Analysis and Simulation of Superconducting Magnetic Energy Storage System

A Thesis Submitted to

National Institute of Technology, Rourkela

In Partial fulfilment of the requirement for the degree of
Master of Technology
In
Cryogenics and Vacuum Technology

By

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(212ME5409)

Under The Guidance of
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Rourkela -769008 (India)
2014

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ACKNOWLEDGEMENT

It is indeed a big joy for me to show my profound gratitude towards my guide, Prof. B. Chitti Babu, Assistant 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 wish to get hold of this chance to convey my deep appreciation to the Department of Electrical 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

Subject field of the energy charging, storing and discharging characteristics of the Superconducting Magnetic Energy Storage system have been theoretically studied in the time to make an integrated mathematical model and the simulation model to analyses the characteristics of charging and discharging practically in Matlab.

In this paper a novel controller is designed for controlling the Magnetic Energy storage system ensure (a) fast return of energy to the super-conducting coil under constant current mode and (b) a constant and sinusoidal input supply current irrespective of the varying load demand with and without harmonics. A special feature of this controller is its ability to smoothly charge the superconducting coil using constant current charging so that it can be ready for the next discharging operation as soon as possible.

Matlab, Simulink is done under this paper with Matlab coding for generating the graph. The results suggest that the Theoretical and Simulink graph is approximately similar and with is the more simple Controller is designed for the Energy Discharging.

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

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CERTIFICATE

This is to certify that the report titled “Analysis and Simulation of Superconducting Magnetic Energy Storage System”,submitted to the National Institute of Technology, Rourkela by **Mr. Kumar Sheelvardhan, Roll No**. **212ME5409** for the award of Master of Technology in Electrical Engineering, 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.

B. Chittibabu

Prof. B. Chitti Babu

Supervisor

Department of Electrical Engineering

National Institute of Technology,Rourkela

CONTENTS

List of Symbols

U	Voltage Source, V
$U_R(t)$	Feedback Voltage Source, V
I_0	Initial current, A,
I(t)	Instantaneous Current, A
$I_R(t)$	Feedback Current, A
R	Internal Resistance, Ω
η	Energy utilization Factor
E	Inductive Energy J
Z	Load resistance, Ω
L	Initial inductance, H
t_s	Constant Power Discharging Time, sec
ε	Consumed Energy Factor

List of Figures

CHAPTER 1

INTRODUCTION

Superconducting Magnetic Energy Storage Devices can store the excessive electronic energy as electromagnetic energy in high temperature superconducting inductors and releases the stored energy if required .MES is a large superconducting coil capable of storing electric energy in the magnetic field generated by the current crossing through it. The real Power as well as the reactive power can be absorbed or by release from the MES coil according to system power requirements. The advantage of MES devices compared to the other energy storage devices are high energy storage density, high energy storage efficiency, long application lifetime and few environmental pollution. So the major application of Superconducting Magnetic Energy Storage(SMES) system is in Power system load levelling, Power system stabilizers, Fault Current Limiter and voltage support for critical loads because of SMES high efficiency and speedy reaction to power demand.

To develop the superconducting inductor or magnet used in MES system is mainly contributed from superconductivity field while the basic energy storage are contributed from the storage devices. Currently the worldwide theoretical and observational studies of MES mainly Focus on the interactive influences between Magnetic Storage system and the power grids, even so, on the point is no integrated theoretical study on independent MES.

In the paper, High Temperature Superconducting(HTS) inductive energy controlled discharging characteristics have been theoretically analyzed, with the intention to study the feasibility of SMES by introducing HTS technology. An SMES device is a DC current device that stores energy in the magnetic domain. The current running through the superconducting wire in a large magnet creates the magnetic domain. Since energy is storage in circulating current, energy can be pulled from an SMES unit with near instant reaction to energy stored or delivered over periods ranging from a fraction of a second to several hours.

An SMES unit consists of large superconducting coil at the cryogenic temperature. This Temperature is sustained by a crystal a Dewar that contains Helium or Nitrogen liquid vessels. A bypass switch is applied to cut energy losses when the scroll is on standby. It also serves other function such as by passing the coil current if utility tie is lost, removing converter from service or protecting the coil if cooling is lost.

1.1 History of Superconducting Magnet:

Superconducting Magnetic Energy Storage is a novel technology that stores electricity from the grid within the magnetic field of a coil comprised of superconducting wires with near zero loss of energy.

SMES is a grid enabling device that stores and release large quantities of power almost instantaneously. The organisation is capable of releasing high levels of ability within a fraction of a cycle to replace sudden loss or dip in line power. Strategic injection of brief bursts of power can play a crucial part in maintaining grid reliability, especially with today increasingly congested power lines and the high penetration of renewable energy sources such as wind and solar.

A typical SMES consists of two parts- cryogenically cooled superconducting coil and power conditioning system which are motionless and result in higher reliability than many other power storage devices. Ideally,once the superconductivity coil is charged, the current will not decay and the magnetic energy can be stored indefinitely.

Benefits of SMES:

- Improves power quality for critical loads and provides carryover energy during momentary voltage sags and power outages.
- Improves load levelling between renewable energy sources and the transmitting and distribution network.
- Environmentally beneficial as compared to batteries, superconductivity does not bank on a chemical reaction and no toxins are brought out in the operation.
- Enhances the transmission line capability and performance- SMES features a high dynamic range, an almost infinite cycling capability, and an energy recovery rate close to 100%.
- Ultra-High field operation enables long term storage SMES system in a compact device with cost advantages in material and system cost.

Relevance:

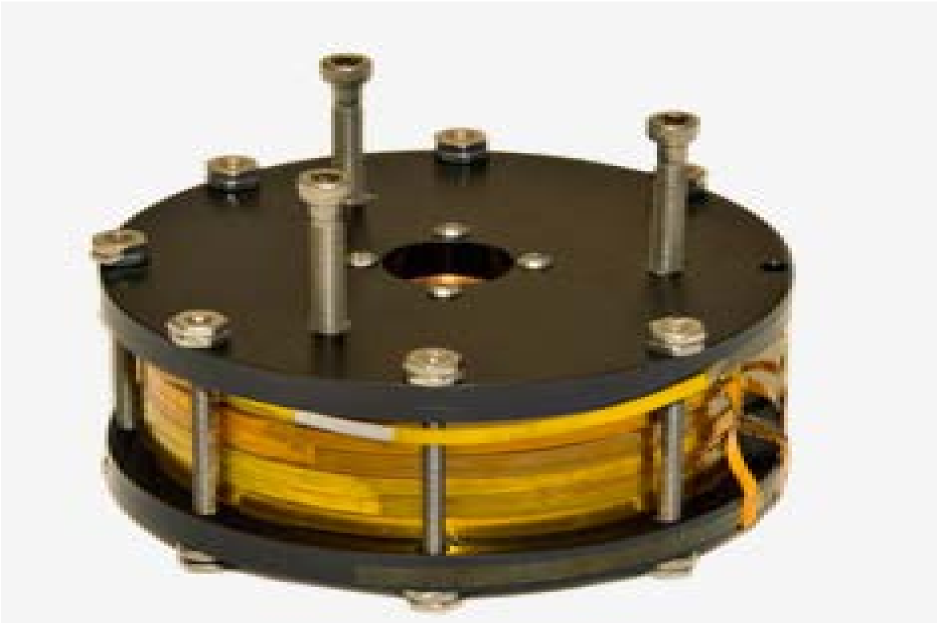
- Modular units can address both long term and short term storage requirements to help load levelling on the grid being fed by variable renewable sources such as solar and wind. Exceeding round-trip efficiency requirements at 85%, SMES can have both energy storage and dynamic compensation capabilities thanks to the nearly instantaneous dynamic response of the superconducting coil.

