is shown in Fig 3.

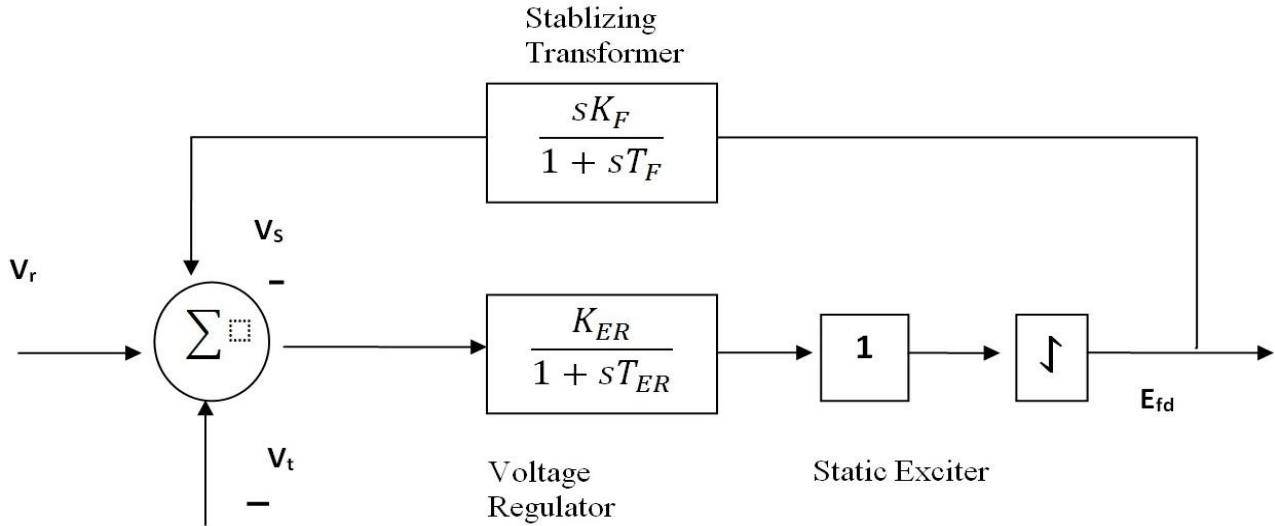


Fig 3 Block model of Static Excitation System [5]

In the figure E_{fd} denotes excitation voltage of the field which is given to the synchronous generator. V_t is fed back from the generator using d-axis rotor voltage V_d and q-axis rotor voltage V_q .

3.3 Steam Turbine and Governor System

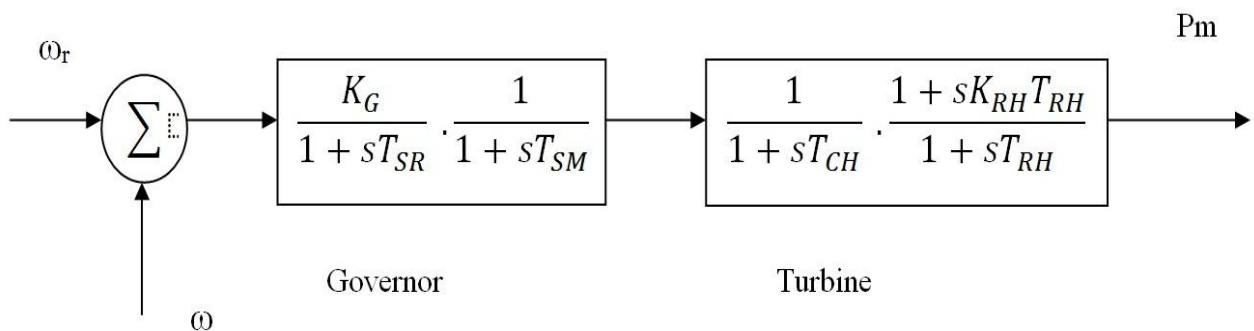


Fig 4 Block model of Governor and turbine [8]

Turbine and governor part is represented by four variables of state space model. Hence it gives four Eigen values during calculation. P_m is sent to the mechanical power of the synchronous generator. ω is the angular rotor speed which is fed with a reference ω_r speed to get angular speed deviation $d\omega$.

