STUDY OF POWER CONDITIONING SYSTEM OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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STUDY OF POWER CONDITIONING SYSTEM OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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By

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Dedicated to my beloved parents and my brother

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CERTIFICATE

This is to certify that the Thesis Report entitled "**STUDY OF POWER CONDITIONING SYSTEM OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM**", submitted by Ms. BHAGYASHREE MISHRA bearing roll no. 212EE4392 in partial fulfillment of the requirements for the award of Master of Technology in Electrical Engineering with specialization in "Power Electronics and Drives" during session 2012-2014 at National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

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ABSTRACT

A Superconducting Magnetic Energy Storage System (SMES) can be utilized for the compensation of nonlinear and pulsating loads. In this paper a power conditioning system (PCS) is designed to achieve SMES to work as a shunt active power filter and power conditioner at the same time. Two Hysteresis band controllers have been implemented to obtain (i) a sinusoidal input source current in phase with fundamental component of line to neutral source voltage irrespective of the load conditions (ii) Charging and discharging of SMES under constant voltage control mode. DC link voltage is kept constant by DC/DC Bidirectional Converter and source current is controlled by Voltage Source Converter (VSC). The magnitude of reference source current is obtained by controlling the energy of SMES by using Fuzzy Logic Controller (FLC). As it is a nonlinear controller it gives better performance than previously used PI controller in parameter variations and load disturbances. Analysis of the circuit operation under Fuzzy controller is presented in detail. Simulation has been done in **MATLAB/Simulink** and results are presented demonstrating the feasibility of the proposed power conditioning system.

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CHAPTER I

1.Introduction

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1.1 Introduction

Superconductivity is a phenomenon of exactly zero resistance occurring in some materials when their temperature goes below a certain critical temperature. SMES (Superconducting Magnetic Energy Storage System) is a long superconducting coil that has the ability to store energy in the form of magnetic field generated by the direct current flowing in it up to indefinite instant. Applications of Superconducting Magnetic Energy Storage system (SMES) are being studied and presented in many papers in recent years. Some important applications include energy storage, system stability enhancement, diurnal load leveling and voltage stability (Transient and dynamic), static VAR compensation, current harmonics mitigation. The demand of electricity from consumers and industries is constantly changing from time to time. During peak load hour as the demand increases the voltage at the load end starts falling leading to voltage instability and collapse of total power system if load leveling is not done for the continuation of power supply. Load leveling plays an important role in case of industrial load where violation of maximum power demands and power factor causes penalty to the industry concern. Load leveling can be ensured by storing the excessive energy of source during low-load hours and delivering the stored energy back in peak load hour. To satisfy the above criteria, energy storage devices are usually required such as batteries or superconducting magnetic energy storage systems [1].

For the above applications the power conditioning system of SMES consists of a voltage source converter (VSC) and a DC/DC bidirectional converter. As SMES acts as a DC current source, choice of current source converter (CSC) is obvious. But due to large fluctuations in current and voltage across SMES coil a high power rated CSC is required which becomes impractical [2]. So, VSC is the alternative choice and it requires a DC/DC converter to connect the current controlled SMES to voltage controlled converter. Both the converters are decoupled by dc-link. The first converter VSC interfaces dc-link with the ac supply system. It is regulated to obtain a source current in phase with source voltage irrespective of the load conditions. DC/DC bidirectional converter is used to control charging and discharging of SMES coil. Making the dc-link voltage constant ensures direct exchange of power between grid and coil.

Due to inherent simplicity and benefits Hysteresis band controller is used to control both the two converters [5], [6]. In the voltage source converter it is used to control the source current, thus acting as a active power filter and in dc/dc converter it controls the charge-discharge cycle and the dc-link capacitor voltage. Hysteresis controller creates a band to bind the controlled variable within it. Switching pulses are generated when the controlled variable reaches the upper and lower bounds. A Fuzzy Logic Controller (FLC) is used to control the SMES coil energy that indirectly controls the charging and discharging of coil. Previously, PI controller was used to control the coil energy, but in this paper a nonlinear FLC is introduced whose performance is better than PI controller. The output of fuzzy logic controller is taken as the magnitude of reference source current. Magnitude of source current is varied during the whole day to control the charge-discharge cycle of SMES using FLC. Practically, the operation of a superconductor is in form of pulsed signals that leads to ac current losses in the coil. These losses should be taken into account during the design of the SMES refrigeration system [3].

1.2 Literature Review

Since last forty years research and investigations in the area of Superconducting Magnetic Energy System (SMES) has been emerged. In early 1970's vigorous investigations were started by the University of Wisconsin and by The Department of Energy at Los Alamos National Laboratory [11]. Again during 1980's a case study to analyze the technical and economic advantages of a SMES for practicality was started by the Electric Power Research Institute (EPRI). In 1983 the Department of Energy in association with the Bonneville Power Administration did experiment on a 30 MJ SMES unit on the Western US Power System to dampen power oscillations on the Pacific Intertie [12]. During that time the Department of Defense showed interest in SMES technology as a viable source of power in form of pulse to be supplied to the Ground Based Free Electron Laser (GBFEL) [13].

As a result of this, a program was sponsored by the Defense Nuclear Agency to design, invent and test a 22 MWhr - 400 MW SMES Engineering Test Model (ETM). The ETM has the following two objectives: (1) To assess the viability of using a SMES system to ensure load leveling and enhance system stability for remunerative and electrical usage. (2) To demonstrate the practicality of using the SMES system as a pulsed power source to power ground based defense systems [2]. In this project the SMES-ETM consists of two groups of two series connected superconducting coils each having rating of 50A 61.2H. The Power Conditioning System (PCS) consists of four modules each of 100 MW 24-pulse Voltage source converters (VSC), a two quadrant chopper and dc-link capacitor to connect the superconducting coil with the ac supply system. The 24-pulse VSC consists of four 3 phase 6-pulse 25 MW VSCs and the switching device is GTO anti-parallel with diode. To produce actual 24-pulse waveform four star-delta transformers with appropriate phase differences are connected in parallel. Here output real and reactive power is controlled to generate the pulse of GTO and SMES coil currents in the two groups are dynamically balanced by a differential real power command.

Initially to interface the SMES with the supply network current source converters (CSC) were used [59] – [60] as SMES is a current controller device. The charging and discharging of SMES can be controlled directly by regulating the switching pulses of CSC. In this topology SMES is connected to CSC on one side and the ac power network on the other side. As SMES is inherent current source the exchange of active and reactive power becomes fast and independent by using CSC.

In the year 1998, a power conditioning system that can be used for the mitigation of nonlinear and pulsating loads, was proposed [14]. In this thesis the VSC used is IGBT based and three PI controllers are used to regulate the SMES energy, dc-link capacitor voltage and the source current. The main objective was to make source current in phase with source voltage irrespective of nonlinear loads. The control loops were analyzed to determine the gains of the three controllers.

All the PCS developed till 2003 were controlling the SMES in voltage controlled mode. In this mode SMES is charged under constant voltage which takes more time. An improved controller is proposed and the main objective of the proposed improved controller is to rapidly charge the superconducting coil with charging under constant current to ensure that it can be used for the next discharging cycle in a minimum time [15]. The charging of SMES coil is done under constant current mode and discharging done in constant voltage mode to have an instantaneous response. To have this control the PCS is implemented with a bidirectional converter with a single pole double throw (SPDT) switch. The VSC used is IGBT based and control of source current is done using linear PI regulator.

For controlling the desired system parameters converters are required to be controlled nonlinear controller whenever there occurs a change in operating conditions. Previously, simple linear PI controllers were used to control the source current which does not give satisfactory performance during parameter variations. To have better performance nonlinear controllers are introduced such ac Fuzzy Logic controller, Neural Networks. Since several past years fuzzy control technique is adapted as the most accurate and viable area of investigation in the application of fuzzy set theory [16].

The pioneering research of Mamdani and his colleagues on fuzzy control [17]-[20], [21] was inspired by Zadeh's seminal papers on the linguistic approach and system analysis based on the theory of fuzzy sets [22], [23],[25], [26]. Fuzzy Logic controller does not need the exact mathematical modeling of the system and it is a trial and error procedure which can be developed from past experiences just like human thinking. At present there no methodology to design a fuzzy control system but C. C. Lee has summarized some fuzzy systems, which includes fuzzification and defuzzification methods, the derivation of the database and fuzzy control rules, the definition of a fuzzy implication and an analysis of fuzzy reasoning mechanisms in [27].

Except of load leveling and harmonics filtration SMES can be in other purposes which are describes in [31]-[55]. Some important applications of SMES are voltage stability, tie-line power control and load frequency control, synchronous resonance damping, spinning reserve, system stability, which is described in section 2.3.

1.3 Research Motivation

Except of superconducting magnetic energy storage system there are many techniques to store energy such as battery storage (BESS) and pumped hydro electric systems. But these systems suffers from drawbacks such as limitation in life span, injection of hazardous materials to the environment, constraints in ratings in case of BESS and limitation in environmental and geographical conditions along with requirement of large space for hydro electric plant [4]. In case of SMES once dc current flows in the coil it can store energy for indefinite periods and discharges it instantaneously as theoretically it has zero resistance, hence zero time delay. This property makes SMES to discharge practically in milliseconds. Load leveling is essential in modern power system to supply the increasing power requirements and to avoid the collapse of supply network.

Due to advancement of technologies, applications of non-linear load using static power converter has been increased causing injection of harmonics. Various active power filter topologies and control strategies have been developed [7]-[10], but shunt active power filters have been emerged as the most fruitful alternative to mitigate current harmonic. Series compensation is used to inject voltage at a specific angle with the supply voltage in case of sag and swell. On the other hand, shunt compensation is used to inject current to optimize source current for active power filtering. SMES has the property of controlling real and reactive power independently. So, the power conditioning system (PCS) of SMES can be controlled to eliminate current harmonics and to act as an active power filter as well as power conditioner which is connected in shunt with the supply network.

1.4 Objective

The main objectives of this work are

i. To perform load leveling using SMES. Energy is stored in off-peak hours and discharged in peak load hour to avoid instability of the system.

ii. In addition to give back-up supply SMES is regulated to obtain source current in phase with phase-to-neutral source voltage so as to act as a shunt active filter. The real and reactive power delivered to the load is controlled independently.

iii. The DC-link voltage is made constant to ensure direct exchange of energy between source and SMES.

iv. To control the charge-discharge cycle of SMES so that it can be charged up to the rated current. The SMES energy is controlled to achieve this.

1.5 Thesis Organization

The thesis organization is described below

CHAPTER-I contains the introduction to superconductivity and how it is utilized to satisfy the desired function in power system. The cause or motivation for which the research was done is also described. The techniques to solve the problem statement proposed in past years were studied and presented in literature review. Finally from research motivation and literature review, the objectives of the research work were decided which is shown in this chapter.

CHAPTER-II includes introduction to Superconducting Magnetic Energy Storage System (SMES), its applications in power system to enhance stability, increase damping and many others. Also the applications of superconducting materials in electrical machines, power cables, transformers etc are described in this chapter.

CHAPTER-III presents the principle of operation of SMES connected with grid in which energy balanced theorem is applied. Then the proposed topology for Power Conditioning System (PCS) is described after comparing all the possible topologies.

CHAPTER-IV describes the control strategy of SMES to control the source current, dc-link voltage and charge-discharge cycle of SMES. The construction and principle of operation of controllers used, which are Fuzzy Logic controller and Hysteresis band controller, are also included in this chapter.

CHAPTER-V is the final chapter in which results obtained by simulating the model is presented. Along with this all the results were compared and discussed. It also contains the conclusion and future scope of the proposed research work.

CHAPTER II

1.Superconducting Magnetic Energy Storage System (SMES)

2.Practical Utilities of SMES

3.Applications of SMES

2.1 Superconducting Magnetic Energy Storage System

An SMES is a device that mainly reserve energy in the form of magnetic field. The dc current flowing in a superconducting coil, which is wound around a long core magnet, creates the magnetic field. Here, as the stored energy is in form of circulating current, it can be consumed from an SMES unit with spontaneous response. Here, also energy can be reserved or supplied over short or long periods lasting from milliseconds to many hours. An SMES unit [fig 2.1] includes of a large superconducting coil, whose temperature is maintained below the cryogenic temperature by a cryostat or Dewar that contains either helium or nitrogen liquid as the coolant. During standby condition, to reduce the energy losses a bypass switch is used. It also has certain merits that include shorting dc coil current if existing tie line is lost, give protection to the coil if cooling is lost or disconnecting power converters from service [28]. Several factors are considered in the design of the coil to obtain the desired optimum possible performance of an SMES system at the economic cost [29]. Some important factors are coil fabrication, energy reserve capability, topology and operating temperature. A trade-off is made among each factor keeping eyes on the parameters of energy/mass ratio, Lorentz forces, stray magnetic losses, and minimizing the losses for an authentic, stable, and cost effective SMES system. The structure of SMES coil can be either as a solenoid or a toroid. Due to its simplicity and economy, the solenoid type [30] has been widely preferred. The rating of SMES unit is decided by its requirement needed. According to the rating or energy/power capacity of SMES, the coil inductance and current rating as well as the optimum voltage and current rating of PCS is determined. The operating temperature of a superconducting device is a trade-off among economic and the operational needs. Low-temperature superconductor (LTS) devices are generally utilized at present, while high-temperature superconductor (HTS) devices are needed to be developed with high efficiency and less cost.