1.2 <u>History of HTS Magnetic System</u>:

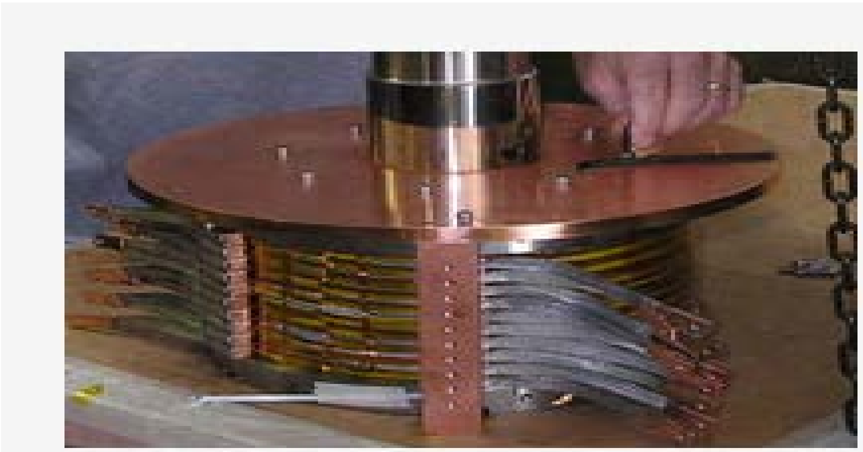
In 2004, Cryomagnetic completed and successfully tested a 3.57 tesla superconducting magnet system using BSCCO-223 high temperature superconducting tape.

The Magnet operates at approximately at 37 Kelvin.The room temperature bore is 3.50 inches.The completed system has never experienced a quench and has been tested up to the limit of the 125 ampere power supply.This system is being used with gyrotron tube, so a complex magnetic field shape was required.New winding hardware and techniquies had t e developed to insure he success of this project.

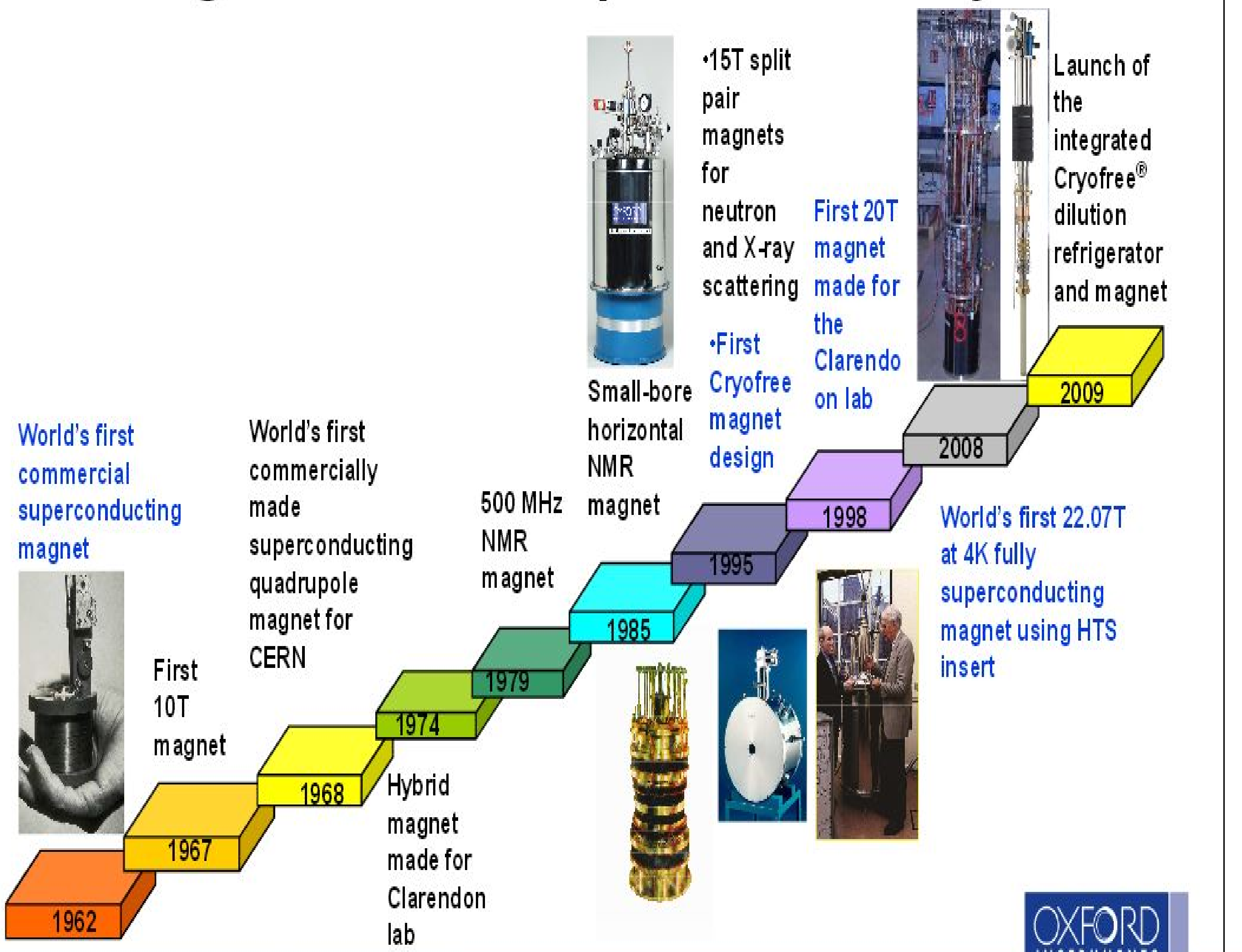
In 2005, Cryomagnetics constructed the first stacked pancake coil wound with long lengths of YBCO high Temperature superconductor.This project was conjunction with Oak Ridge National Laboratories.New techniques for construction are being developed to insure long term reliability.



As High Temperature superconducting tape becomes more affordable and the technology matures, Cryomagnetics groundbreaking experience will allow us to take advantage of higher field and larger bore system.



Leading the field of Superconductivity



1.3 Thesis Objective

The objectives to be achieved in this subject area:

- To utilize the developed algorithm to resolve the differential equations characterizing the superconducting magnet in Matlab M-file.
- Patterning of the SMES circuit with different values of parameters with comparing each characteristic with the superconducting inductor.
- To observe the Current and residual energy characteristic plot with the time period and similarly with the Power deliver in the circuit, Effective energy utilization factor is too characterized with the internal resistance
- To execute an analysis for the optimal configuration of Controller used for discharging of Superconducting Inductor. The controller should be stable with input response and simple in design, Matlab Embedded Function is used to design this under Matlab Simulink.

1.4 Thesis Layout

Chapter 1 contains the Introduction to the research work, its importance, history of the SMES magnet and the HTS magnet with Thesis objective and its Layout.

Chapter 2 is Literature Review and Research Methodology on previous research studies on the Superconductivity Magnetic Storage system.

Chapter 3 presents Mathematical analysis of the SMES model by driving the circuit differential equation and solving it for the current and voltage value.

Chapter 4 presents the Modelling of this Model by attaching new component in it and making it work for the circuit.

Chapter 5 presents the simulation results of all the three models in the SMES circuit and showing the graph of variation from the convectional inductor model.The stimulating ciruits of the Matlab is also provided in this chapter with the Matlab coding sed in this model.

Chapter 6 presents the conclusion of the whole project.

CHAPTER 2

LITERATURE REVIEW

A limited number of studies have been undertaken on illumination and visibility in the context of their impact on superconductive magnet.The following segment depicts previous research work carried out by different investigators in India and abroad.

[1]: The paper reported work on the superconductive magnetic storage system using a superconducting inductor in the network and verify its result mathematically and also by stimulation on Matlab. Power electronic devices are utilized to design the controller for controlling the three states. They have also done work on SMES technology for using in future smart grids. The compensation power arrangements in a hybrid energy storage system using small scale SMESs. The application of high temperature superconducting transformers has been done and HTS rated current capability, it is also essential to realize the relevance and precise performance test and protection system for HTS transformers has done.