3.4 Superconducting Magnetic Energy Storage Unit

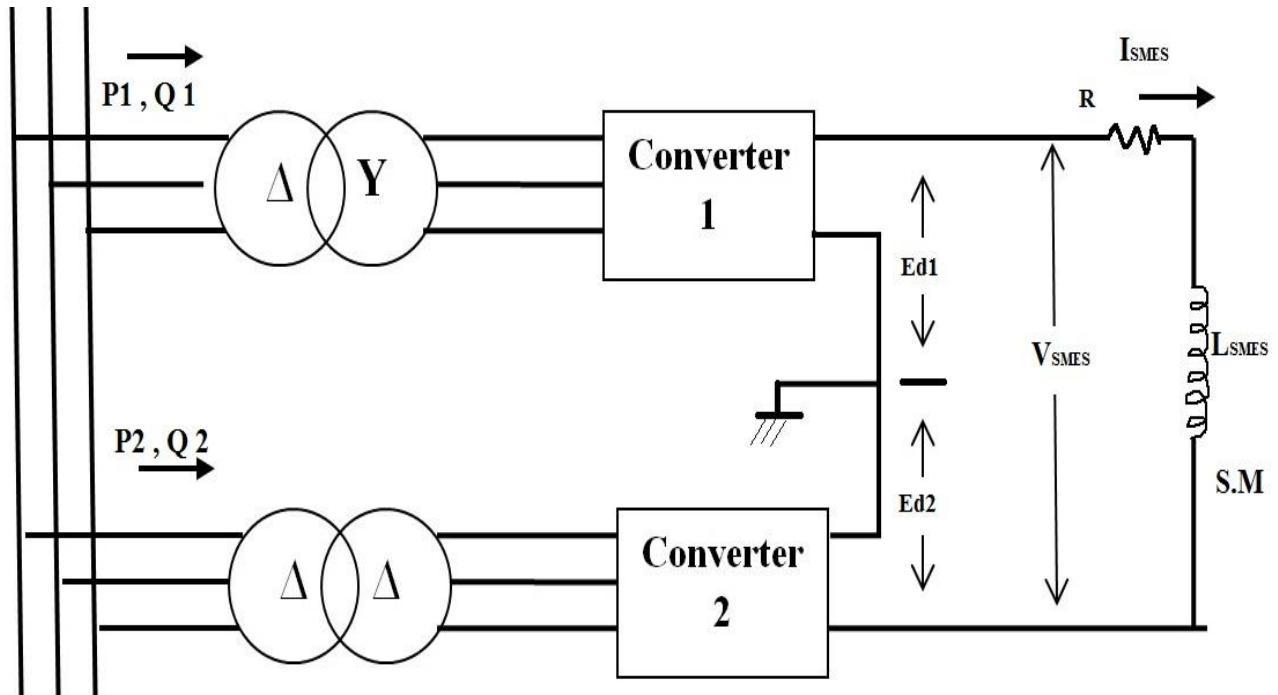


Fig 5 Block Model of fundamental SMES Unit [10]

SMES unit consists of two sets of transformer that are connected to A.C three phase line. Other end of the transformer is connected to two a 12-pulse convertor, two sets of 6 –pulse bridge force commutated converter, which is in series with the superconducting inductor L_{SMES} .

We are only considering the active power (P) control using the SMES so reactive Q is not considered. That's why we used force commutators where firing angle of thyristor is fix. When no power is transferred, maximum charging mode happens at 0° and for maximum discharging mode 180° .

Since the I_{SMES} current going through bridge is not reversible, active power P_{SMES} simply has positive and negative value depending upon the situation it can deliver or withdraw power hence keeping the system stable.

Active power of SMES P_{SMES} , current I_{SMES} and voltage V_{SMES} of SMES is related as [8]

$$P_{SMES} = V_{SMES} \cdot I_{SMES} \quad (7)$$

If V_{SMES} is positive value that means that energy is transferred to SMES from power system and if V_{SMES} is negative that means energy is taken out from SMES n transferred to the power system. We know current across a coil is given as [9]

$$\frac{dI_{SMES}}{d\tau} = \frac{(V_{SMES} - R_{SMES}I_{SMES})}{L_{SMES}} \quad (8)$$

Since we are taking a superconductive coil , we know its resistance is zero , so putting $R_{SMES} = 0$ in Equation (8) and Integrating equation (8) from initial time 't_o' to 't' with initial current of superconducting coil as I_{SMO} , we get current I_{SMES} in terms of Voltage V_{SMES} of superconductor and initial current I_{SMO} is given by[8]

$$I_{SMES} = \frac{1}{L_{SMES}} \int_{t_0}^t V_{SMES} d\tau + I_{SMO} \quad (9)$$

Energy that is being stored inside the superconducting coil can be written as [5]

$$W_{SMES} = W_{SCO} + \int_{t_0}^t P_{SMES}(\tau) d\tau \quad (10)$$

Where W_{SCO} is the energy stored inside the coil at $t=t_0$ and is given as

$$W_{SCO} = \frac{1}{2} L_d I_{SMO}^2 \quad (11)$$

Change in the rotor angular speed is caused due to any external disturbance that is related to the SMES voltage V_{SMES} as given below. [9]

$$\Delta V_{SMES} = \frac{K_c}{1+sT_c} \cdot \Delta\omega \quad (12)$$

Where K_c is the gain of control loop of SMES and T_c is the time constant of the control loop.

Equation (9) and (12) hence is used to design the SMES model in matlab for simulation.

CHAPTER 4

4. MODELING OF SMES AND CONTROLLER

4.1 SMES Modeling

Using the above analysis and equations we can easily design a SMES model that can be used in the matlab with the synchronous generator connected to infinite bus.

From Equations (9) and (12) we can make a model that will give us the power of the SMES P_{SMES} which will vary in accordance to the change or deviation of the angular rotor speed of the synchronous generator.

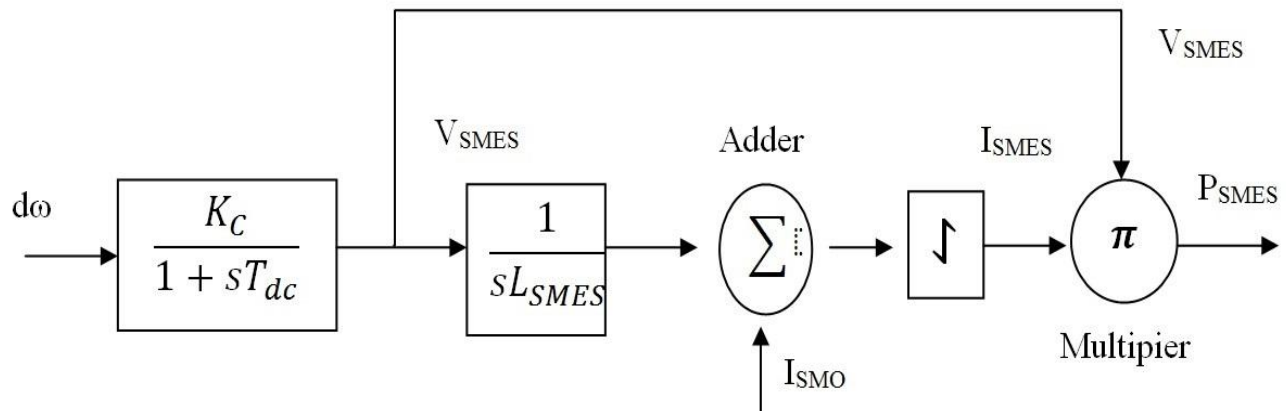


Fig 6 SMES simulink model [8]

The deviation in the angular speed of the rotor of the synchronous generator is feed to the transfer function containing loop gain and time constant of feedback loop of the SMES coil.