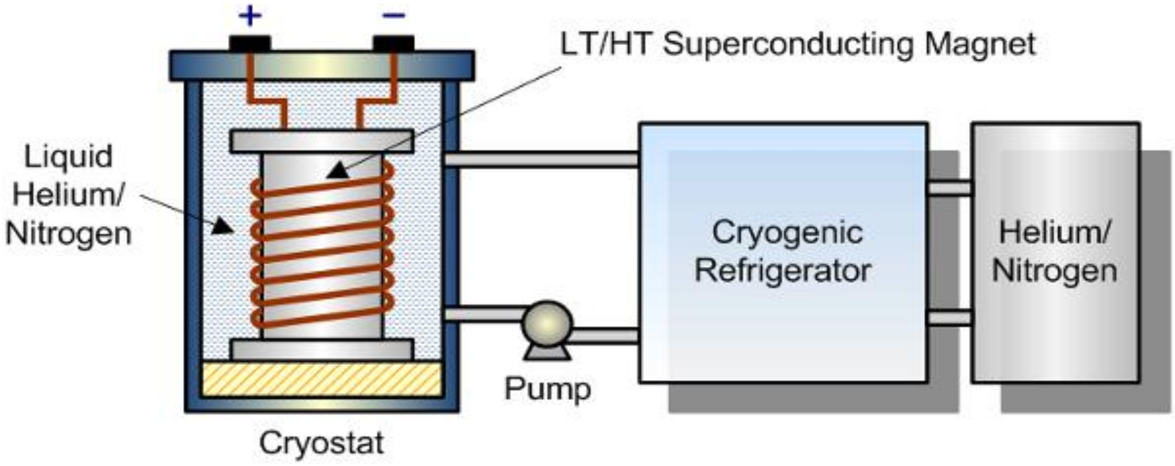

Figure 2.1: Basic Structure of SMES Unit

2.2 Practical usage of SMES:

1. Induction heating
2. Fault current Limiter
3. Superconducting power cables
4. Superconducting Power Transformer
5. Rotating electrical machines with superconducting windings
6. Cryo-machines and electrical machines with massive superconductors
7. Super conducting magnetic energy storage system (SMES)
8. Magneto hydrodynamic generators (MHD)
9. Electrodynamic Levitation (e.g., high speed trains)
10. Particle accelerator (detector magnets, beam guidance magnets)
11. Synchrotron radiation sources

2.3 Applications of SMES:

1. **Energy storage:**

   An SMES has the potential to become a reservoir of energy rated up to 5000 MWhr with an exceptional exchange efficiency (up to 95%) as well as an instantaneous response time for dynamic change of energy flow (milliseconds) [31]–[39]. For this prospective SMES is essential for large variations in energy demands between peak-load demand in day-hours and off-peak hours as well as huge quantity of stored/reserved energy for the alternative of major unit failure. This can be an alternative to the requirement of spinning reserve.

2. **Load following:**

   An SMES unit has an inherent quality to follow system load changes almost with no time delay which ensures the output power generated by conventional generating units to be constant. [31], [34].

3. **System stability:**

   Whenever there is a transient in power system, it results in low frequency power oscillations. SMES unit takes care of it and damp it out so that frequency can be stabilized. [31], [32], [40], [41], [54], [55].

4. **Minimization of ACE:**

   An SMES unit can be the key operator in an AGC control loop to reduce the area control error up to a minimum value (ACE) [31].

5. **Spinning reserve**

   “Spinning reserve” is the amount of generated power that is unused or stored in order to supplement during major energy loss or tripping of a large generating unit or major transmission line. An SMES unit has a tremendous amount of energy storage capacity when it is in the charging mode with its rated current. This lowers the costs for spinning reserve requirements over comparable values. [31], [32], [34].

6. **Reactive Power control and power factor Correction**

   An SMES unit can extend the stability limit and enhance the power carrying capacity of a transmission system by improving the power factor [31].

7. **Black start capability**

   An SMES unit can provide power to turn on a generating unit without taking power from the grid. This provides for grid restoration when area failures have occurred [31].

8. **Bulk energy management**

   An SMES unit has the ability to store large quantities of energy, and thus can act as a storage and transfer point for bulk quantities of energy based on the economics, potentially lowering the cost of electricity [31].

9. **Transient voltage dip improvement**

   Transient voltage sag occurring for many cycles can result when a large disturbance on the power system occurs. SMES and associated converter equipment has been demonstrated to be successful for providing voltage support which can result in increasing the limits of power transfer in the transmission system [35].

10. **Dynamic voltage stability**

    When the loading level of a transmission line goes beyond limit due to loss of generation and dynamic voltage support is not possible, it is called dynamic voltage instability. But, It has been shown that SMES is effective in mitigating dynamic voltage instability by supplying reactive power almost with no time delay supplanting loss of generation or a major transmission line [34], [35].

11. **Tie line control**

    Area control error is generated when the actual power for each control area deviates from the scheduled power due to ramp up of generation in one area and reduction in other areas. SMES can reduce this area control error by injecting controlled amount of virtual real and reactive power for satisfactory operation [35].

12. **Under frequency load shedding reduction**

    When the power system experiences the removal of a major resource such as a generating plant or major transmission lines the system frequency will drop down and continue to decline until the generating resource—load balance is maintained. Because SMES can supply real power rapidly into the system, it is an effective method to solve, or lessen, under frequency load shedding because it reduces the discrepancy between load and supply power of the system disturbance [35].

13. **Circuit breaker reclosing**

    During the reclosure of circuit breaker after the clearance of fault, the power angles on either side of circuit breaker needed to within certain limits. The protective relays will not allow operating the breaker if the above condition is not satisfied. By supplying certain amount of real power SMES can reduce the power angle across the breaker to make is short circuit so that continuity of power supply can be restored [35].

14. **Power quality improvement**

    SMES can provide tremendous potential and erase out disturbances on power systems rather it will negatively effects sensitive customer loads. In case of occasional disturbances such as transmission line flashovers or lightning strikes occur, power can be lost if the transmission line shuts down, or major voltage sag occurs. SMES has very fast response and can inject real power in less than one power cycle preventing important customers from losing power [35].

15. **Backup power supply**

    SMES can be beneficial for industries when there occurs a loss of important generating unit, by supplying tremendous amount of energy and acting as a reliable back-up. It is a cost-effective solution and recovers the industries in major disturbances. [34], [35].

16. **Sub synchronous resonance damping**

    Generators which are synchronized with transmission lines which have large amount of series compensation (series capacitors) can be injected to sub synchronous resonance (SSR) due to source inductances, which may end with a severe damage to the generator. SMES as an active device can be controlled to assure recovery from SSR and allow upper levels of series compensation to be implemented [35], [42], [43], [44], [45], and [47].

17. **Electromagnetic launcher**

    An electromagnetic launcher requiring higher rated pulsed power sources has been invented as a rail gun for military purposes. A rail gun can launch projectiles at velocities higher than 2000 m/s, overcoming the conventional constraints. Due to its high power density, SMES is a very comfortable energy storage device for an electromagnetic launcher [52].

18. **Wind generator stabilization**

    Wind generators have transient stability problems during network disturbances. An SMES unit based on a self-commutated inverter using IGBT or gate-turn Off (GTO) thyristor is capable of controlling both the active and reactive powers simultaneously. Therefore, it can act as a good tool to stabilize the wind generator system considerably [48], [50].

19. **Minimization of power and voltage fluctuations of wind generator**

    Due to irregular fluctuations of wind speed, output power and voltage of wind generator varies randomly. These variations pose serious problems on the system, for example, lamp flicker and inaccuracy in the timing devices. Since an SMES unit is capable of controlling both the active and reactive powers independently, it can act as a good tool to decrease voltage and power variations of the wind generator system within considerable limit [46], [49], [51], and [53].

CHAPTER III

1.Principle of Operation

2.System topology

3.1 Principle of Operation

The systems works on the principle of energy balance between sources, load and SMES coil [15]. The source current can be described as

$$I_s = I_l \pm I_i \tag{1}$$

Where I_s = Source Current

I_l = Load Current

I_i = Inverter Current

The output current of inverter is

$$I_i = f(I_o, D, M) \tag{2}$$

Where I_o = SMES coil current

D = Duty cycle of dc/dc converter

M = Modulation index of inverter

Under load leveling condition the source current charges the coil when load power is less then source power. When, there is an increase in load occurs source power increases with load to its maximum and coil discharges to make energy balance between source, load and SMES. In the whole operation dc link voltage is kept constant.

When the superconducting coil is in charging mode, the voltage across the capacitor will be decreased by

$$\mathrm{V_{dc}(t + \Delta t) = V_{dc}(t) - (\frac{I_o(t)}{C})\Delta t} \tag{3}$$

Where $V_{dc}$is the capacitor voltage (V), C is is the dc-link capacitance (F), and I_o is the current in the inductor that increases by an amount of

$$I_o(t + \Delta t) = I_o(t) + (\frac{V_{dc}(t)}{L})\Delta t \tag{4}$$

When the coil is in discharging mode, the voltage across the capacitor increased by

$$V_{dc}(t+\Delta t) = V_{dc}(t) + (\frac{I_o(t)}{C})\Delta t \tag{5}$$

And current in the inductor reduces up to

$$I_o(t+\Delta t) = I_o(t) - (\frac{V_{dc}(t)}{L})\Delta t \tag{6}$$

Similarly, in the inverter side, the function of the hysteresis controller to control the value of ac source current so as to modify the effective value of capacitor voltage in the following fashion. When current builds up, i.e., source current increases toward the upper-limit

$$I_s(t+\Delta t) = I_s(t) + (\frac{V_s - V_{dc}(t)}{L_s})\Delta t \tag{7}$$

The capacitor voltage will be build up as

$$V_{dc}(t+\Delta t) = V_{dc}(t) + (\frac{I_s(t)}{C})\Delta t \tag{8}$$

In the same manner, when the upper limit is reached, the current will now start to fall toward the lower limit; the value of the source current then becomes

$$I_s(t+\Delta t) = I_s(t) + (\frac{V_s - V_{dc}(t)}{L_s})\Delta t \tag{9}$$

And capacitor voltage will be reduced up to

$$V_{dc}(t+\Delta t) = V_{dc}(t) - (\frac{I_s(t)}{c})\Delta t \tag{10}$$

The exchange of power in load leveling condition is represented in [fig 3.1]. Under load leveling condition the source current charges the coil when load power is less then source power. When, there is an increase in load occurs source power increases with load to its maximum and coil discharges to make energy balance between source, load and SMES. In the whole operation dc link voltage is kept constant.

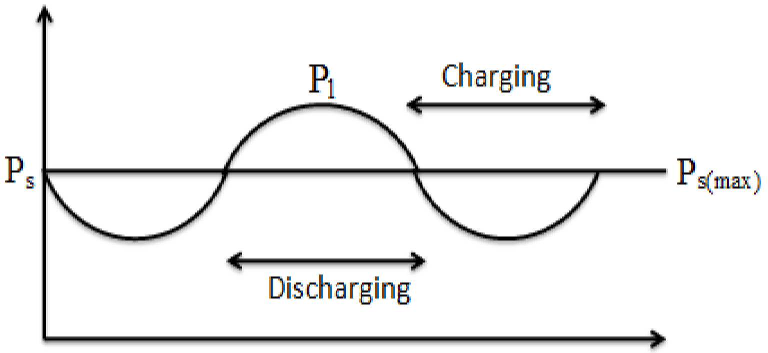

Figure 3.1: PCS operation under Load Leveling

3.2 System Topology:

The topology of the system which is being studied is presented in [fig 3.2.1]. It consists of a supply network with a source supplying a nonlinear load and SMES is synchronized with the network with the help of Power Conditioning system (PCS) at the PCC. According the configuration of PCS, SMES is broadly classified into two types viz: CSC based SMES and VSC based SMES.

3.2.1.1 VSC Based SMES

The structural figure of the SMES unit with VSC-based PCS [47], [56], [57] is shown in the [fig 3.2.1.1] that includes of a star-delta transformer, a basic six-pulse PWM converter with insulated gate bipolar transistor (IGBT) as the switching device, a two quadrant bidirectional dc-dc chopper using IGBT, and an inductor as the superconducting coil. The decoupling of ac/dc converter and the dc-dc bidirectional converter is obtained by a large dc link capacitor. A power electronic link between the ac supply network and the dc current controlled superconducting coil is established by the PWM VSC. The reference currents in d-axis and q-axis are determined by proportional integral (PI) controllers acting on the error between the actual and reference dc link voltage and the error between the actual and reference terminal voltage, respectively. Then the voltages in d-axis and q-axis are estimated by the error between estimated d-q axes currents and their actual detected values and transformed into abc-quantities to obtain the reference sinusoidal signal. The PWM signal is obtained for the switching of IGBT by comparing the reference signal obtained from abc conversion with the high frequency triangular carrier signal. Throughout the operation the dc voltage across the capacitor is kept at its reference value by the six-pulse PWM converter [48], [49], [50], and [55].