[2]: The paper describes about the controller used in SMES to control the discharging of the inductor and also introduces the study on current researches on power system application of SMES system.The work associated with the incorporation of a superconducting magnetic energy storage coil into a voltage source inverter based static synchronous compensator in damping dynamis oscillation in power system.The performance of the static synchronous compensator, a self commutated solid state voltage converter, can be mproved with the addition of energy storage.Its hows that dpending on the location of the compensator and SMES combination , simultaneous control of real and reactive power can be significantly enhance the performance of a transmission grid.

[3]: The paper introduces the first moving conduction cooled high temperature superconducting magnetic energy storage system built up in China.The SMES is rated at 380V,consisting of the high temperature magnet confined in a dewar,the cryogenic unit, the convertor ,the monitoring and control unit and the container etc.Laboratory and field test have been carried out to investigate the operational characteristics and to demonstrate the SMES effectiveness on improvements of system voltage stability and on the oscillation damping.

[4]: The paper investigate the impact of integrating a Battery Energy storage system and Superconducting Magnet Energy storage across the DC us of static compensator.This allows fast control of both real and reactive power to improve the power system transient stability and to provide extra damping against the power system oscillation in a multi-area system inked by weak inter-connection.Comparative dynamic performance of these devices are presented in this study.A control strategy is proposed to integrate these devices to improve the active power management within the constraints of the power system to which the divece is connected.

[5]: The work the High Temperature Superconductor of the inductive type with iron core has been explained and fabricated by this report.

[6]: The Superconductor is cooled by liquid Nitrogen at 77K and the prototype less than 1kVA has been fabricated.The reasons which affect or degrade the operation of the Superconductor Fault Current Limiter are investigated by T.Verhaege.

[7]: The design and simulation using the numerical calculation model in the computer of a magnetic-shield type superconducting fault current with high Tc Superconductor limiter has been reported by in this report . The ceramic superconductors are used at liquid nitrogen temperature. The flux jumping phenomenon is derived and its requirements are explained.

[8]: In this paper the principle of the High Temperature Superconductor Fault Current Limiter with resistive and shielded core type has been excused. The great size and its use only for AC Current is the main disadvantage of the shield core type. The transient behaviour of the Fault Current has also been talked over.

[9]: The formation of the America Superconductor in 1987 enhances the evolution of the High Temperature Superconductor applications. The American Superconductor is also developing the HTSFCLs.A MATLAB-based power system toolbox (PST) dynamic simulation and design concepts of the power system has been explained.

[10]: The aim of this MATLAB based Power System Toolbox is to supply a flexible environment for performing power system simulations. The MATLAB coded functions are in the equipment models that can be utilized in simulation. It can simply be utilized for design or simulation of small power systems and is chiefly used for teaching in the institutes to undergraduate students.The analysis of the faults in the interconnected power system has been explained in this paper.

[11]: Experiments were done by the undergraduate students of the Drexel University's Interconnected Power Systems Laboratory (IPSL). The behaviour of the current and voltage during fault is analysed. The paper explains how to create a fault in the system. The hardware and software tasks performed during experiments are explained.The short circuit currents and fault currents of an industrial plant have been analysed in this paper.

[12]: In this paper mathematical modelling of each part is served and the fault currents are computed from the mathematical construction of the elements**.** The Digital simulation is executed utilizing the Power System Blockset (PSB) of MATLAB. The example is a Graphical User Interface as well. The factors affecting the Stability of the Power Systems have been discussed and explained here. Power System Stabiliser are explained. Basically, this paper covers all the factors that affect the stability of the power systems and methods to improve the stability of the system are also discussed.

[13]: It explains the different simulation that can be done in PSAT on the Power System networks. PSAT is also provided with a complete set of user-friendly graphical interfaces and a Simulink-based editor of one-line network diagram. The use of PSAT in universities and commercially is explained in this report. The power systems, web virtual laboratory is becoming popular and is being used in the universities for teaching of power systems. This paper also explains how the problems of the people who use PSAT are solved through PSAT web forum.

Research Methodology

In China, one SMES circuit is offered with the Superconducting Inductor and variable load and variable source in 2007.It deals with the improved controller with the power electronics material including the Current charging controller. Analytical Model of this circle is developed using MATLAB software for analysis of the different parameters both for magnet and superconducting magnets.

CHAPTER 3

MATHEMATICAL ANALYSIS OF MODEL

3.1 Energy Charging:

The basic MES Circuit is shown in Figure 1

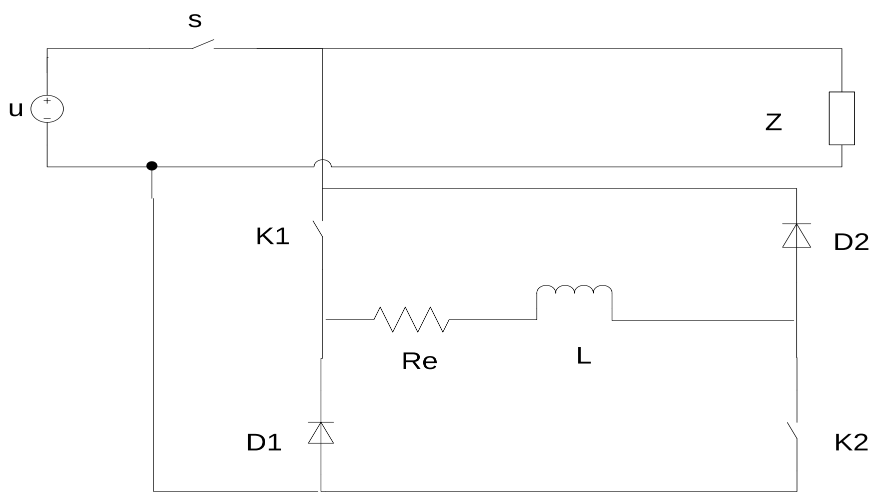


Figure 1

In Energy-charging state switch – S close, K_1 close, K_2 close;

So Governing Equations are:

If Inductor is initially loaded with initial current I0 then, granting to the Kirchhoff's voltage law (KVL), the voltage equation of the charging circuit should be

$$U - L\frac{dI(t)}{dt} - I(t)R_e = 0 \qquad (1)$$

So the charging current I (t) at any time it can be expressed by

$$I(t) = I_0 \exp\left(-\frac{R_e t}{L}\right) + \frac{U}{R}\left[1 - \exp\left(-\frac{R_e t}{L}\right)\right] \qquad (2)$$

For a superconducting inductor with zero immunity, i.e., Re≈ 0, then I (t) can be expressed by

$$I(t) = \frac{U}{L}t + I_0 \qquad (3)$$

When I0 = 0, the charging circuit is run at zero-state response state and Eq. (2) And

Eq.(3) can be simplified by

$$I(t) = \left(\frac{U}{R_e}\right)\left[1 - \exp\left(-\frac{R_e t}{L}\right)\right] \qquad (4)$$

$$I(t) = \frac{U}{L}t \qquad (5)$$

The voltage across the power inductor V(t) can be expressed by

$$V(t) = L\frac{dI(t)}{dt} \qquad (6)$$

The stored energy of the power inductor E(t) can be expressed by

$$E(t) = \frac{1}{2}LI^2(t) \qquad (7)$$

The consumed energy of the power inductor Q(t) can be expressed by

$$Q(t) = \int_0^t [I^2\,(t)R_e]dt \qquad (8)$$

3.2 Energy Storing:

In Energy-storing state switch – S open, K_1 open, K_2 close;

Storing Circuit will operate at Zero input State Response and according to KVL, the Voltage Equation for storing circuit is

$$L\frac{dI(t)}{dt} - I(t)R_e = 0 \qquad (9)$$

So the strong current at any time it can be expressed by

$$I(t) = I_0 \exp(-\frac{R_e t}{L}) \tag{10}$$

In the Superconducting Inductor with Zero resistance effect (R_e=0), then the storing current and stored energy can remain unchanged.