From Equation (12) we know that this change in ω will give the changed V_{SMES} i.e. voltage across the coil. Using the equation (10) we get current I_{SMES} across the coil from the voltage V_{SMES} by integrating and adding the initial current I_{SMO} .

For the system to not get damaged we use a saturator to limit the current across the coil. Now current across the coil of superconductor I_{SMES} and voltage across the coil of superconductor V_{SMES} is sent to a multiplier and we know from equation (7) it will give power P_{SMES} across the coil.

4.2 Eigen Value Calculation

All the subsystems are connected in matlab i.e. synchronous generator, turbine and governor; excitation system and SMES unit are connected together with an infinite bus having initial conditions. Here we took initial condition as load 0.8p.u and 0.85 power factor. Since all these system are non- linear, we linearize these first into linear form and then we get Eigen values

The system is simulated and then in matlab we linearize the system using following command

```
Lin = Linearize ('filename.mdl')
```

It will generate 3 matrices first the state space matrix and input and output variables matrix.

We can save the matrix 'a' into a variable Am using

```
Am = Lin.a
```

Since the 'Am' now contains matrix A, using 'eig' command we can find Eigen values of the system.

```
Eig(Am)
```

We found the Eigen values for three conditions. First without SMES and PI controller, second with SMES but without PI controller and third with SMES and PI controller.

A total of ten relevant Eigen values we get three from generator, four from governor and turbine block, two from excitation block and one from SMES block.

Table 1. System Eigen Values at p.f=.85 and load =0.8 p.u

| Without SMES and no PI | With SMES but no PI | With SMES as well as PI |
|------------------------|---------------------|-------------------------|
| -215.5 | -215.485 | -215.562 |
| -42.705 | -42.658 | -49.546 |
| -0.125 | -0.125 | -0.125 |
| -.034+- j9.12 | -0.043+- j9.14 | -2.134+-j9.13 |
| -1.993 | -2.0732 | -2.1204 |
| -1.850 | -1.858 | -3.249 |
| -20 | -20 | -20 |
| -5 | -5 | -5 |
| -10 | -10 | -10 |
| | -38.4615 | -8.0000 |

When no PI controller is there, we replace PI controller with a unity gain. We have found Eigen values for one load condition so we are doing damping improvement for this load only. For other loads we have to calculate the Eigen values at that load and proceed.

4.3 Controller Design and Parameter Calculation

Basic PI controller block is given by

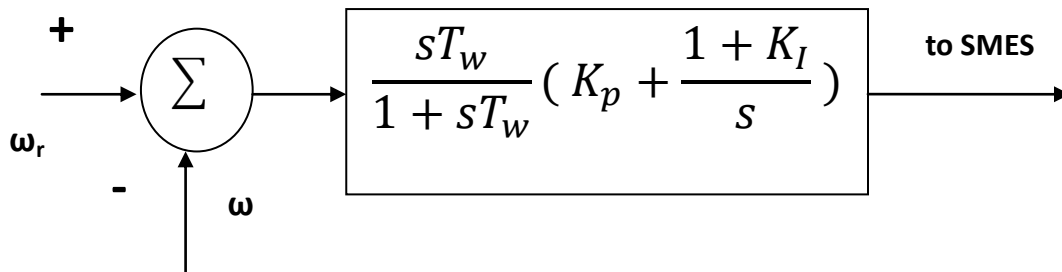


Fig 7 PI controller

The PI controller is fed with the reference angular speed taken 1 p.u generally ω_r and rotor angular speed ω . This PI controller output is attached to the SMES unit. T_w is known in system parameters, values of K_I and K_p can be found by modal control approach using pole placement method (Ref 9).

Linearized differential equations that we obtained from matlab can be written in form:

$$\dot{X}(t) = AX(t) + BU(t) \quad (13)$$

Where $X(t)$ is the state vector ($\Delta\omega$, $\Delta\delta$, ΔV_{SMES} , $\Delta e'_d$, ΔP_r , ΔP_m , ΔP_h , ΔP_c , ΔE_{FD} etc.)

$U(t)$ is U_{SMES} which is control signal that comes out of PI controller

$$Y(t) = C X(t) \quad (14)$$

Y is basically the output vector which is $\Delta\omega$ here. A , B and C are matrices with constant values of the given system. Taking Laplace transformation of equation (13) and (14), we get

$$sX(s) = AX(s) + BU(s) \quad (15)$$

$$Y(s) = CX(s) = G(s)U(s) \quad (16)$$

Control signal from PI controller $U(s)$ can be written as [8]

$$U(s) = H(s)Y(s) \quad (17)$$

$$U(s) = \frac{sT_w}{1+sT_w} \left(K_p + \frac{K_I}{s} \right) Y(s) \quad (18)$$

Where K_p and K_I are controller parameters that are supposed to be found. Characteristic equation related to any system with closed loop is given by

$$1 - C(sI - A)^{-1}BH(s) = 0 \quad (19)$$

For any system with close loop with Eigen value ρ is given by [8]

$$1 - C(\rho I - A)^{-1}BH(\rho) = 0 \quad (20)$$

Or

$$H(\rho) = [C(\rho I - A)^{-1}B]^{-1} \quad (21)$$

$$H(\rho) = \frac{\rho T_w}{1 + \rho T_w} \left(K_P + \frac{K_I}{\rho} \right) \quad (22)$$

For this paper we have taken the Eigen value at $-2.134 \pm j9.13$. We have two variables and two equations by using given Eigen value one by one and solving it, we get the value of K_p and K_I .

After solving we got $K_p = 7.4$ and $K_I = 660.39$.