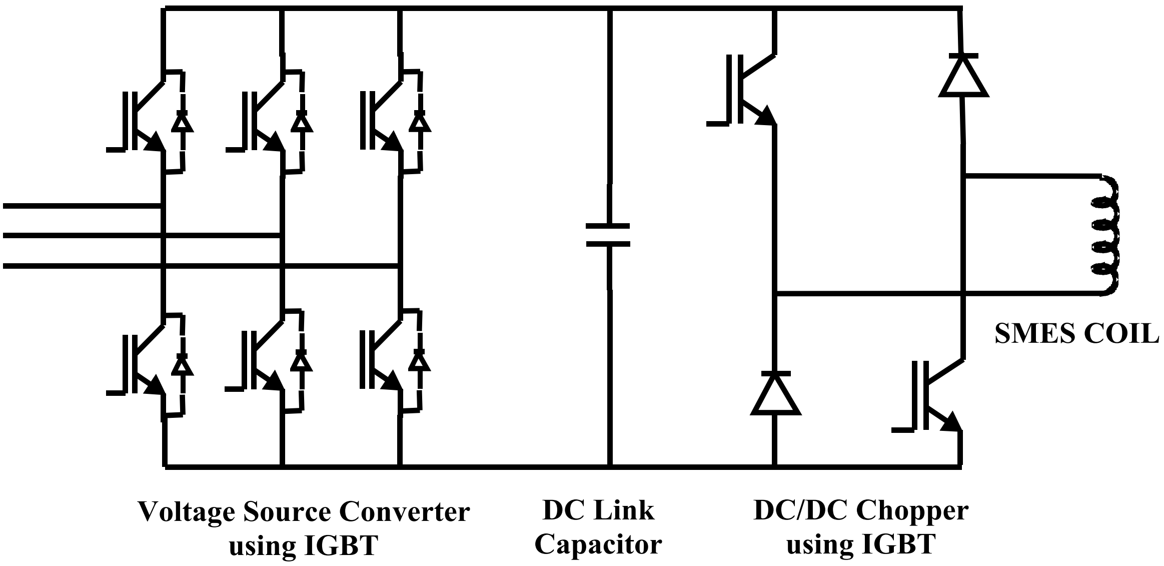

Figure 3.2.1.1: Power Conditioning System using Voltage Source Converter

A voltage bidirectional dc-dc chopper is used to regulate the charge-discharge of the superconducting coil. The dc-dc chopper is controlled to make the voltage across SMES coil such as positive (IGBTs are switched ON) or negative (IGBTs are switched OFF) and then the energy reserved in SMES can be supplied or consumed accordingly. Hence, the charging and discharging of superconducting coil depends on the average voltage per cycle across the coil that is calculated by the duty cycle of the two-quadrant chopper. In order to obtain the PWM gate pulses for the IGBTs of the dc/dc converter, the estimated signal is compared with the triangular/saw-toothed carrier signal [58].

3.2.1.2 CSC-Based SMES

The basic topology of the CSC-based SMES unit is shown in [fig: 3.2.1.2]. The ac side of CSC is interfaced to the supply power lines but dc side is directly connected with the superconducting coil. At CSC input terminal, a bank of capacitors are connected to mitigate the reserved energy in inductances of transmission lines by commutating the direction of the current flowing. Moreover, the capacitors can act as a buffer to eliminate the harmonics of high-order in the ac line current. An advantage of CSC is that by modulating the triggering pulses of the switching devices, suitable PWM currents in all the three phases can be generated which is directly controlled by dc current flowing in SMES. Practically the SMES system is an inherent current controlled system, which leads to very spontaneous exchange of both real and reactive powers among the CSC and supply grid [59].

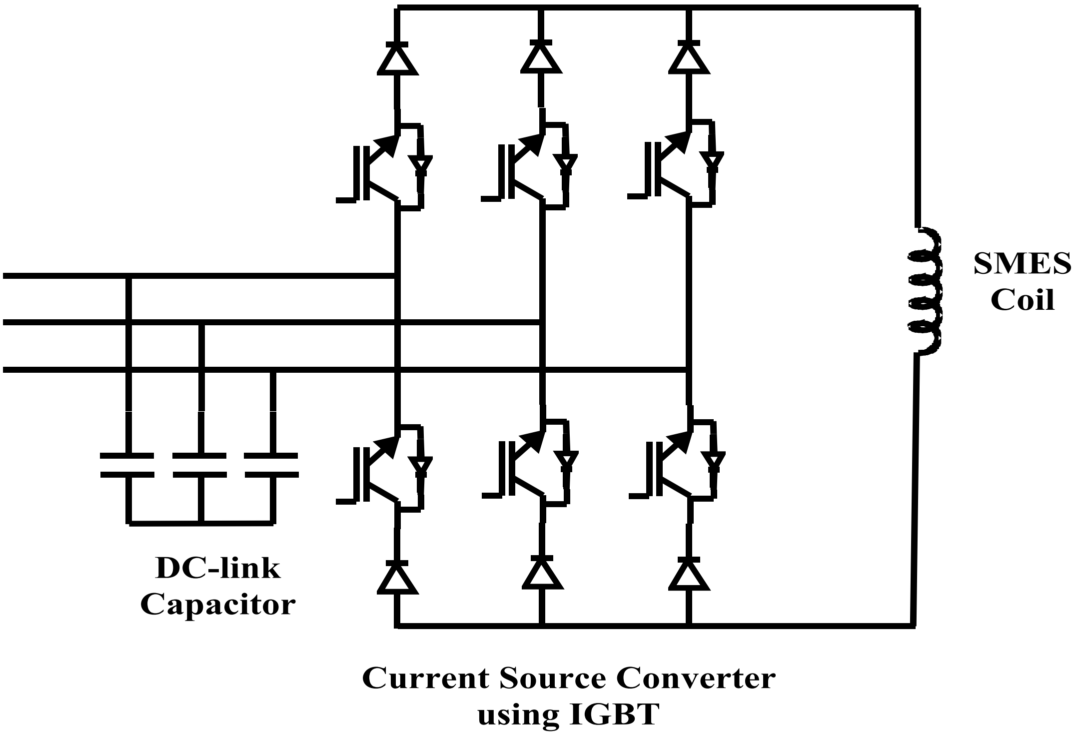

Figure 3.2.1.2: Power Conditioning System using Current Source Converter

In case of SMES using twelve-pulse CSC, to decrease the total harmonics distortion (THD) of the source currents, a more appropriate PWM switching scheme is adopted to minimize the 5th, 7th, 11th, and 13th harmonics. By varying the modulation index between 0.2 and 1, the 5th, 7th, 11th, and 13th harmonics can be eliminated [60]. In comparison to a six-pulse CSC, voltage ripples on the dc side in case of the twelve-pulse CSC is smaller, which means a further minimization of the ac losses in the SMES coil.

The comparison between VSC based SMES and CSC based SMES in various prospective is enlisted in the [table 3.2.1] given below.

Criteria	VSC based	CSC based
Real and Reactive Power	In this case, independent control of real and reactive power flowing between supply network and SMES is possible. It can also supply rated reactive power even at less or no coil current.	Here, control of real and reactive power flowing between supply network and SMES is independent. It can also supply high level of reactive power, but the reactive power is dependent on coil current.
Control structure	As the VSC based PCS consists of not only an AC/DC but also a DC/DC converter, the control is quite complicated than that of CSC based PCS.	CSC based PCS consists of only one AC/DC converter, hence easier to control. It has an additional advantage when used in high power circuit, of being paralleled in multiple stages.
THD	low	low
Coil voltage ripple	There appears ripple in coil voltage when used in VSC topology.	Ripple across coil voltage is low especially in twelve-pulse one. This implies a reduction in the superconducting coil ac losses.

Table 3.2.1: Comparison between VSC and CSC based Power Conditioning System

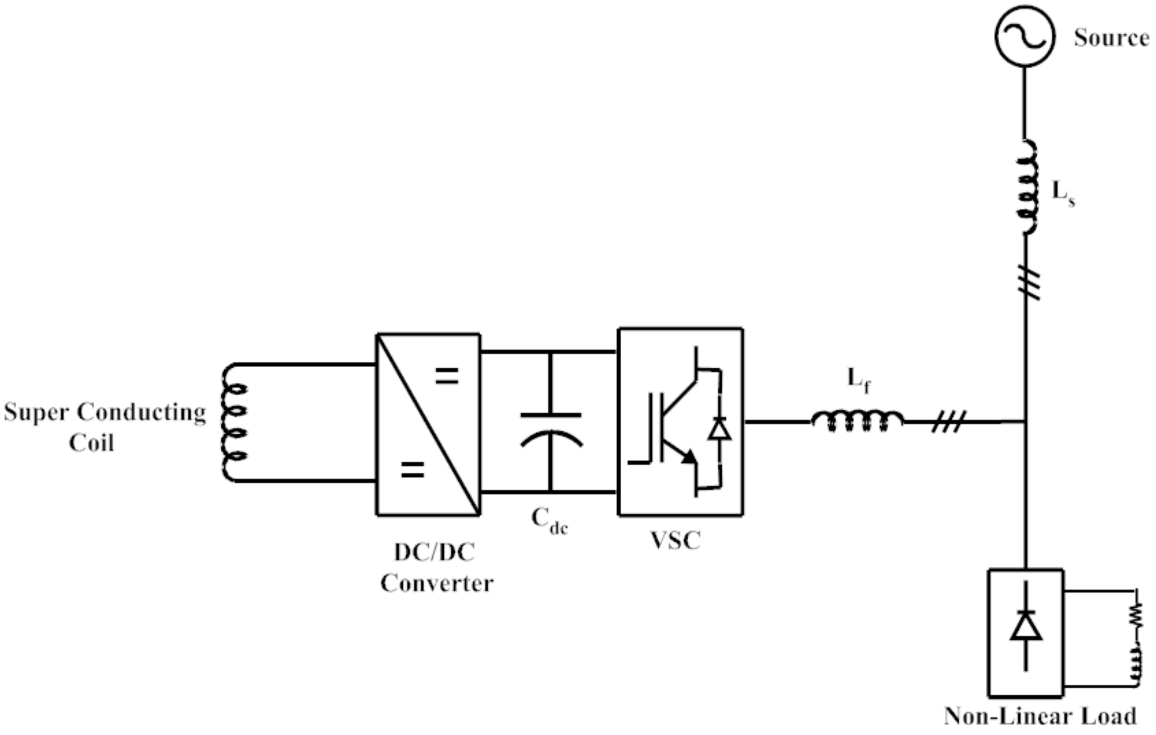

Figure 3.2.1: Proposed System Topology

Here, the PCS consists of a VSC and A DC/DC converter [fig 3.2.1] to control the source current as well as the charge-discharge cycle of SMES. DC/DC converter is a simple voltage bidirectional converter consists of IGBTs and diodes as shown in the [fig 3.2.2]. When the switches are ‘ON’ SMES coil gets charged and positive voltage is applied on it; when they are ‘OFF’ negative voltage is applied on it and it discharges through diode. In both modes current remains unidirectional. During standby condition one of the switches is ‘ON’ and current circulates between that switch and one diode. The switching of this is regulated to get a constant dc-link voltage. Here, VSC is a six-pulse conventional full bridge converter. IGBT anti-parallel with a diode is used as the switch to get bidirectional current. It is controlled to operate in both rectifying and inverting modes which is described later in this paper.

3.2.2 DC/DC Converter

The prime function of the DC-DC chopper is to control the energy flow through the SMES coil; that is the charge-discharge cycle of SMES. During the charging period of SMES, the chopper connects the DC link voltage to the SMES so that the current inside the SMES increases making power flow from the DC link towards the SMES coil. When the SMES needs to be discharged, the chopper connects the SMES with the DC link voltage but with opposite polarity, so that direction of power flow can be changed. The rate of charge/discharge is regulated by the magnitude and direction of voltage across the SMES coil. In other words, a variable voltage is applied across the SMES coil by the DC-DC chopper to make the desired energy flow in or out of the storage device. A detailed configuration of the two quadrant chopper is represented in [fig 3.2.2]. The different modes of operation of a chopper are described below.

As shown in [fig 3.2.2], when the two IGBTs are triggered simultaneously and the diodes become reverse-biased, current flows from source to SMES coil and a positive voltage is applied across it. So the coil gets charged. Again, when the two IGBTs are switched off and the diodes become forward biased, current flows in the same direction through SMES coil but a negative voltage is applied across it. Hence, the coil discharges. The applied voltage across the SMES coil is controlled by regulating the conduction time of the IGBT over the switching cycle. While the duty cycle is 0.5, average voltage across the SMES coil and average DC current in the VSC are both zero, and net power transferred throughout one complete switching cycle is zero. For a duty cycle larger than 0.5, the coil gets charged; while at less than 0.5, the coil gets discharged. Therefore, the control of charge/discharge is established by regulating the duty cycle of the switching devices.