3.3 <u>Energy Discharging:</u>

It includes two different modes *(a)Uncontrolled Discharging*

(b)Controlled Discharging

(a)Uncontrolled Discharging:

When the Inductor is charged, then the source and charging will be disconnected from the circuit and Inductor starts Discharging at an uncontrolled pace, at this state the all the switches will remain unresolved.

According to the KVL, the Voltage Equation of the Uncontrolled Discharging state will be

$$L\frac{dI(t)}{dt} - I(t)R_e - I(t)Z = 0 \tag{11}$$

Presume that the equivalent impedance of the load Z is R, then the uncontrolled discharging current can be expressed by

$$I(t) = I_0 \exp[-\frac{(R+R_e)t}{L}] \quad (12)$$

For a superconducting inductor with zero immunity, i.e., Re≈ 0, then I (t) can be expressed by

$$I(t) = I_0 \exp(-\frac{Rt}{L}) \quad (13)$$

(b)Controlled Discharging :

The controlled discharging mode is a complex operating state formed by energy-storing state and uncontrolled discharging state. The required discharging power P1 (t) = U1 (t) I1 (t), the controlled discharging circuit operates at the uncontrolled discharging state while the potential drop across the load UR (t) or the current through the load IR (t) is lower than U1 (t) or I1 (t), and operated at energy-storing state while UR (t) or IR (t) is higher than U1 (t) or I1 (t). The control scheme of the controlled discharging mode is depicted in Figure 2.

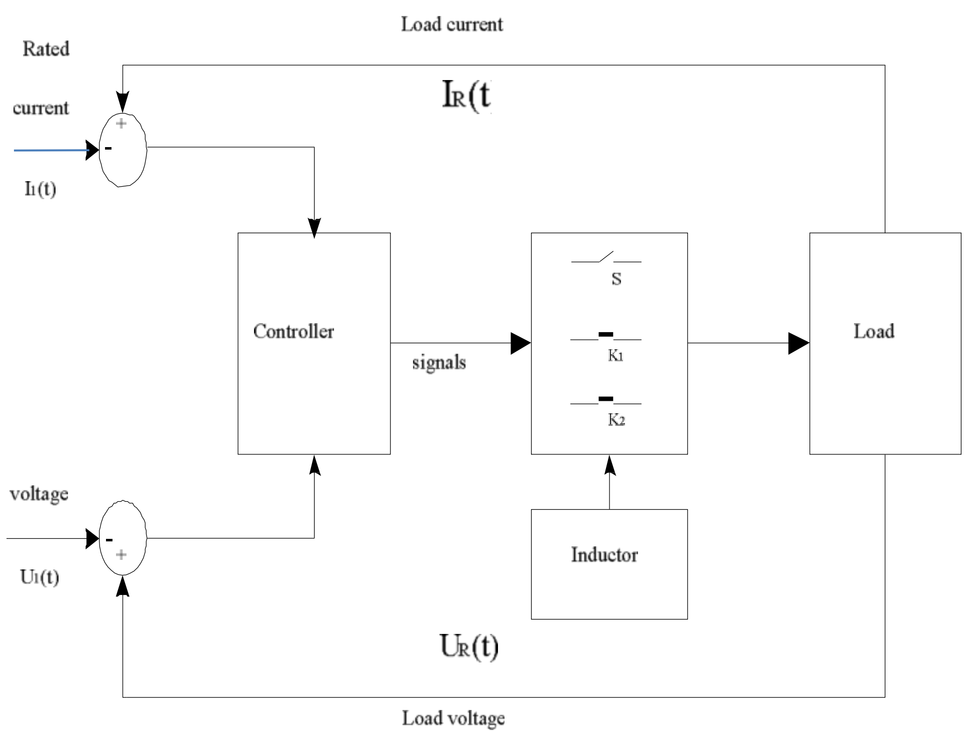


Figure 2

Initial current is I_0. Granting to the rule of conservation of energy, the energy equation of the controlled discharging circuit should be

$$\frac{1}{2}LI^2(t) = \frac{1}{2}LI_0^2 - Q(t) - \int_0^t P_1(t)dt \qquad (14)$$

And so the residual current in the Inductor is

$$I(t) = \sqrt{I_0^2 e^{-\frac{2R_e t}{L}} - \frac{2}{L} e^{-\frac{(2R_e t)}{L}} \int_0^t P_1(t)\, e^{\frac{2R_e t}{L}} dt} \qquad (15)$$

For Superconducting Inductor (Re=0), I (t) can be expressed equally

$$I(t) = \sqrt{I_0^2 - \frac{2}{L}\int_0^t P_1\,(t)dt} \qquad (16)$$

Assume that P_1 (t) =P_1= U_1I_1 (constant value), i.e., the circuit is operated at constant-power discharging mode.Then above equation will get

$$I(t) = \sqrt{I_0^2 e^{\frac{-2R_e t}{L}} - \frac{P_1}{R_e}(1 - e^{\frac{-2R_e t}{L}})} \quad (17)$$

$$I(t) = \sqrt{I_0^2 - \frac{2}{L} P_1 t} \quad (18)$$

When I(t) decreases to I_1(t) or I_1, the power inductor can't be discharged at rated discharging power P_1(t) or P_1, then the discharging circuit is equivalent to be operated at uncontrolled discharging mode .

In the constant-power discharging mode, assume that I (t) =I1 at a certain time outs, and so this is the so-called constant-power discharging time.

$$t_s = \frac{L}{2R_e} \ln \frac{I_0^2 + \frac{P_1}{R_e}}{I_1^2 + \frac{P_1}{R_e}} \quad (19)$$

$$t_s = \frac{\frac{L}{2}\left(I_0^2 - I_1^2\right)}{P_1} \quad (20)$$

Lets us Assume that the equivalent resistance of the Load is R, then the calculation formula for I(t) with Superconducting Inductor can be expressed as

For Conventional Inductor:

$$I(t) = \sqrt{I_0^2 e^{\frac{-2R_e t}{L}} - \frac{P_1}{R_e}(1 - e^{\frac{-2R_e t}{L}})}, \;\; t \leq t_s \tag{21}$$

$$I(t) = I_0 e^{[-\frac{(R+R_e)t}{L}]}, \; t > t_s \tag{22}$$

For Superconducting Inductor:

$$I(t) = \sqrt{I_0^2 - \frac{2}{L} P_1 t}\,, \qquad t \leq t_s \tag{23}$$

$$I(t) = I_0 e^{[-\frac{Rt}{L}]}, \qquad t > t_s \tag{24}$$

The corresponding effective energy utilization factor η is

$$\eta = \frac{2P_1 t_s}{L I_0^2} \tag{25}$$

Energy Utilization factor for convectional inductor and superconducting inductor can be given as

$$\eta = \frac{P_1}{I_0^2 R_e} \ln \frac{I_0^2 + \frac{P_1}{R_e}}{I_1^2 + \frac{P_1}{R_e}} \tag{26}$$

$$\eta = \frac{I_0^2 - I_1^2}{I_0^2} \tag{27}$$

The corresponding consumed energy factor(ξ) with conventional inductor can be expressed by

$$\xi = \frac{LI_0^2 - LI_1^2 - 2P_1 t_s}{LI_0^2} \tag{24}$$

Above Equation can be simplified as

$$\xi = 1 - \frac{I_1^2}{I_0^2} - \frac{P_1}{I_0^2 R_e} - \frac{P_1}{I_0^2 R_e} \ln \frac{I_0^2 + \frac{P_1}{R_e}}{I_1^2 + \frac{P_1}{R_e}} \tag{25}$$

CHAPTER 4

MODELING OF SMES

According to the above theoretical analysis, the integrated SMES model has been developed to investigate the whole shooting, storing and discharging characteristics, as described in Figure 3. The input signals of the integrated MES mathematical model developed include feedback signals (e.g., the current through the shipment, the voltage across the load, and so forth), basic parameters (e.g., the inductance of the inductor, the charging voltage of power supply, the rated current of the inductor, etc.), and model selection signals which are applied to pick out different operating state and achieve the transition between different operating states. The basic charging model, storing model, and discharging model are combined by the accountant to take shape a whole internal MES model. The output signals of the integrated MES mathematical model developed include the current through the inductor, the stored energy of the inductor, the consumed energy of the inductor internal resistance, the useful energy of the committal, the current through the load, The potential difference across the load falls.