CHAPTER 5

5. SIMULATION AND RESPONSE CURVES

In this section the whole system we developed is being simulated for initial given load of 0.8 p.u and .85 power factor. Synchronous generator taken has the power of 160 MW with rated voltage of 15 KV. Which is attached to an infinite bus with initial load and line resistance $R_L = .028$ p.u and inductance $L_L = .5$ p.u.

SMES, governor and turbine and excitation system all are connected. After that we add a large disturbance to the system at the infinite bus end for some initial cycles that will produce oscillations and will create undamped signals which will be reduced by using SMES.

5.1 Simulation of System with SMES but without PI controller

We added a three phase fault at the infinite bus end of the system which created oscillations due to the short circuit condition. In this case we removed the controller part and added a unity gain and observed the change in rotor speed ω of the synchronous generator as well as the power P_{SMES} of the superconducting coil.

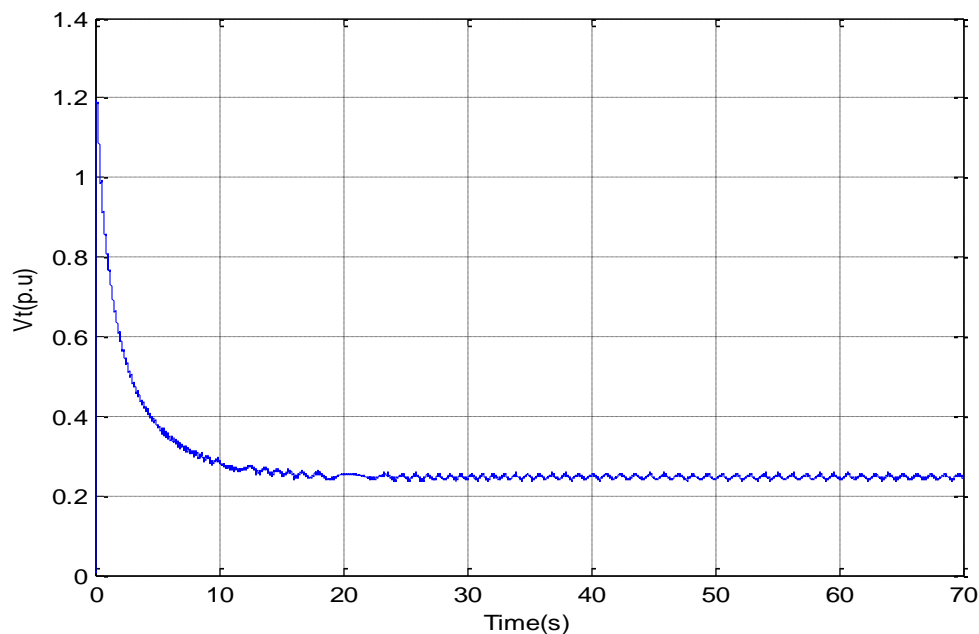


Fig 8 Graph between terminal voltage V_t (p.u) vs Time

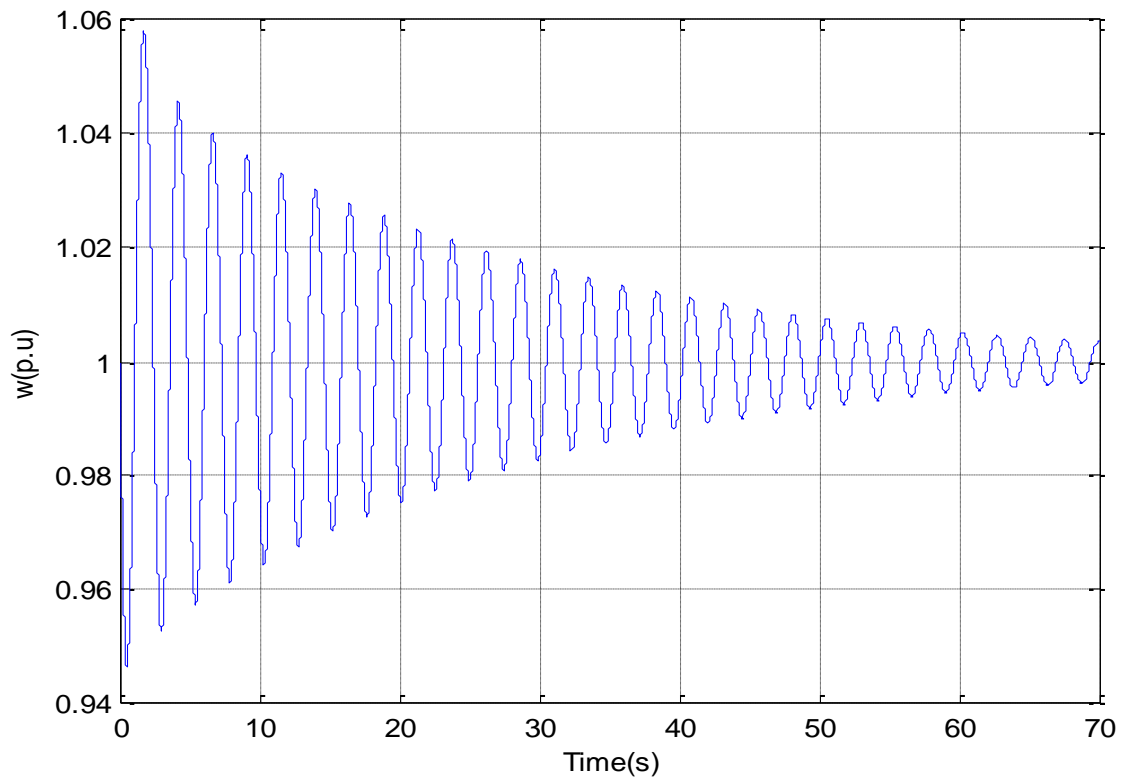


Fig 9 Graph between rotor angular speed ω (p.u) and time

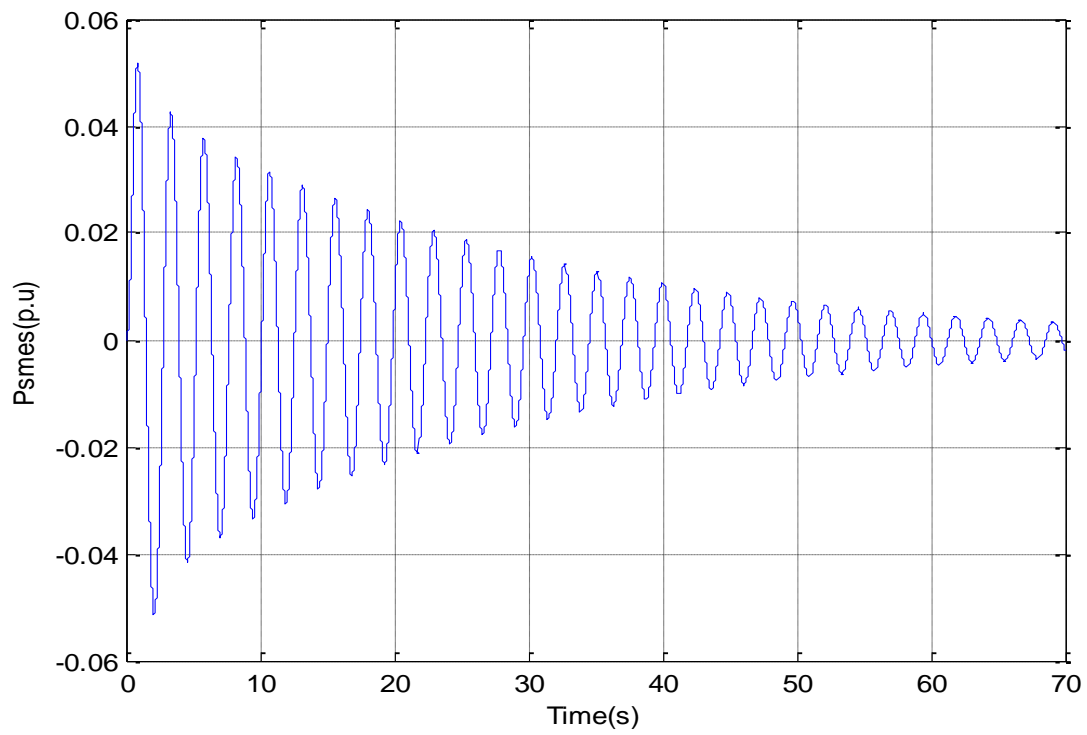


Fig 10 Graph between P_{SMES} (p.u) and Time

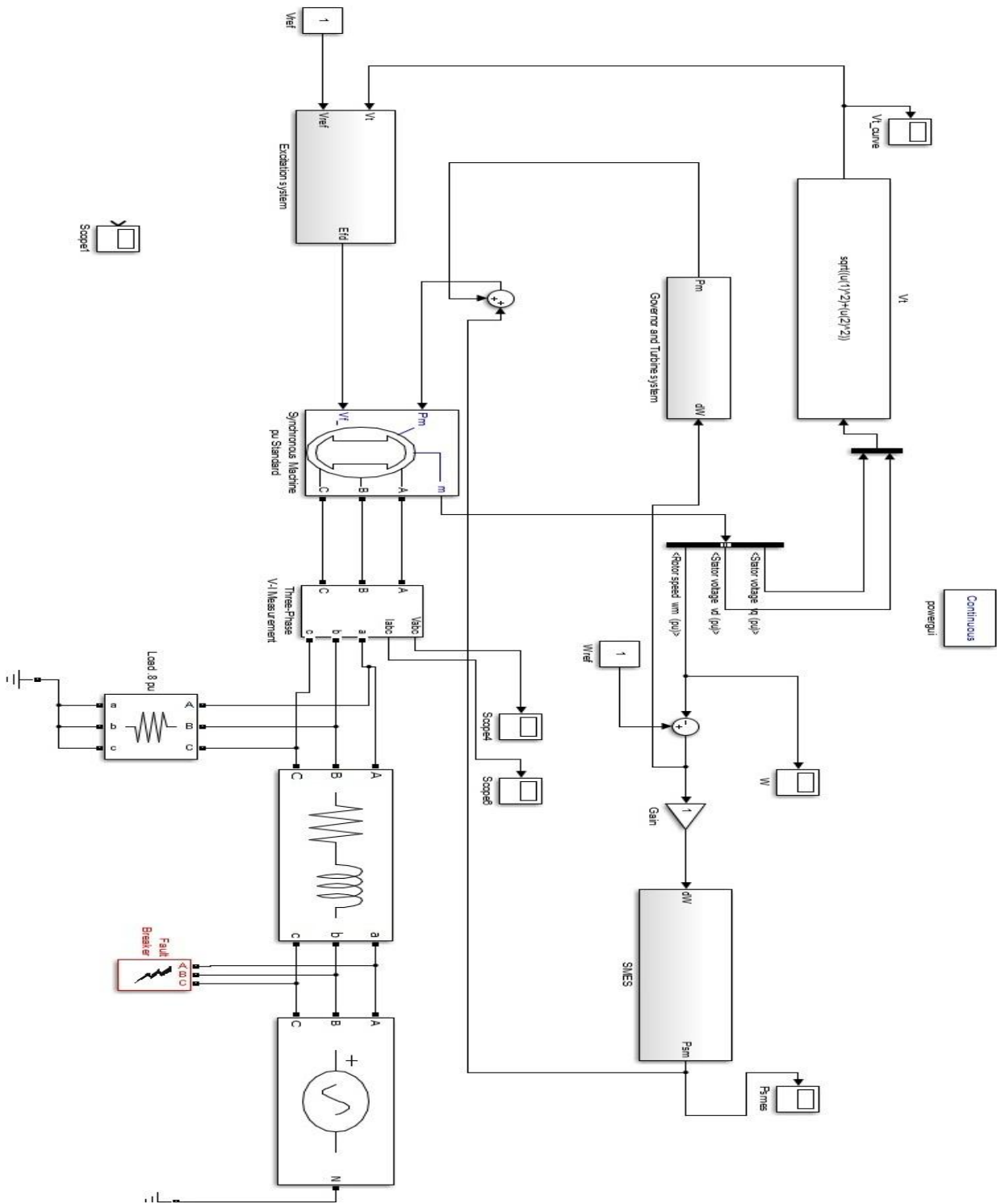


Fig 11 Simulink model of system with SMES but without PI controller

5.2 Simulation of System with SMES and PI controller

We added a three phase fault at the infinite bus end of the system which created oscillations due to the short circuit condition. In this we kept both SMES and PI controller unit and observed the change in rotor speed ω of the synchronous generator as well as the power P_{SMES} of the superconducting coil. V_t of terminal will be almost constant in both cases. Damping in this case is very smooth and fast as compared to the previous case.