The amount of switching and ripples can be reduced by some modifications in the operation of the chopper as follows. When the SMES is not connected to the grid and it stores energy for future references, either one of the IGBTs needs to be turned on to make a short current path with one of the diodes. When only IGBT1 is turned on, current flows through D1 and IGBT1 and voltage across SMES coil is zero (due to short circuit). During this interval, the dc-link capacitor and the SMES coil are disconnected by the IGBT2 and D2 and energy stored remains almost constant as power transfer between source and SMES coil is zero. When the SMES needs to be charged, both of the IGBTs need to be turned on. By doing this, the capacitor voltage is applied to the SMES coil and charges it. When the SMES needs to be discharged, both of the IGBTs need to be turned off. During this time, the current flows through the diodes, charging the capacitor.

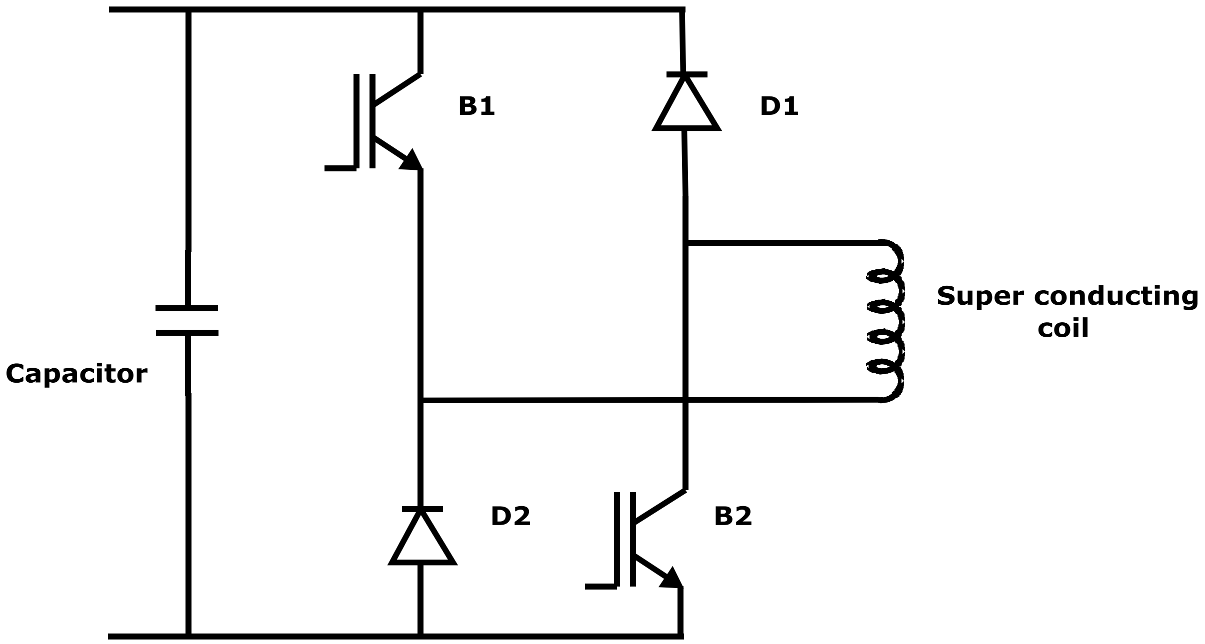

Figure 3.2.2: Two quadrant voltage bidirectional DC/DC converter

CHAPTER IV

1. Control Strategy
2. Hysteresis Controller
3. Fuzzy Logic Controller

4.1 Hysteresis Band Controller

Several linear as well as nonlinear control techniques are there to control the required physical quantity that is mostly the current. Different PWM techniques are mostly used where the reference is compared with a high frequency carrier wave. But Hysteresis controller has emerged as a robust nonlinear controller which is simple and can be easily implemented. Other advantages are

(i) Unconditional stability
(ii) Fast dynamic response
(iii) Good accuracy
(iv) Low cost

Despite of these advantages it suffers from several undesirable aspects. The prime factor is that it produces switching pulses of changing switching frequency. This creates major problems in designing the input filter and unwanted resonances in the input side and produces acoustic noise. Another unsatisfactory feature of the conventional hysteresis control is that its performance is adversely affected by the interference between phase currents, which is common in three-phase systems with isolated neutral [65]. Several advancements to the original control structure have been proposed for industrial applications [61]–[63]. Firstly, phase current decoupling techniques have been developed [61]. In second, fixed switching frequency has been obtained by a variable width of the hysteresis band as function of the instantaneous output voltage, dc-link capacitor voltage and coupling inductances [61], [64].

[Fig 4.1] shows the conventional sinusoidal hysteresis band current control technique used for the control of the source current**.** It consists of a hysteresis band around the reference source current. The reference source current is represented as $\mathbf{I_s^*}$ and actual source current is represented as $\mathbf{I_s}$. The hysteresis band current controller determines the pattern of switching signals of VSC in PCS [67]. The switching logic is formulated as follows:

When $i_s < (i_s^* - HB)$ upper switch is OFF and lower switch is ON for leg “a”: (SA=l).

When $i_s > (i_s^* + HB)$ upper switch is ON and lower switch is OFF for leg “a”: (SA=O).

Similarly, the switching functions for phases B and C are determined using respective reference and actual currents and hysteresis bandwidth (HB).

The switching frequency of the hysteresis band current control technique described above depends on how rapidly the current decays from the upper limit of the hysteresis band to the lower limit of the hysteresis band, or vice versa [66]. The rate of change of the actual source currents to be controlled determines the switching frequency, therefore the switching frequency does not settle at a fixed value in the overall switching operation, rather changes along with the current waveform. Furthermore, the value of line inductance of the power conditioning system and the dc link capacitor voltage are the main parameters determining the rate of change of source currents. Capacitor voltage and the line inductances of the whole configuration are also responsible for the switching frequency of the system.

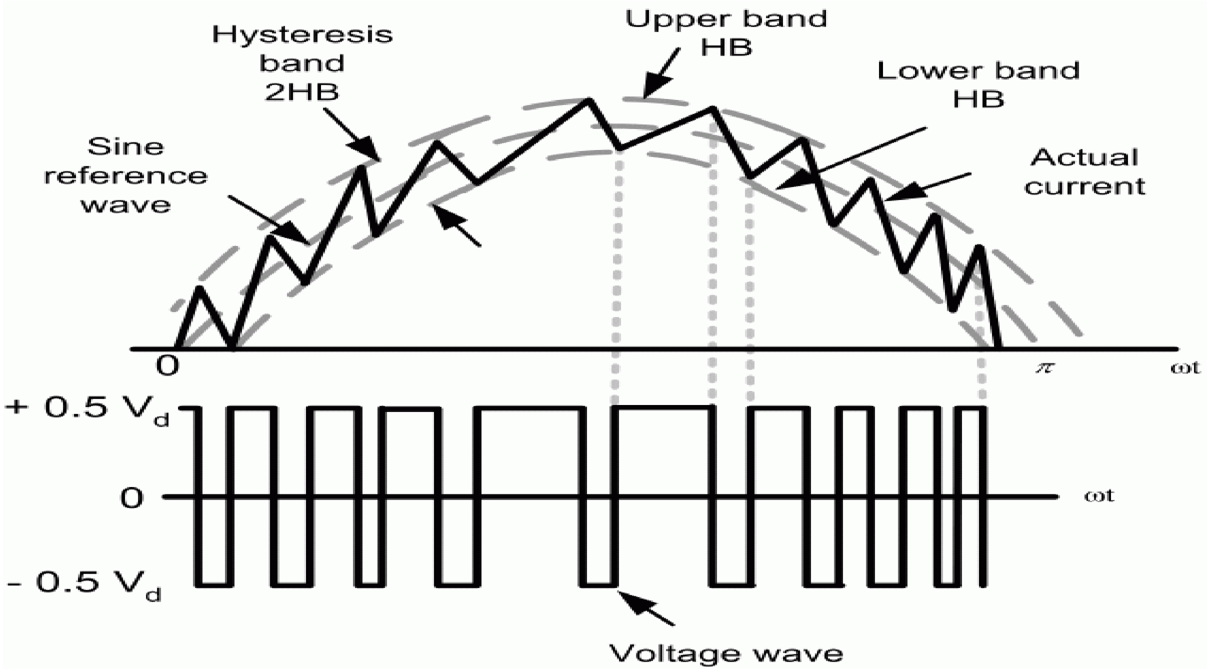

Figure 4.1: Operation of Hysteresis Band Controller

In this paper both the voltage source converter and DC/DC bidirectional converter are controlled by simple Hysteresis band controller. It is a nonlinear controller and can be easily implemented with good accuracy. [Fig: 4.1] shows the controller diagram of VSC which is intended to control the source current. The error between actual and reference source current is given as the input to hysteresis controller that generates switching pulses for VSC. Whenever the error reaches the upper bound of hysteresis band the upper switch becomes ‘OFF’ and when it touches lower bound lower switch becomes ‘ON’.

DC/DC bidirectional converter is a voltage bidirectional converter. The switching is controlled by hysteresis controller to regulate the dc link voltage. The error between reference and instantaneous dc link voltage is given as input to hysteresis controller to generate switching pulses of both the switch.

4.2 Fuzzy Logic Controller

Fuzzy logic controller is a set of linguistic control rules related by the dual concepts of fuzzy implication and the compositional rule of inference [27]. It is based on human thinking and decision making quality that uses natural language to define its rules. Actually, it provides an effective means of enrolling the approximate, inexact nature of the real world. It was first proposed by L. Zadeh, Professor at University of California in 1965 as away to process imprecise data. Zadeh thought process behind Fuzzy Logic was “Attempt to mimic human control logic”. He used fractions, partial membership instead of crisp set, Boolean, true/false. Then Mamdani and his colleagues got inspired by Zadeh’s seminar paper on linguistic approach and system analysis based on the theory of Fuzzy sets. Some basic designs of fuzzy sets and fuzzy operations are given below in [fig: 4.2.1].

Conventional linear controller linearizes the nonlinear system to an approximate model that does not guarantee satisfactory performance. Non-linear controllers are developed, but they require accurate mathematical modeling of the system which is a tedious and hard to obtain for a complex nonlinear system. Hence, fuzzy logic controller is preferred as it does not require accurate mathematical modeling of the system.

Fuzzy logic controller incorporates four basic things: a fuzzification interface, a knowledge base, decision making logic and a defuzzification interface [fig 4.2.1].

(i) Fuzzification Interface

It measures the input variables and conducts scale mapping to transfer the range of input variables into corresponding universe of discourse. After that mapping of numeric input variables is done to linguistic variables under different fuzzy so that they appears as different labels of fuzzy sets [fig 4.2.2].

(ii) Knowledge Base

It is composed of ‘data base’ and ‘rule base’ [table 4.2] that contains linguistic variables to define control policies and set of control rules. The control rules are completely based on the behavior of physical system and process to be controlled.

(iii) Decision Making Logic

It is the key member that performs fuzzy implication by inferring fuzzy control rules. It has the ability of simulating human decision making quality based on fuzzy concept.

(iv) Defuzzification

It performs a scale mapping which maps the fuzzy output variables to the corresponding universe of discourse.

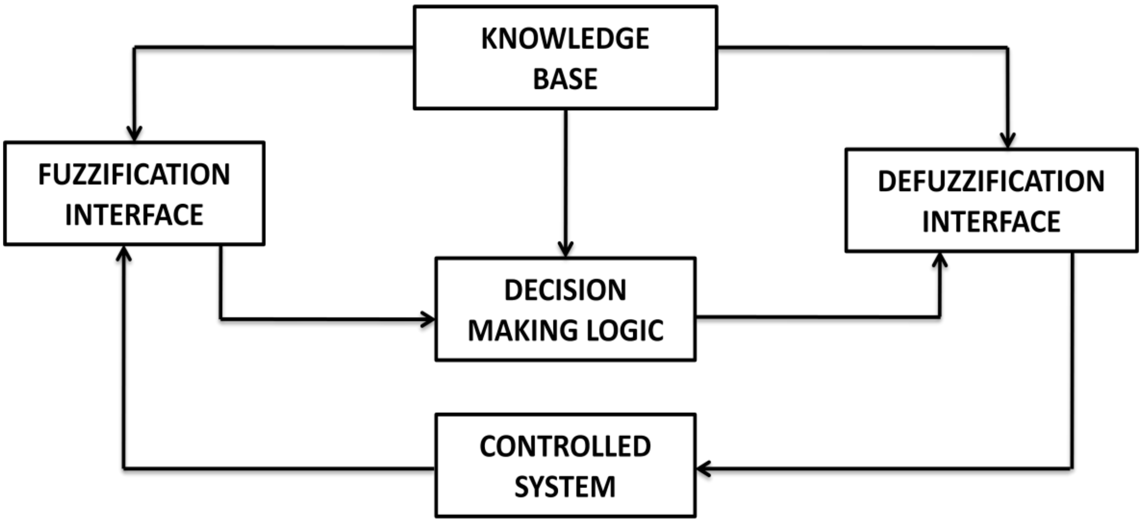

Figure 4.2.1: Block Diagram of Fuzzy Logic Controller

Here, a two input one output Fuzzy Logic controller with 49 rules is implemented. Error and change in error between the actual and reference SMES energy are taken as input and change in magnitude of reference current is taken as output. Seven fuzzy sets: Negative Large (NL), Negative medium (NM), Negative small (NS), zero (ZE), Positive small (PS), Positive medium (PM), Positive large (PL) are chosen to map each input variables. Triangular membership function is used for its simplicity. Fuzzification is done in continuous universe of discourse and defuzzification using ‘Centriod Method’. Mamdani’s ‘min’ operator is adopted for fuzzy implication.