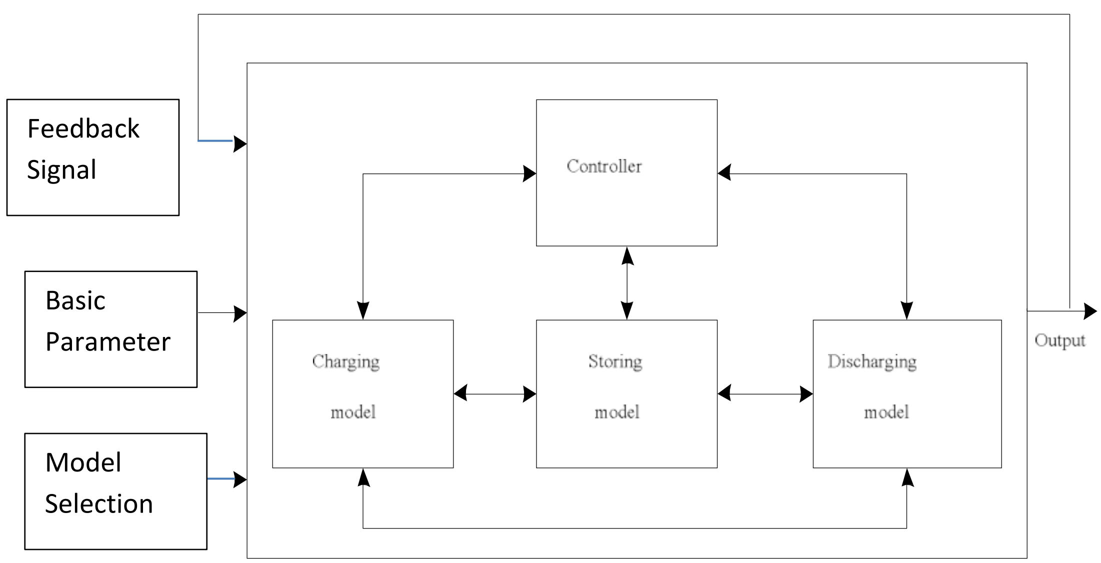


Figure 3

CHAPTER 5

SIMULATION RESULTS OF SMES:

Based on the developed MES mathematical model in figure, case study of whole characteristics of MES system including the energy charging, storing and discharging state will be carried out in this section.

5.1 Simulation of Energy Charging State:

The simulation model is shown of MES for the better characteristics of superconducting inductors. Assume that the charging voltage source U=100V,self inductance of the power inductor L=0.2H,internal resistance Re=5Ώ for conventional inductor, Re=0 for superconducting inductor.

The charging current increases linearly in the superconducting inductor while the charging current increases exponentially in the conventional inductor. The increment speed of the charging energy in the superconducting inductor is much quicker than that in the conventional inductor.