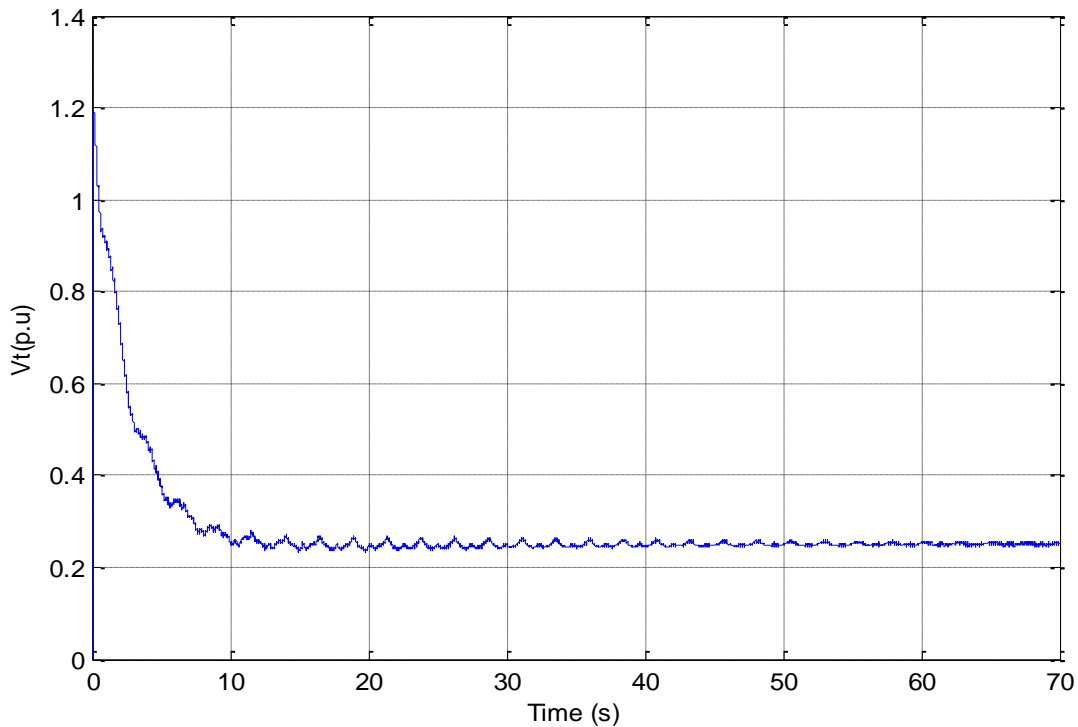


Fig 12 Graph between terminal voltage V_t (p.u) vs Time

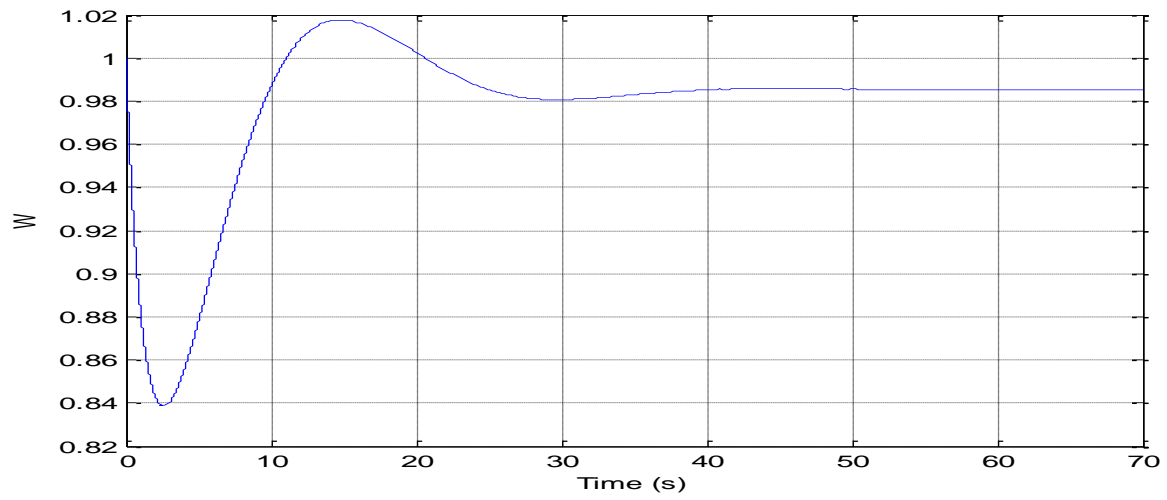


Fig 13. Graph between Rotor angular speed ω (p.u) vs Time

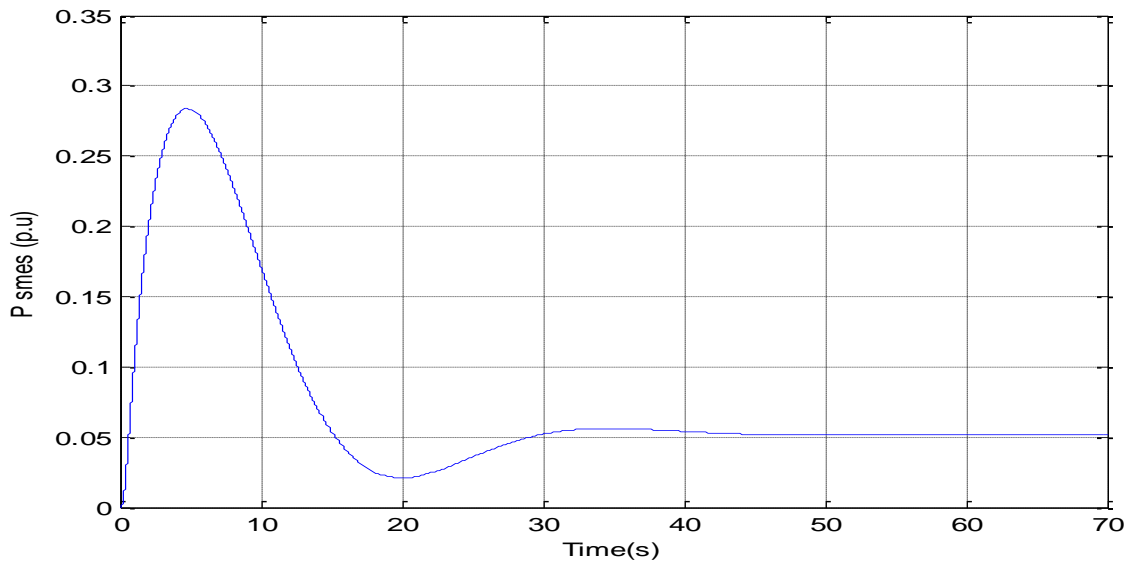


Fig 14 Graph between P_{SMES} (p.u) and Time