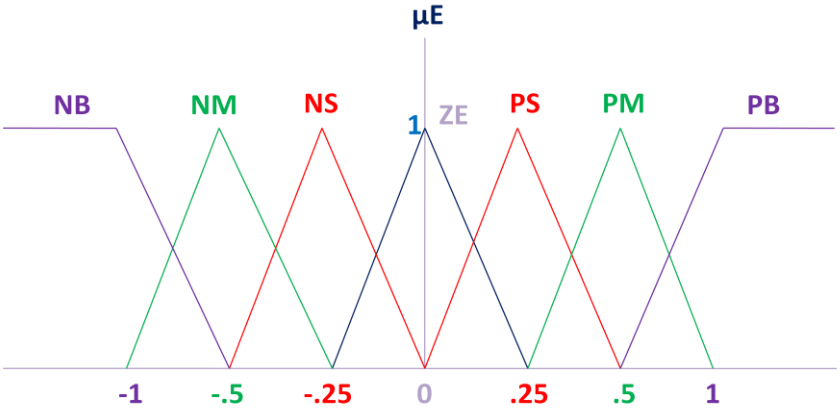

Figure 4.2.2 (a)

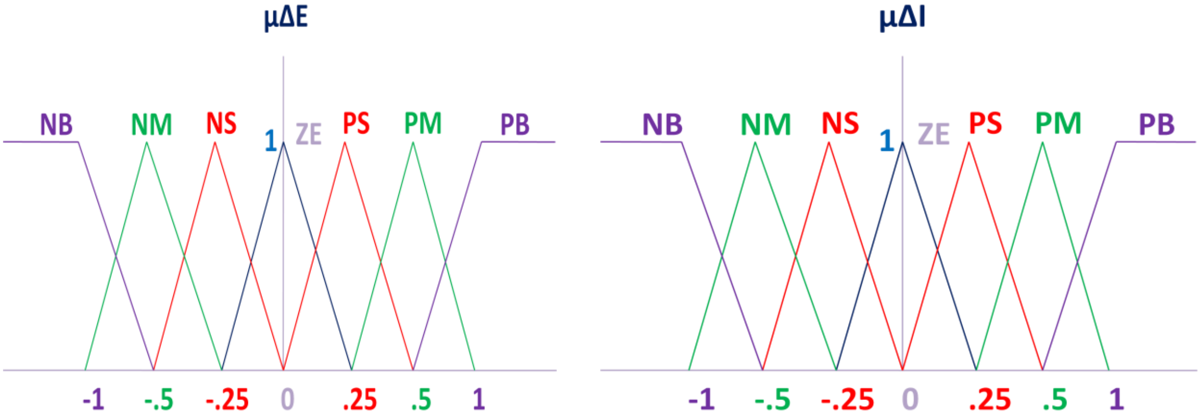

Figure 4.2.2 (b) Figure 4.2.2 (c)

Figure 4.2.2: Input Membership Function of (a) Error ‘E’ (b) change in error ‘ΔE’ (c) change in magnitude of source current ‘ΔI’ in Fuzzy Controller

The rule base is designed based on the theory that, in transient condition large errors need coarse control hence need coarse input variables; whereas in steady state small errors need fine control hence need fine input variables.

E ΔE	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

Table 4.2: Rule Base of Fuzzy Logic controller

4.3 Control Strategy

The SMES is controlled for load leveling and current-harmonics filtration operations. It is a constant dc current source that is controlled to meet the required demand of real and reactive power independently as well as simultaneously. The amount of energy received by SMES depends directly on the magnitude source current and energy delivered depends on load dynamics. When, source current increase current in SMES also increases and it gets charged; when source current decrease SMES current decrease and it discharges. As the source current is kept in phase with the line to neutral source voltage, the reactive power demand of the load is always supported by SMES. But the active power delivered by SMES depends on the capacity of source and load requirement. Under off-load period source supplies power to load as well as the SMES so that the coil gets charged. In peak-load hour source current increases with the increase in load up to its maximum value and the additional active power demand is supported by SMES as it discharges. After charging the current in the coil remains constant at its rated value, called standby period where no energy is consumed or delivered by the coil except the loss due to circulating current.

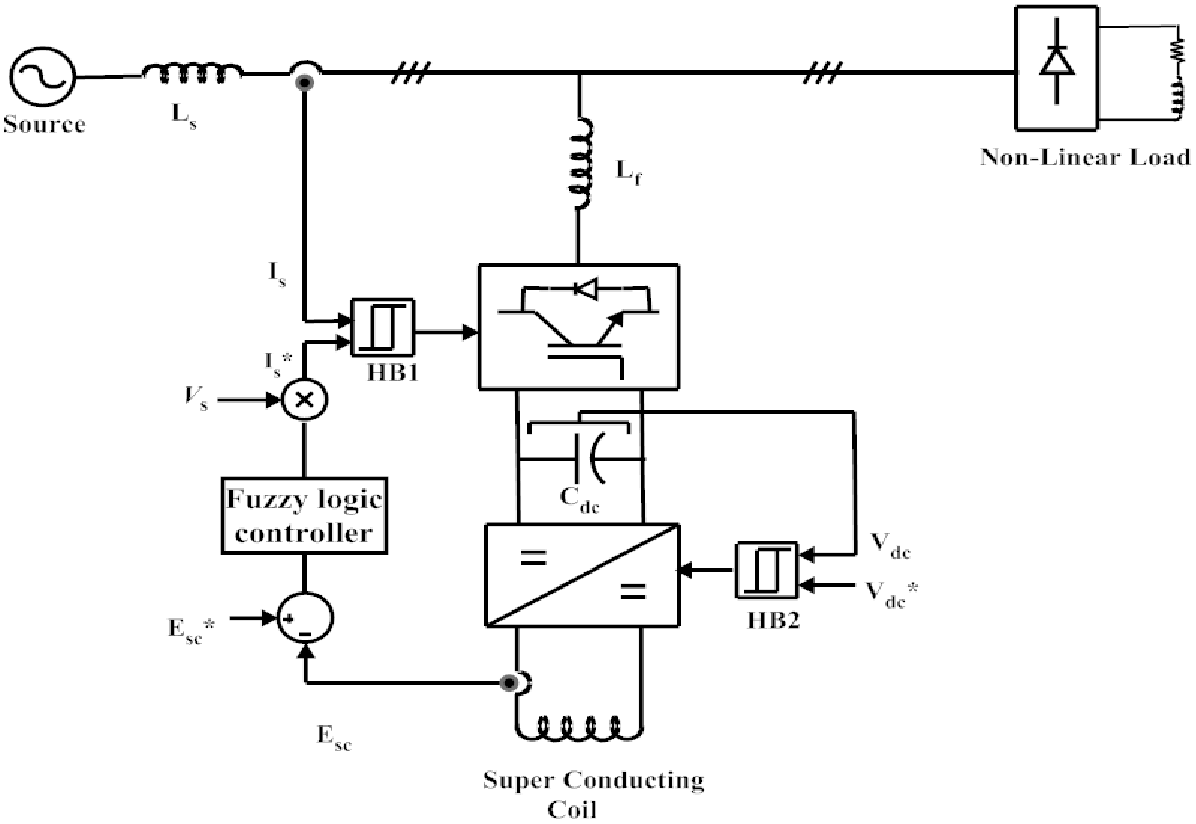

Figure 4.3.1: Proposed control strategy

To control the SMES energy during charging and discharging a Fuzzy Logic Controller is used. It maintains the SMES instantaneous energy at its reference value. Previously, PI controller was used for this purpose. But PI controller gives poor performance in systems having nonlinearity while tuning its gain parameters due to lack of proper understanding about the system parameters. Hence, fuzzy logic controller has been introduced in this thesis to get better performance. It has been proved that fuzzy Logic controller has fast response, small overshoot and better stability in comparison to PI controller. Also design of controller is less complex in FLC as it requires precise modeling rather exact mathematical modeling of the system. The error in actual and reference SMES energy is fed to FLC to get change in magnitude of reference source current as the output as represented in [fig 4.3.2].

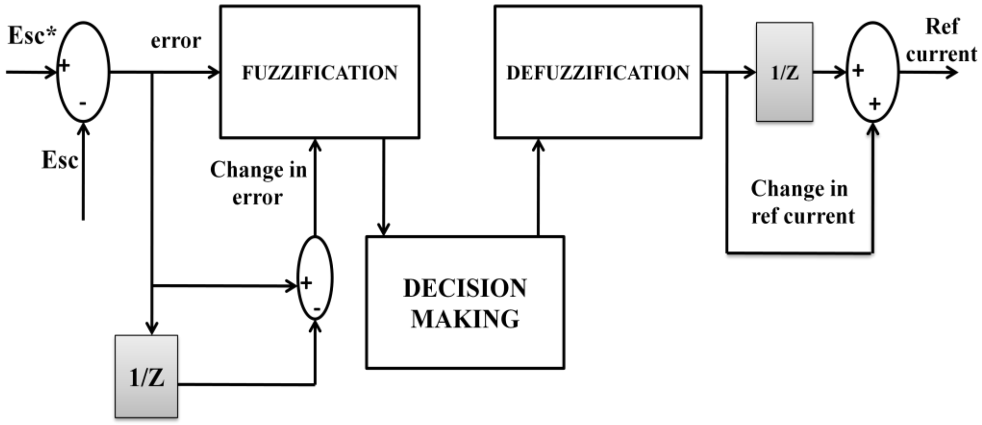

Figure 4.3.2: Proposed Fuzzy Controller

This magnitude of reference source current is then multiplied with the unit vector of line to neutral source voltage to get reference source current. Error in actual and reference source current is then compared and fed to hysteresis controller to obtain switching pulses for IGBTs of VSC [fig 4.3.3]. To make the dc-link voltage constant, instantaneous dc-link voltage is compared with reference dc-link voltage and fed to hysteresis band controller of a tolerance limit of 0.1%.

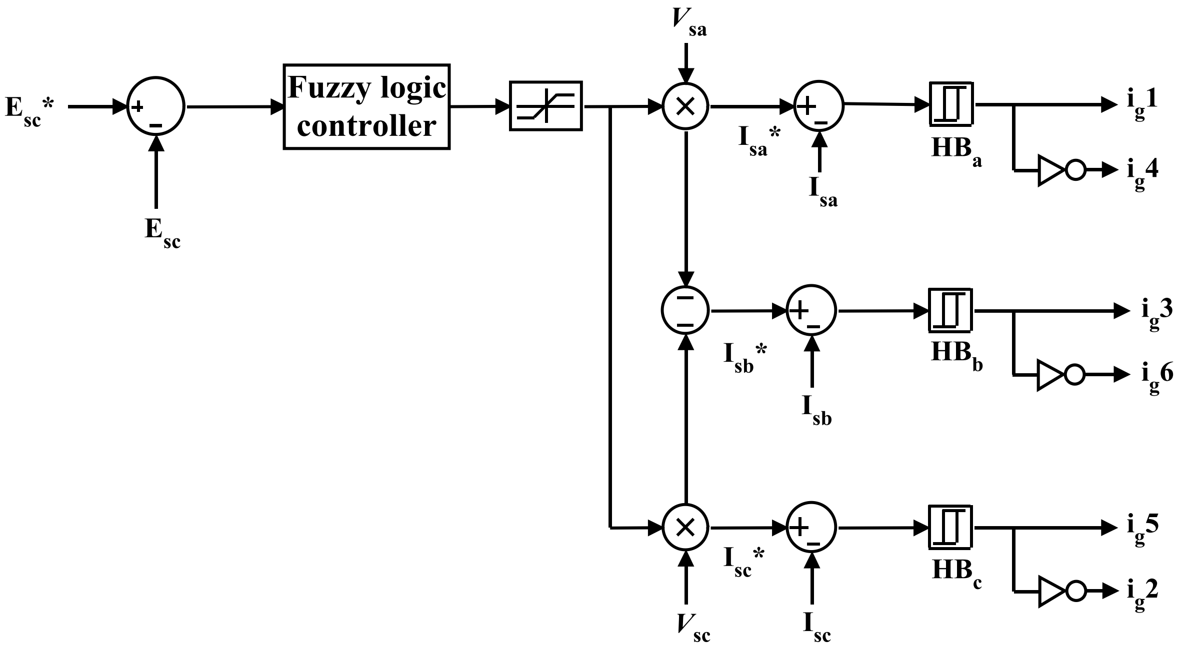

Figure 4.3.3: Switching pulses Generation for VSC

CHAPTER V

1.Simulation Results

2.Conclusion and Discussion

3.Future Scope

4.References

5.1 Simulation Results:

The proposed power system has been simulated using MATLAB/Simulink. Performance of the control system is presented for each mode of SMES. A three phase star connected source of 400V rms voltage is used to supply power to a nonlinear load that is a three phase six pulse diode rectifier. A 1H SMES coil rated with 100A, 5 KJ is connected with the supply network for energy storage. Initially the coil is charged when source current, whose maximum value is 50A, is more than load current, which is 20A. Hence, SMES is charged in voltage controlled mode. SMES gets fully charged in 0.32 sec and current in the coil becomes steady at 100A. At this instant source current decreases and becomes nearly equal to load current. At 0.6 sec load demand is increased up to 60A and SMES starts discharging. Source current also increases up to its maximum value that is 50A which is less than the load demand. So, the extra demand of the load is fulfilled by SMES. In all three modes source current is made in phase with line-neutral source voltage and SMES is performing as a shunt active power filter. Total Harmonics Distortions of source current in all modes are shown in the figures separately. The responses of SMES coil current and voltage, source voltage, source current, load current and dc-link voltage are shown below. Firstly, simulation is performed using PI controller to control the source current by controlling SMES energy. The desired responses are shown in [fig: 5.1.1-5.1.6].