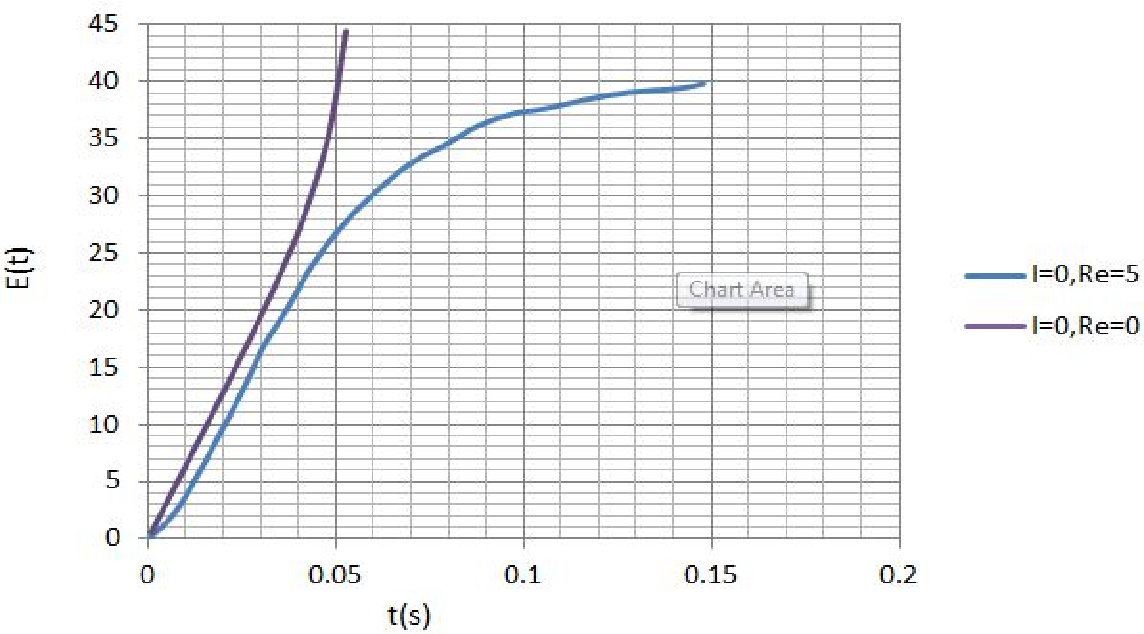


Fig 4 :The charging energy curve with different parameters

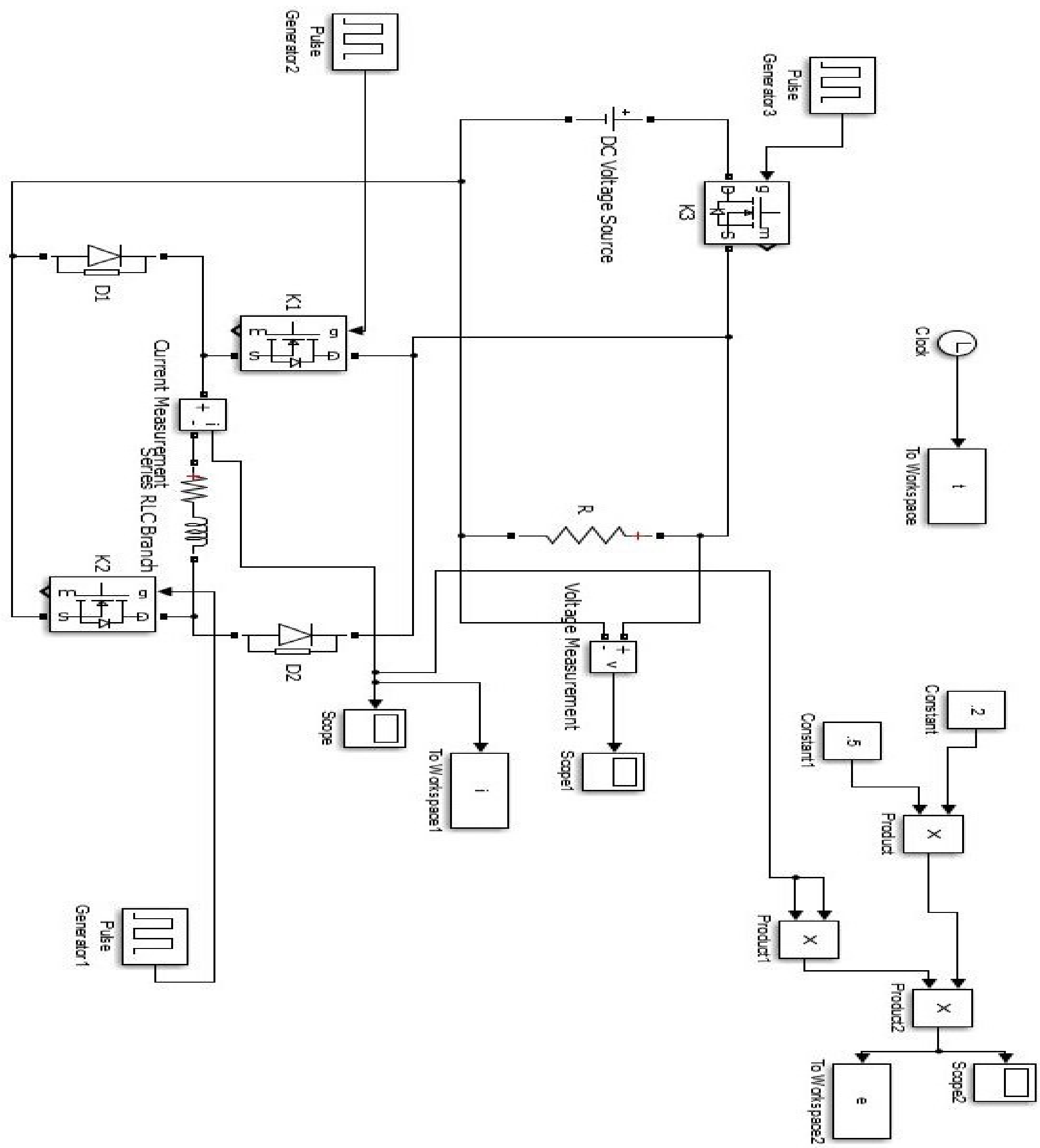


Fig 5 : Simulink model of energy charging state.

5.2 **Simulation Energy Storing State:**

The storing current and residual energy decreases exponentially in the conventional inductor, superconducting inductor with Re = 0, the storing current and residual energy can save the initial values.

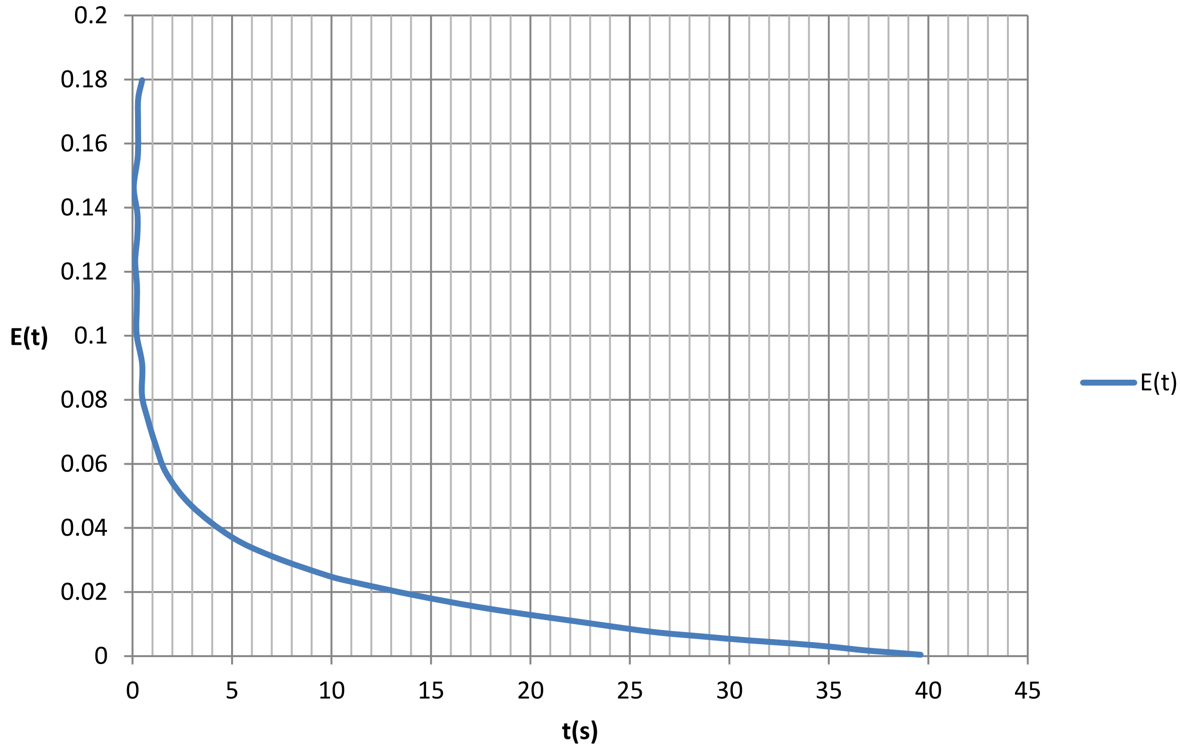


Fig 6 : The residual energy with Re=5Ώ

Assume that the intial current I_0=20A, self inductance of the power inductor L=0.2H,internal resistance of power inductor Re=5Ώ.