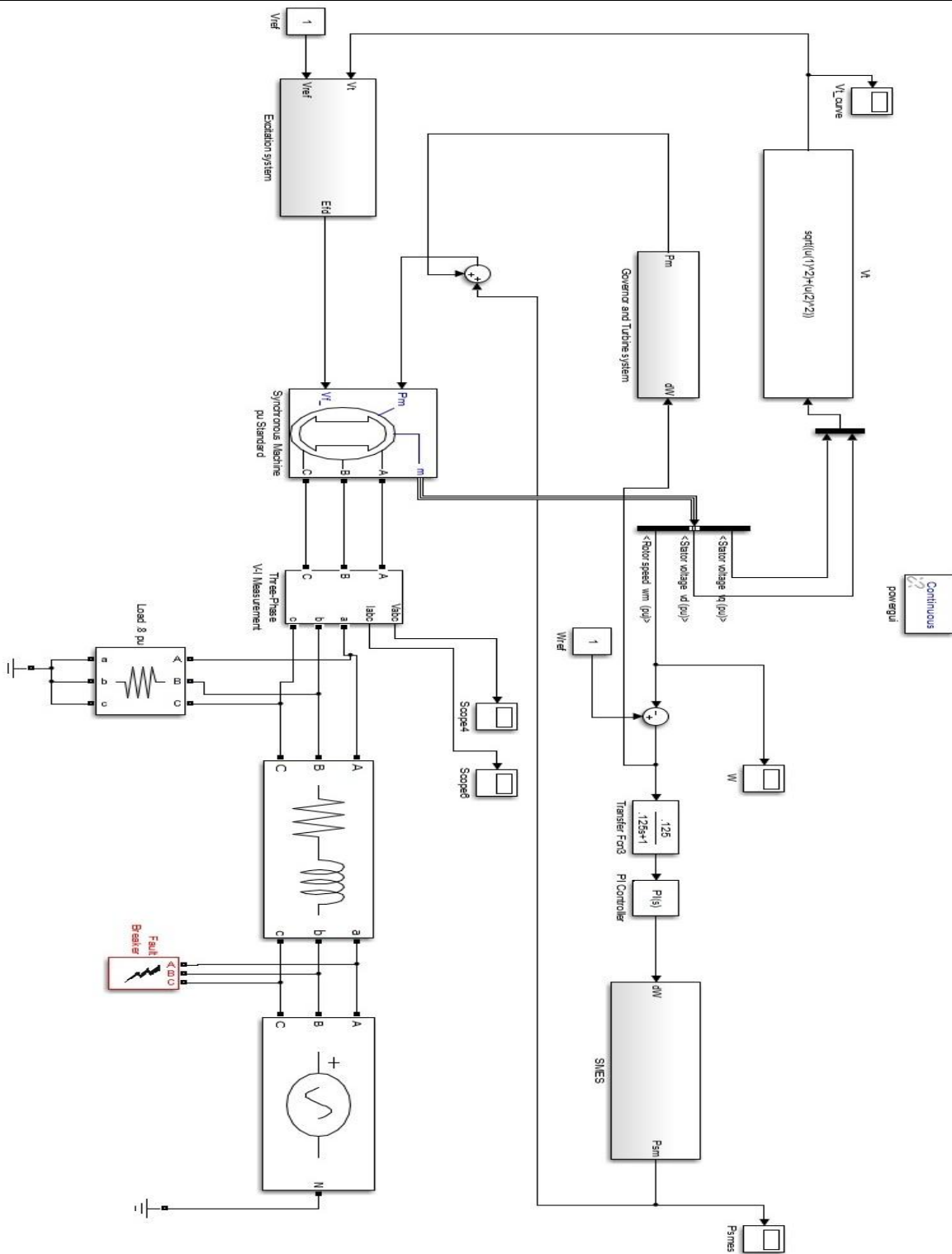


Fig 15 Simulink model having both SMES and PI

6. RESULT AND CONCLUSION

Controller for SMES unit was designed and graphs were plotted by adding disturbance to the system i.e. a large disturbance to the infinite bus end was added.