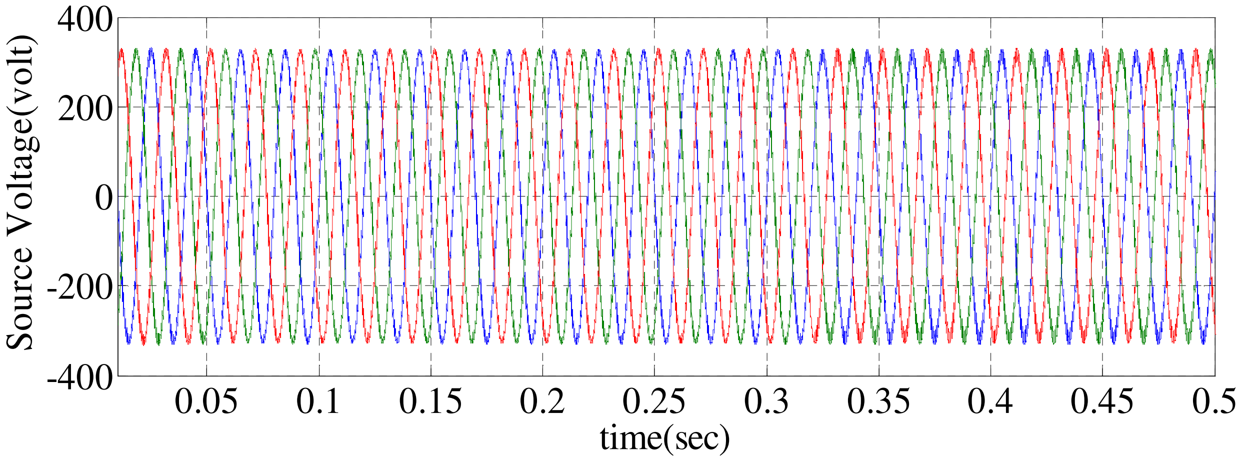

Figure 5.1.1: Variation of source voltage with time using PI controller

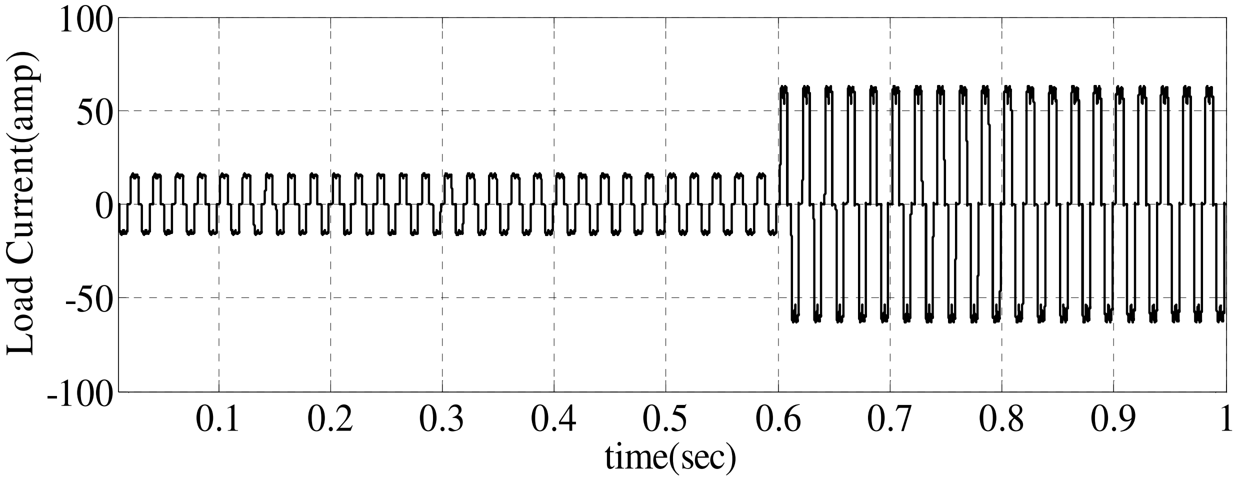

Figure 5.1.2: Variation of load current with time. At 0.6 sec there occurs a change in load which increases the load current

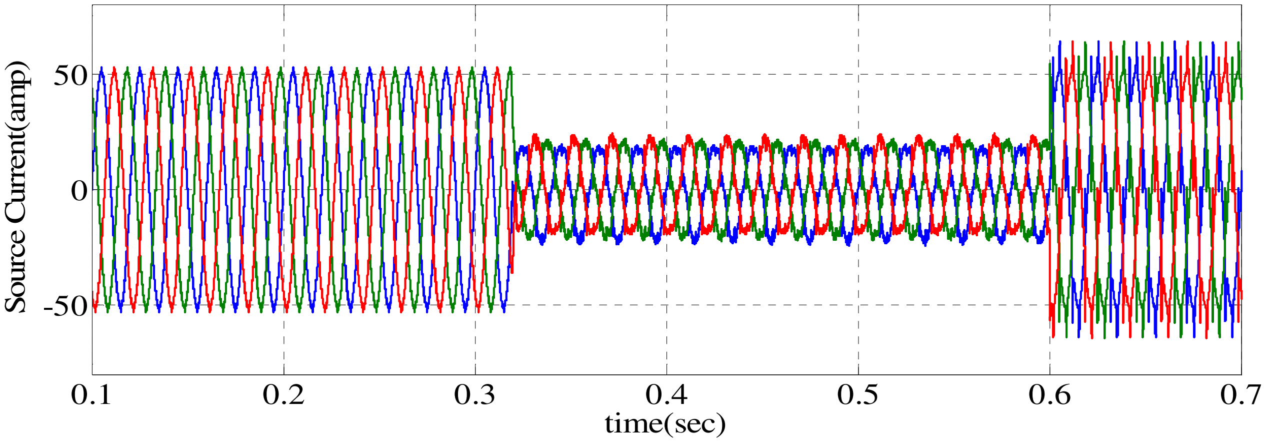

Figure 5.1.3: Variation of source currents in all the phases with time using PI controller. At 0.32 sec it decreases as the coil gets fully charged and at 0.6 sec it reaches its maximum when load demand increases

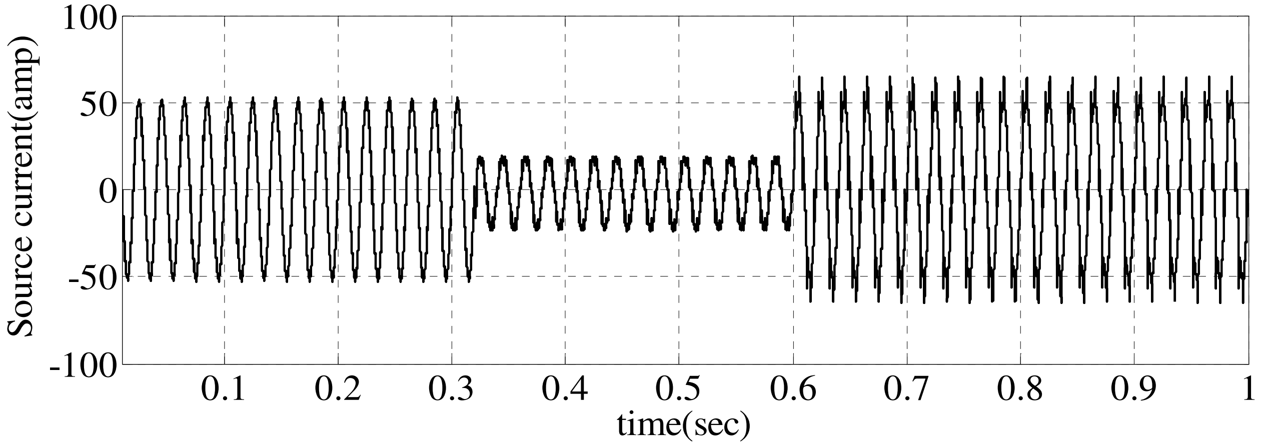

Figure 5.1.4: Variation of source current in one phase with time

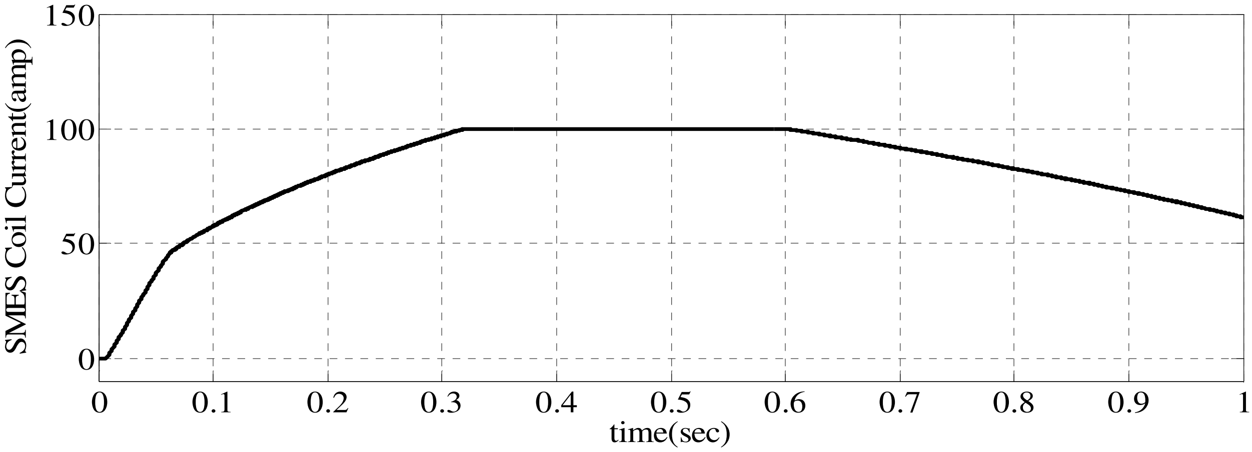

Figure 5.1.5: Variation of SMES coil current with time using PI controller. At 0.32 sec SMES coil gets fully charged with current 100A and it discharges at 0.6 sec when load current increases

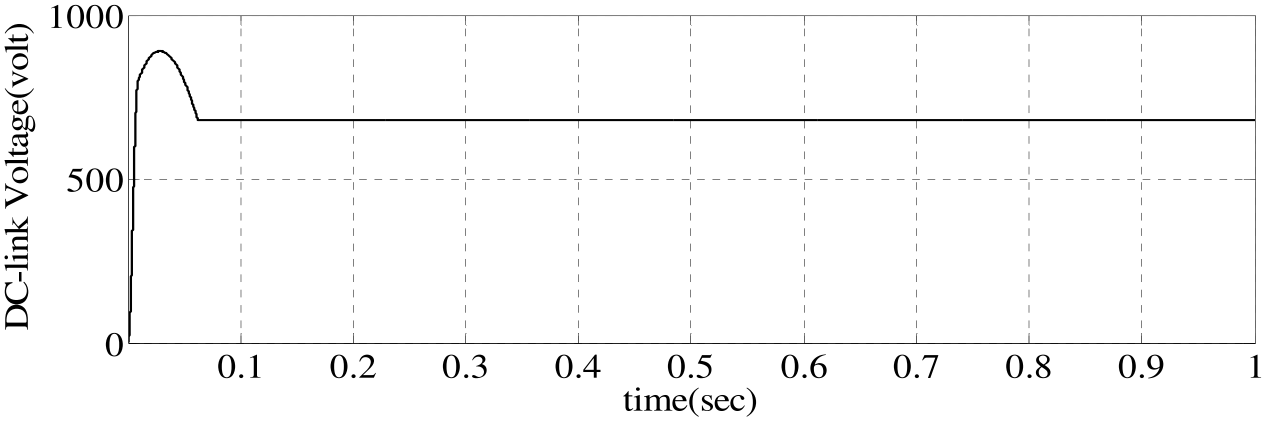

Figure 5.1.6: Variation of dc-link voltage with time using Hysteresis controller. It is maintained constant throughout the whole operation of SMES

The results obtained using PI controller is not fully satisfactory as the THD in source current is more than 5% in stand-by and discharging modes of operation. To reduce the THD less than 5% Fuzzy logic controller is used in place of PI controller. The results obtained using FLC are as follows in [fig: 5.1.7-5.1.12].