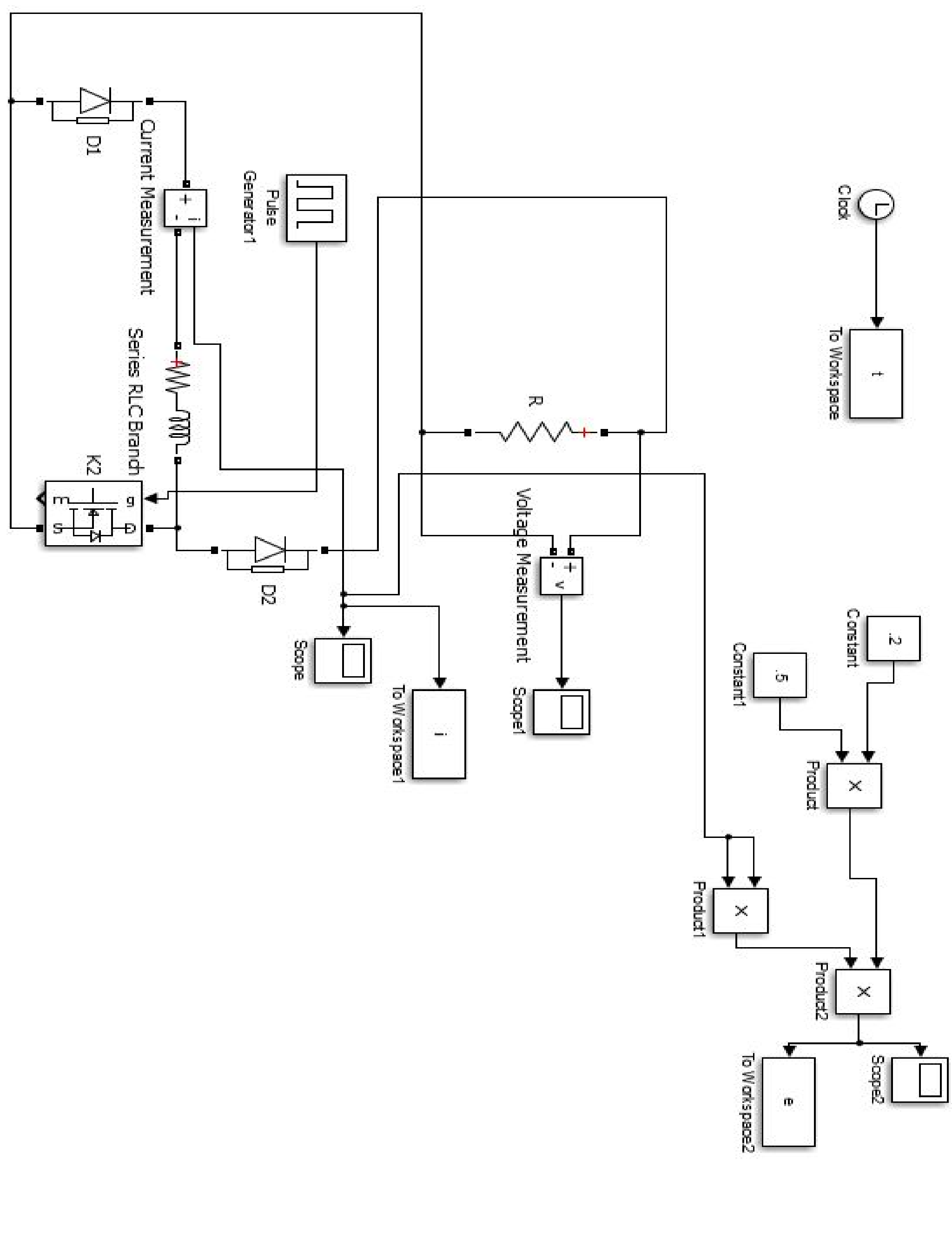


Fig 7 : Simulink model of Energy Storing state

5.3 Simulation Energy Discharging State:

Assume that the initial current I_0 =20A, self-inductance of the power inductor L=0.2 H,internal resistance Re = 5 Ω for conventional inductor, Re=0 for superconducting inductor, then the corresponding constant- power discharging current curves are shown.

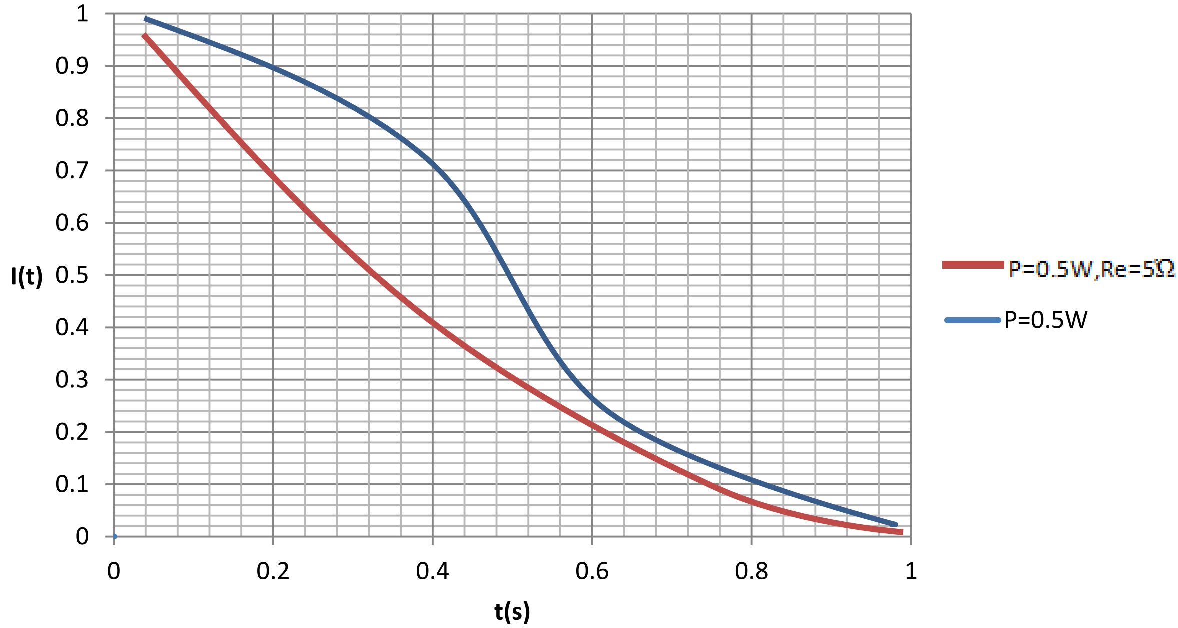


Fig 8: The discharging current curve with Re=0 and Re=5Ώ

For the discharging power of P=0.5W, the simulation value of constant power discharging time t_s are 0.167s and 0.613s for the conventional inductor and superconducting inductor.So the superconducting inductor can achieve larger constant power discharging time comparing to the conventional inductor.