- In first case when no PI controller is added the response curve of damping of rotor angular speed is slower. This is because SMES alone has to handle the deviation in rotor angular speed that is occurring due to disturbance.
- But when we added the SMES with the controller the damping was comparatively faster as well as smooth. This is due to the fact that PI controller reduces the error in deviation occurring in the rotor angular speed due to the disturbance.
- Hence system damping was achieved more effectively by using a controller with SMES unit which stabilized the dynamic disturbance which was created.
- But this method of stabilization is conventional and very much dependent on system parameters and the initial load we are using. For every load we have to design a different controller which is very tedious and complex job.
- A PID controller can be used for active and reactive power control in power system which can stabilize system even under dynamic loads.

7. Bibliography

- 1) D. Sutanto, M. V. Aware, "Improved controller for high temperature super conducting magnetic energy storage (HTS-SMES)" 2009 IEEE Intel. Conf. Appl. Supercond. and Electromag. Dev., 2009: pp.361-364.
- 2) H. J. Boenig and J. F. Hauer, "Commissioning test of the Bonneville power administration 30 mg superconducting magnetic energy storage unit," IEEE Trans. Power Apparatus and Systems, vol. PAS-104, no.2, pp. 302-312, Feb. 1985.
- 3) Y. Mitani, K. T suji and Y. Murakami, "Application of superconducting magnet energy storage to improve power system dynamic performance".IEEE Transactions on Power Systems, vol. 3, no. 4, November 1988.pp 1418-1425.
- 4) John D. Rogers, Robert I. Schemer, Barry I. Miller, And John F. Hauer, "30-MJ Superconducting Magnetic Energy Storage System for Electric Utility Transmission Stabilization" proceedings of the IEEE, vol. 71, no. 9, september 1983.pp.1099-1107.
- 5) A.H.M.A.Rahim, A. M .Mohammad, "Improvement of synchronous generator damping through superconducting magnetic energy storage systems" IEEE Transactions on Energy Conversion, vol. 9, no. 4, December 1994.pp. 736-742
- 6) C.J. WU and Y.S. Lee "Damping of synchronous generator by static reactive power compensator with digital controller" IEEE proceedings-c, vol. 138, no. 5, september 1991 pp. 427-433.
- 7) Marcelo Gustavo Molina, Pedro Enrique Mercado, and Edson Hirokazu Watanabe "Improved Superconducting Magnetic Energy Storage (SMES) Controller for High-Power Utility Applications" 2011 IEEE. Pp. 444-456.

- 8) Chi-Jui Wu, Yuan-Shung Lee “Application of superconducting magnetic energy storage unit to improve the damping of synchronous generator” IEEE Transactions on Energy Conversion, vol. 6, no.4, December 1991.pp. 573-578.
- 9) Chi-Jui Wu, Yuan-Shung Lee “Application of simultaneous active and reactive power modulation of superconducting magnetic energy storage unit to damp turbine generator sub synchronous oscillations” IEEE Transactions on Energy Conversion, vol. 8, no. 1, March 1993.pp 63-70.
- 10) Y.Murakami, K.Tsuji “Simultaneous active and reactive power control of superconducting magnet energy storage using gto converter” IEEE Transactions on Power Delivery, vol. PWRD-1, no. 1, January 1986.pp 143-150.
- 11) S. Banerjee, J. K. Chatterjee, S. C. Tripathy “Application of magnetic energy storage unit as continuous var controller” IEEE Transactions on Energy Conversion, vol. 5, no.1, March 1990.pp 39-45.
- 12) R.F. Giese, T.P Sheahen A.M, Wolsky “High-temperature superconductors:their potential for utility applications” IEEE Transactions on Energy Conversion, vol. 7, no. 3, September 1992. pp. 589-597.
- 13) Q.Jiang, M.F.Conlon “ The power regulation of a pwm type superconducting magnetic energy storage unit” IEEE Transactions on Energy Conversion, vol. 11, no. 1, March 1996. pp 168-174.
- 14) John E. C. Williams “Superconducting Magnets and Their Applications” Proceedings of the IEEE, vol. 77. no.8, August 1989.pp 1132-1142.
- 15) Wei-Jen Lee, Mo-Shing Chen, Fellow, IEEE, And Lucas B. Williams”Load Model for Stability Studies” IEEE transactions on industry applications, vol. ia-23, no. 1, January/February 1987.pp 159-165.

- 16) Michael J. Basler and Richard C. Schaefer, "Understanding Power System Stability", Protective Relay Engineers, 2005 58th Annual Conference for, 5-7 April 2005, pp.46 – 67.

- 17) R. L. Kustan, J. J. Skiles, J. Wang, J. Cleary, and F. Tsang, "Power conversion system for diurnal load leveling with Superconductor magnetic energy storage," IEEE Trans.Magnetics, vol. MAG -23, no.5, pp. 3278-3280, Sept. 1987

8. Appendix: System Parameters [8]

Generator and transmission line

Power 160 MW

Rated Voltage 15 KV

Power .8 p.u

power factor .85

$X_d = 1.70$

$T_{q0} = 0.075$ s

$X'_d = .25$

$T_{d0} = 5.9$ s

$X_q = 1.65$

$D_g = 0$

$R_t = .028$

$L_t = 0.50$

Governor

$K_G = 3.5$

$T_{CH} = 0.05$ s

$T_{RH} = 8$ s

$T_{SR} = 0.1$ s

$T_{SM} = 0.2$ s

$K_{RH} = 0.3$

SMES Unit

$I_{SMO} = 0.6495$

$V_{SMO} = 0$

$L_{SMES} = 0.5$ H

$T_C = 0.026$ s

$K_C = 1.83$

$T_w = 0.125$ s

Exciter

$K_E = 400$

$T_E = 0.05$ s

$K_F = 0.025$ s

$T_F = 1.0$ s