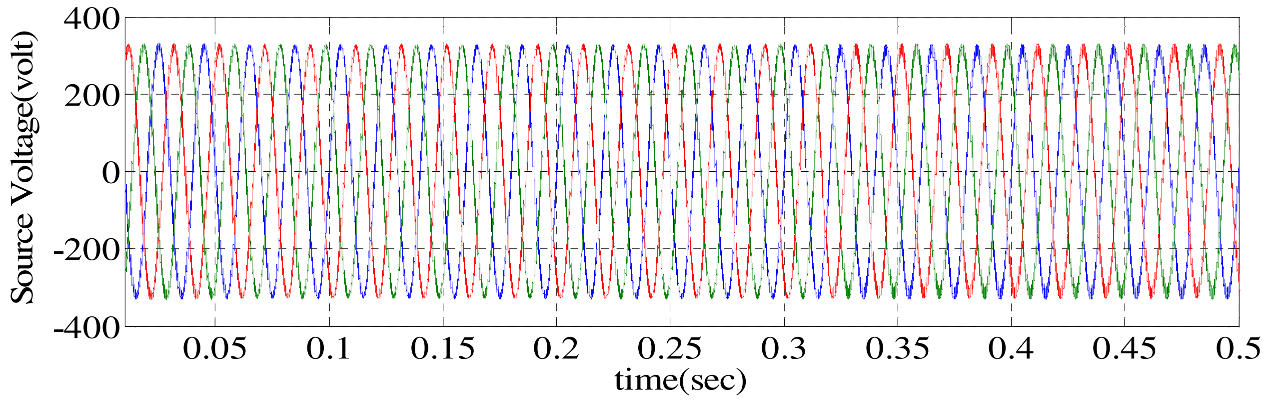

Figure 5.1.7: Variation of source voltage with time using Fuzzy logic controller

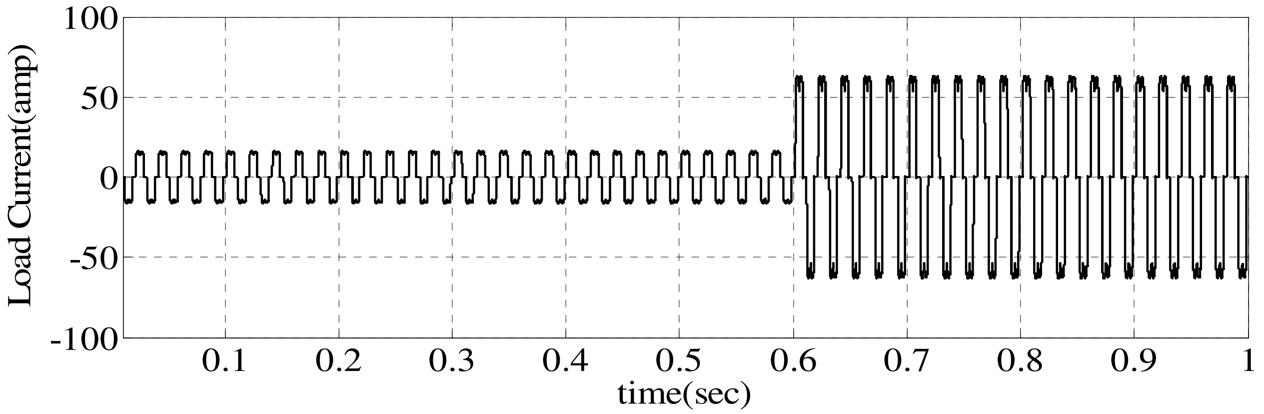

Figure 5.1.8: Variation of load current with time. At 0.6 sec there occurs a change in load which increases the load current

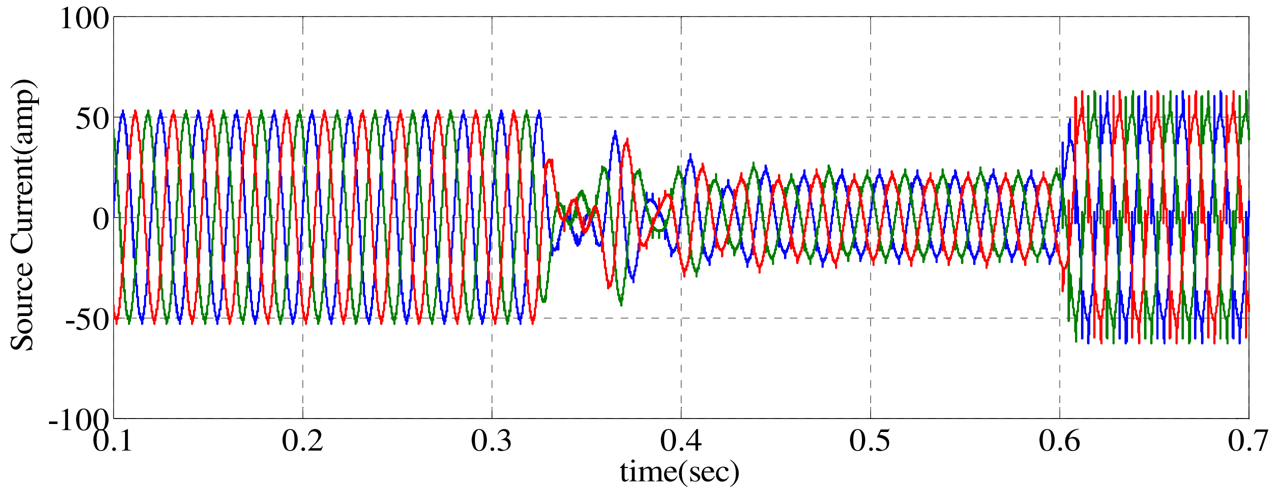

Figure 5.1.9: Variation of source currents in all the phases with time using Fuzzy controller. At 0.32 sec it decreases as the coil gets fully charged and at 0.6 sec it reaches its maximum when load demand increases.

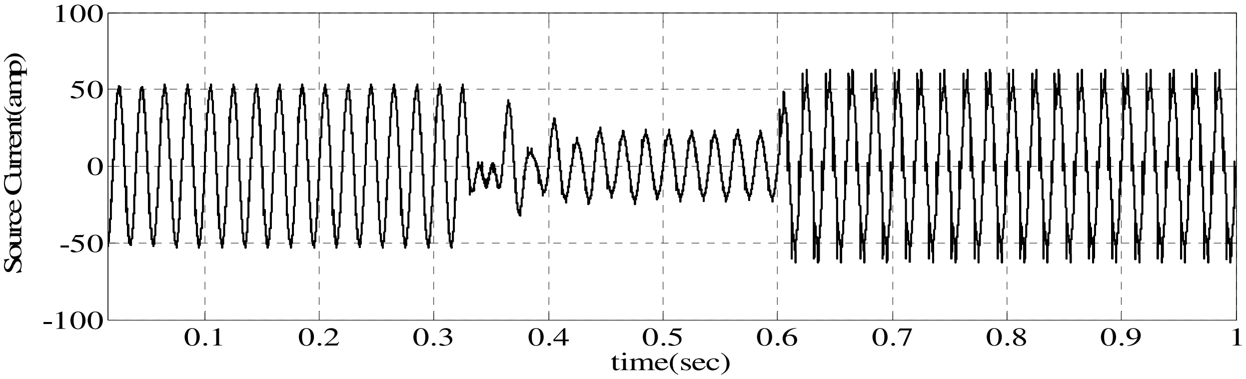

Figure 5.1.10: Variation of source current in one phase with time

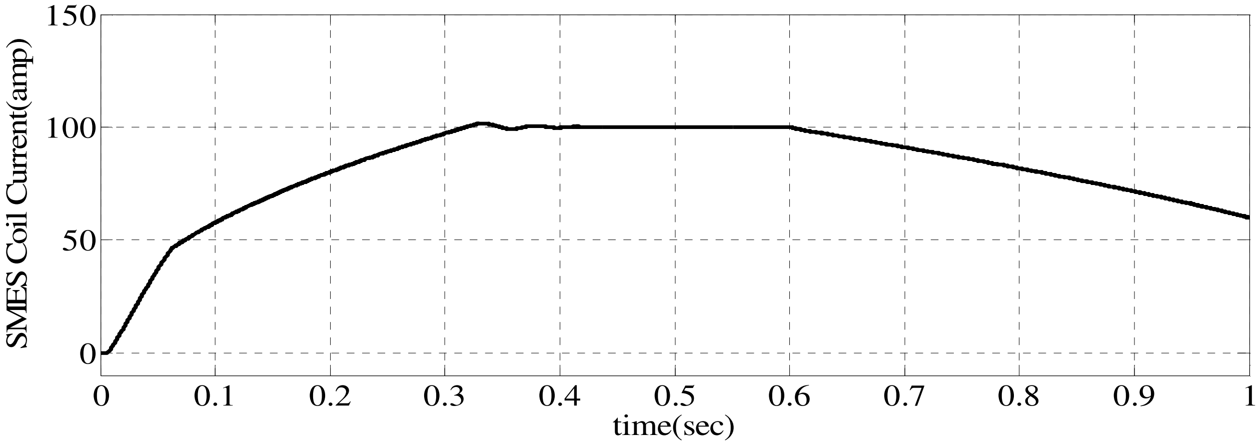

Figure 5.1.11: Variation of SMES coil current with time using fuzzy controller. At 0.32 sec SMES coil gets fully charged with current 100A and it discharges at 0.6 sec when load current increases.

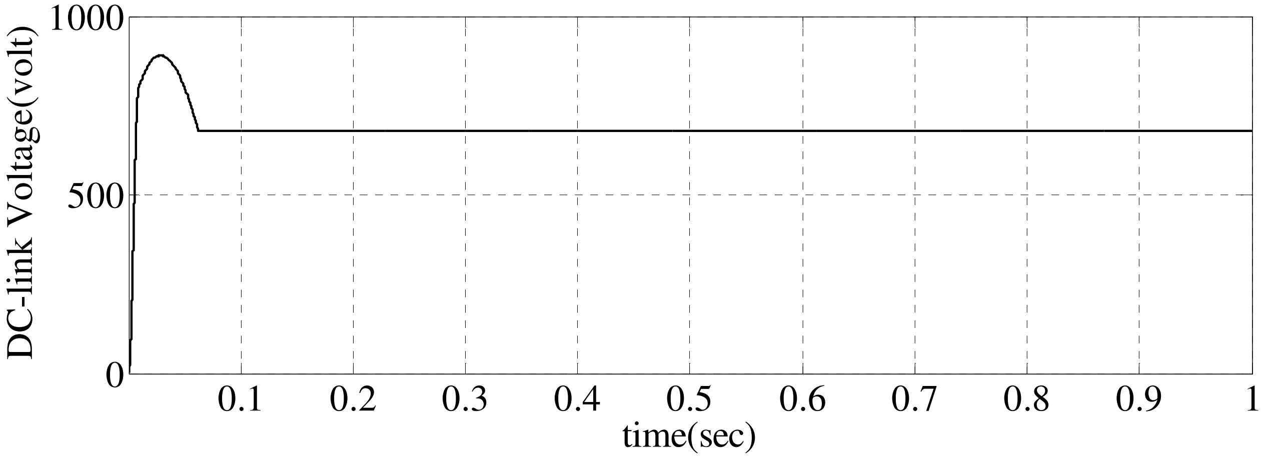

Figure 5.1.12: Variation of dc-link voltage with time using Hysteresis controller. It is maintained constant throughout the whole operation of SMES and same as obtained in PI controller.

The source currents in charging, stand-by and discharging mode of SMES obtained using PI and Fuzzy controller are analyzed and their THD were estimated. Below are the [fig: 5.1.13-5.1.18] and their THD counts.