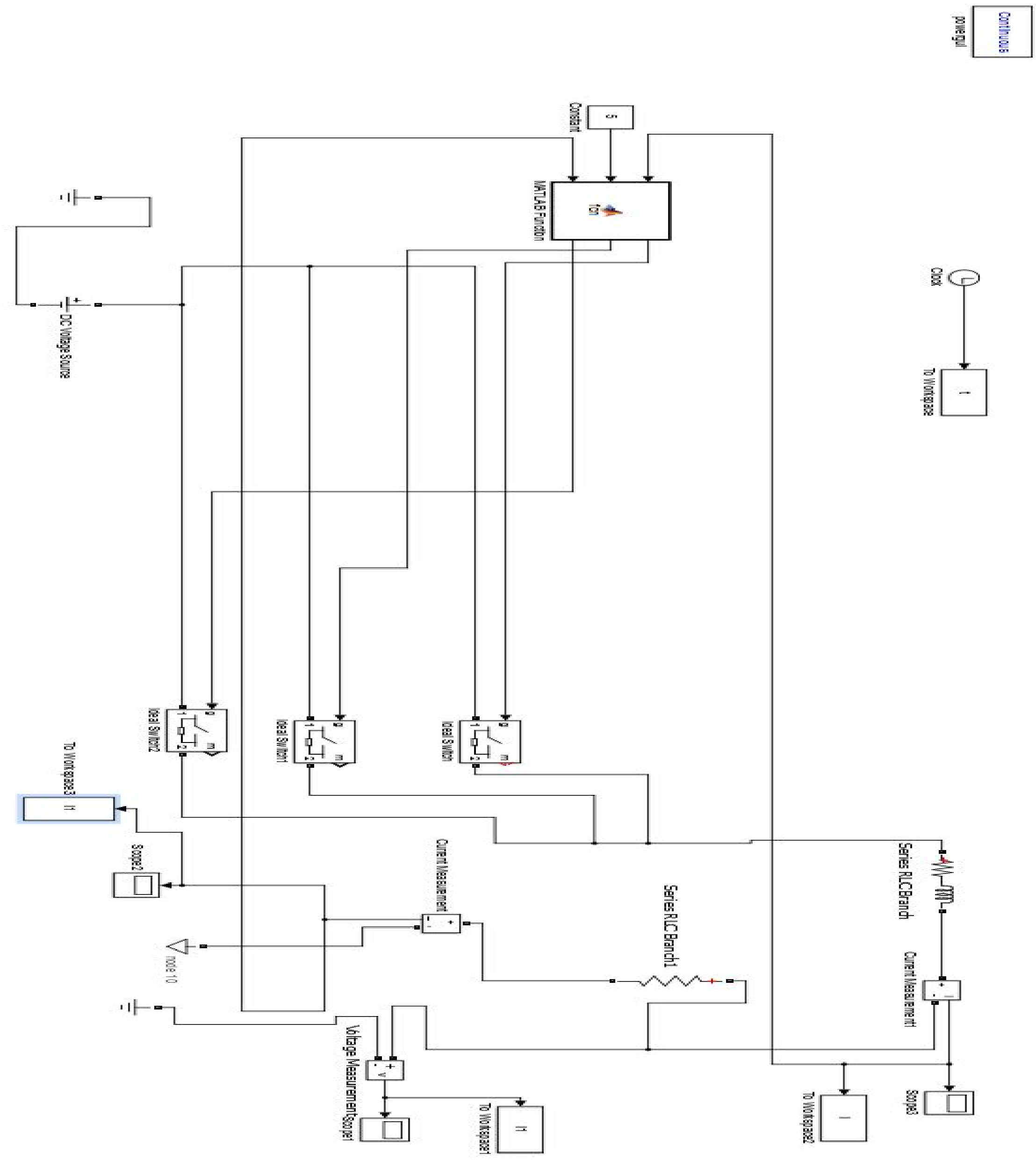


Fig 9 :Simulink model of Controlled Discharging state

5.4 Modelling of Controller:

The Controller used in the SMES is modelled by using Matalb Embeded Function where Matlab coding is written in M file and according to that the controller respond.In this the controller insides logic based on the current feedback and a constant current taken the reference current(I_r).

```
function [x, y, z] = fcn(I1, I2, Ir)
%#codegen
%charging
%U = 100
%L = 0.2
%Re = 5
%I0 = 10
%A = -Re/L
%B = U/Re
%t= [0:0.05:0.1;0.15:0.05:0.25;0.3:0.05:0.4]
%C=t*A
%I = []
%I={I0*expm(C)}+B*{1-expm(C)}
%I=10*expm(t*A)+20*(1-expm(t*A))
%tspan=[0,1,2,3]
%t=tspan
%I(t)= 10*2.56^(t*A)+20*(1-2.56^(t*A))
if I1>I2
X=I1,y=I1,z=I1;
end
%storing
if I1=I2
X=0,y=0,z=I1;
end
%discharging
if I1<I2
```

```
   X=0,y=0,z=0;
else Ir>I1
   X=0,y=0,z=I1;
end

  y = u;
```

5.5 Characteristics of Energy Factor:

The relation curves of the effective energy utilization factor η vs R_e and the consumed energy factor ξ vs R_e are shown if these figures.For a certain discharging power P=0.5W, η increases with the reduction of R_e while ξ decreases with the reduction of R_e. So the inductor with small R_e is favorable to achieve large discharging time and high energy utilization.

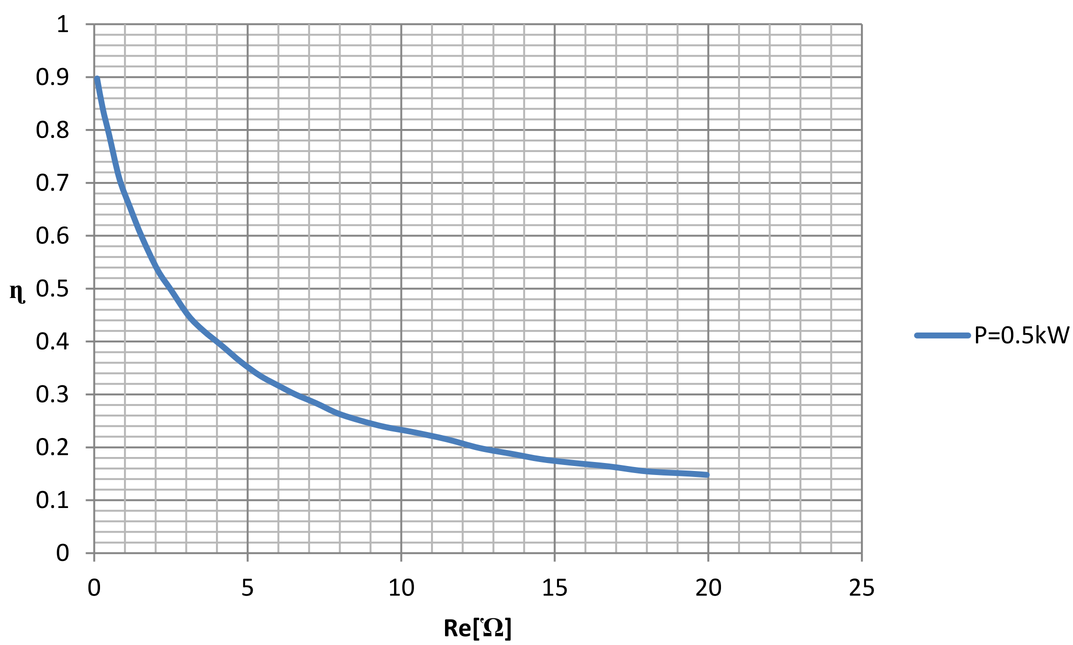


Fig 10 :The effective energy utilization factor η vs R_e

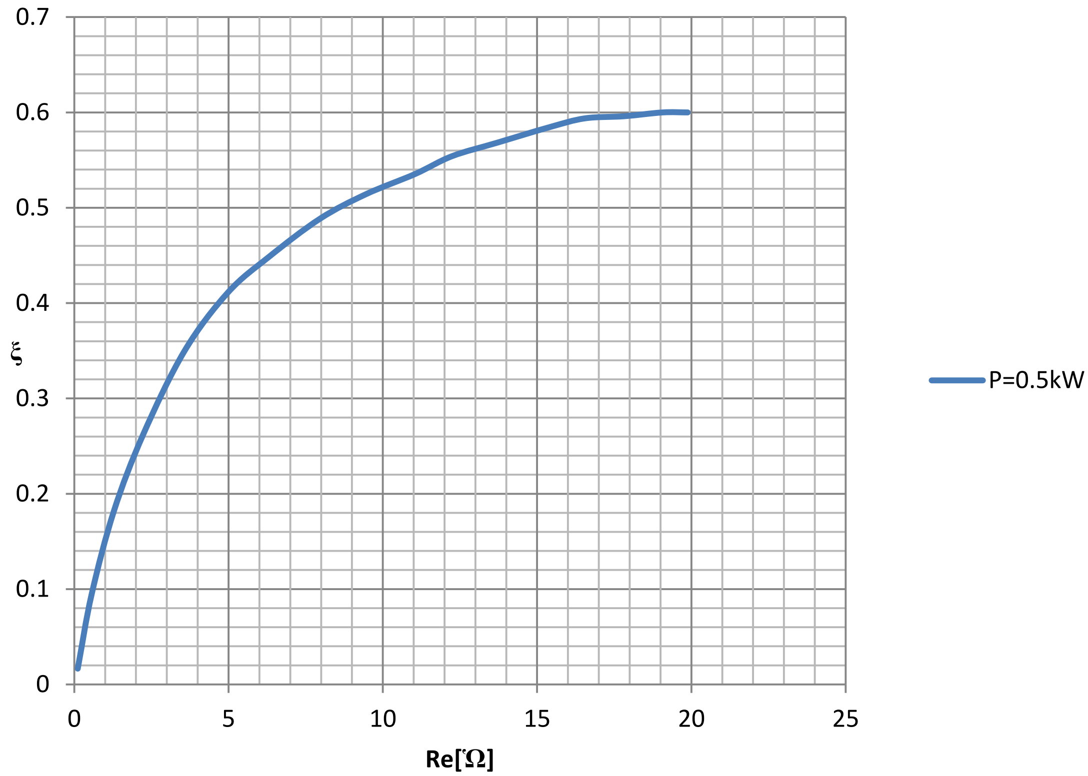


Fig 11: The consumed energy factor ξ vs R_e

6. CONCLUSION

The integrated MES mathematical model has been proposed and developed, with the simulated results obtained, which shows that the developed MES model with certain given input parameters can output the corresponding charging, and storing characteristics at any gone time, e.g., the stored energy of the power inductor, the consumed energy of the power inductor of the developed MES.

The model proposes a method to link Superconducting inductor to Matlab function to design and to implement controlled SMES, by this design we came to know that the Superconducting inductor is very energy efficient and conserves power for the discharging purpose.

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