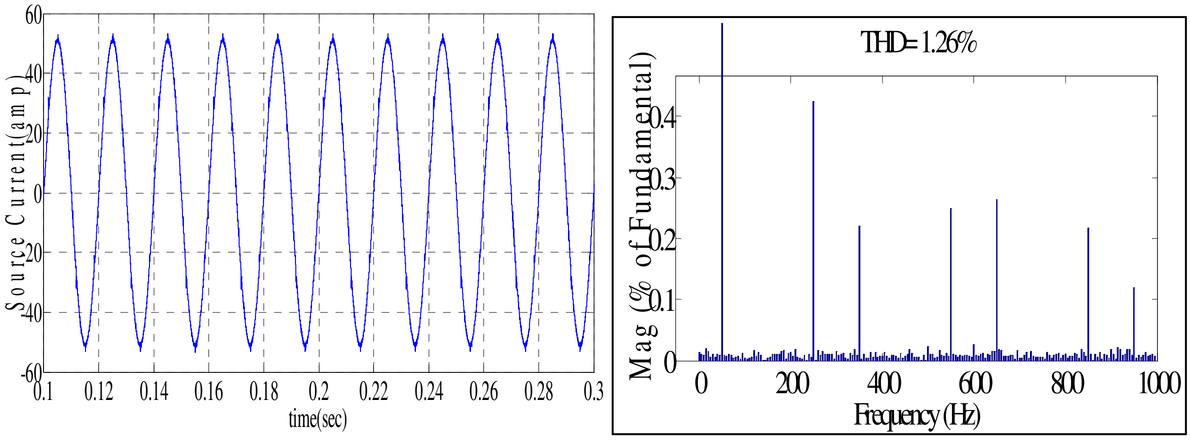

Figure 5.1.13: THD in source current in charging mode of SMES using PI controller

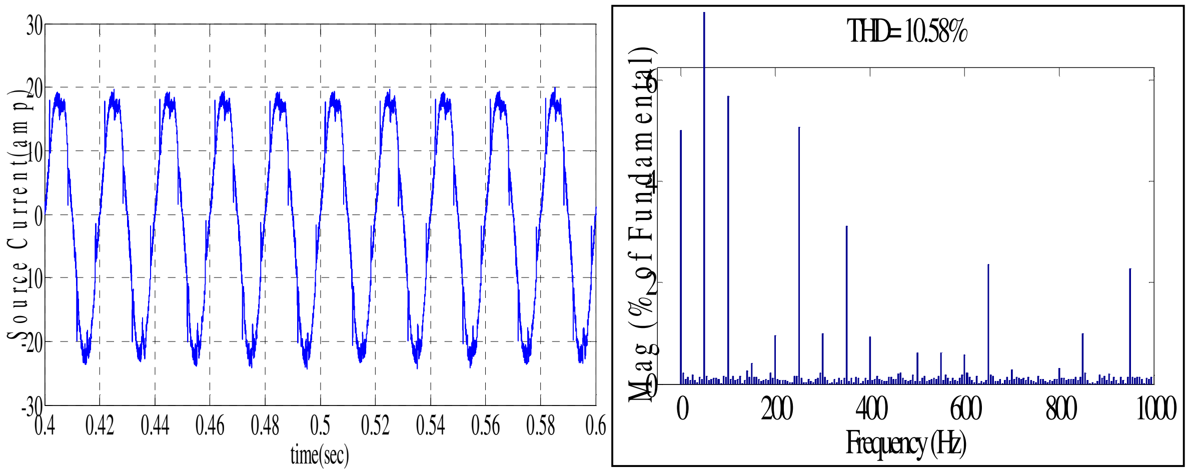

Figure 5.1.14: THD in source current in stand-by mode of SMES using PI controller

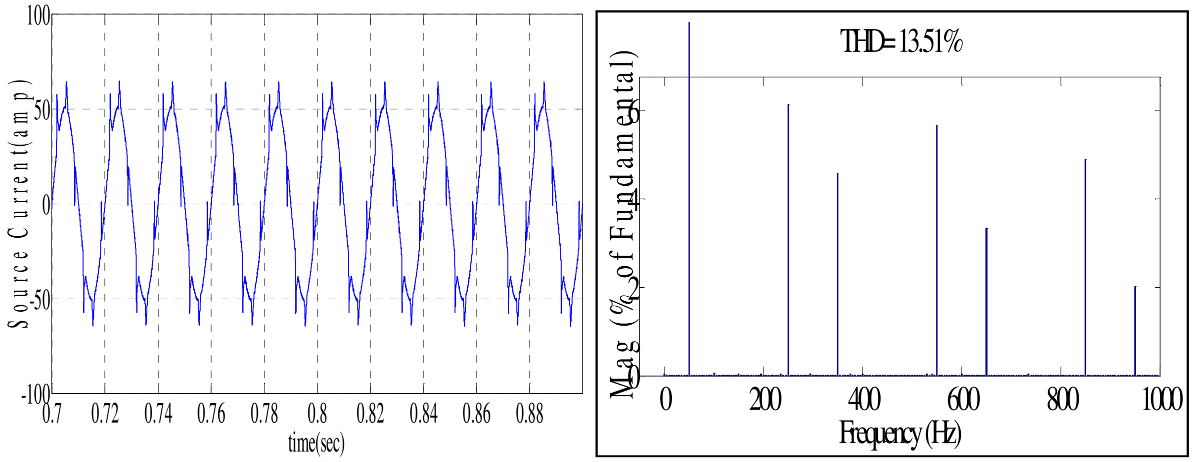

Figure 5.1.15: THD in source current in discharging mode of SMES using PI controller

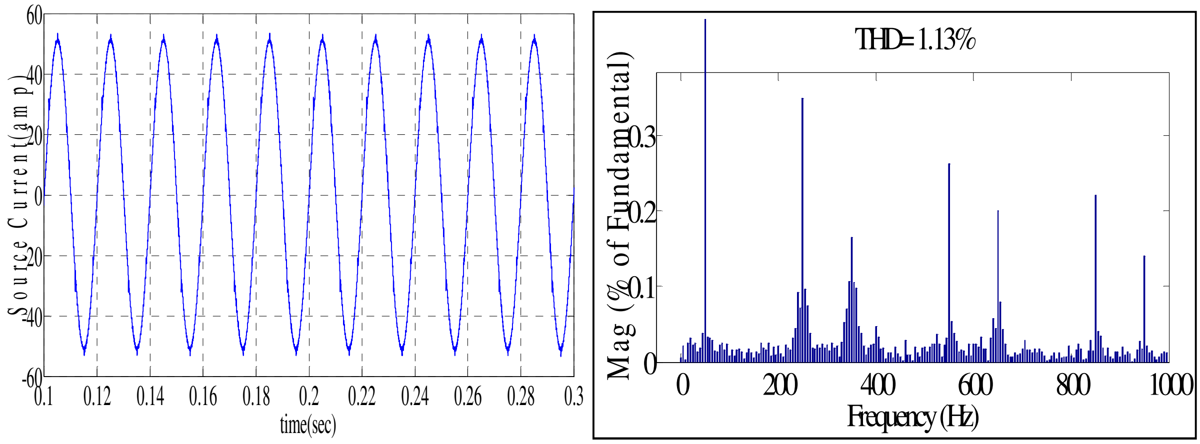

Figure 5.1.16: THD in source current in charging mode of SMES using Fuzzy controller

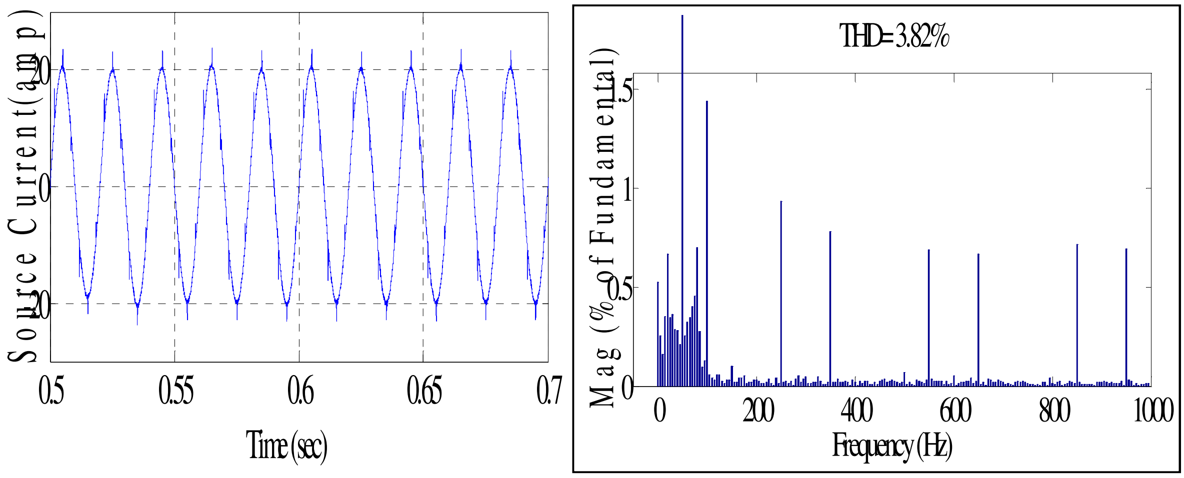

Figure 5.1.17: THD in source current in stand-by mode of SMES using Fuzzy controller

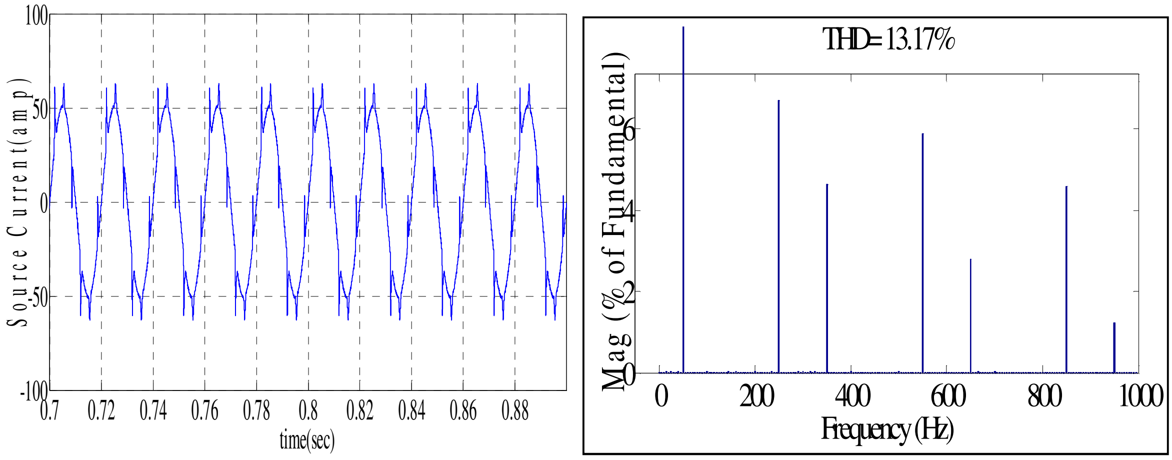

Figure 5.1.18: THD in source current in discharging mode of SMES using Fuzzy controller

The performance in terms of THD count of both PI and Fuzzy controllers are compared and enlisted in the following [table: 5.1].

MODE OF operation of SMES	THD obtained in source current using PI controller	THD obtained in source current using Fuzzy controller
Charging	1.26 %	1.13 %
Standby	10.58 %	3.82 %
Discharging	13.51 %	13.17 %

Table 5.1: Comparison of THD between PI and Fuzzy controller in different modes of operation of SMES

5.2 Conclusion and Discussion

In the above results and analysis it has shown that the complete cycle of SMES that is charging, stand by and discharging can be controlled along with the sinusoidal nature of source current irrespective of load conditions by using both PI and Fuzzy logic controller. Then the results were compared from which it can be shown that the THD obtained in case of Fuzzy controller is less. In case of charging mode of SMES using both PI and Fuzzy controllers THD are below IEEE standard, which is 5%. But during standby mode THD using PI controller is much more than Fuzzy controller and THD in Fuzzy controller is within 5%. It is because of steady state error in SMES energy response introduced by PI controller. The response of SMES energy in PI controller settles quickly, within one cycle and hence the source current changes its magnitude from 50A to 20A, without any undershoot. The dynamic response of PI controller is better but due to steady state error its THD count is more. In case of Fuzzy controller, response of SMES energy takes 2-3 cycles to settles at its reference value. Therefore source current changes its magnitude from 50A to 20A after completion of charging cycle after undergoing overshoot and undershoot but the %age of overshoot and undershoot are within 5% (IEEE standard). During discharging operation of SMES, THD in source current is nearly same in both the controllers which is more than 5% and highly undesirable.

The discussion above finally concludes that, overall performance of Fuzzy Logic controller is satisfactory and better than that of PI controller. Though the harmonics elimination operation of SMES using Fuzzy controller is unsatisfactory in discharging mode, but load leveling, the primary function of SMES is obtained quite satisfactorily.

5.3 Future Scope

The THD in discharging mode can be lowered by a better design of fuzzy controller using optimization techniques to make an adaptive Fuzzy system. The range of membership function of input variables in Fuzzy controller can also be optimized to get more accuracy. Due to Hysteresis controller the switching frequency of IGBT is not constant and varies at each instant. This problem can be avoided by the use of Adaptive hysteresis controller in which the switching frequency is kept constant and the hysteresis band is varied accordingly. Further improvements can be done by increasing the level of DC/DC converter and controlling its switching using PWM controller so that harmonics can be minimized.

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