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Simulation and DC Analysis of SMES System using IGBT for a High Power DC Application

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Abstract - *Energy storage systems offer possible solutions for improving efficiency and power quality. It can also increase the reliability of power grid with significant penetrations of renewable energy. Significant developments and research works have recently been made in high power storage technologies such as superconducting magnetic energy storage (SMES), super-capacitors and flywheels. This article explains the design of a SMES for power compensation with very fast response time This devices have a very fast response time and are appropriate for applications with rapid charge and discharge requirements..In order to increase energy dumping speed, IGBT (insulated gate bipolar transistor) is used. Also the IGBT have advantage of handling high power. This paper provides an overview and preliminary study of the design of superconducting magnetic energy storage (SMES) systems using IGBT.*

Key Words: IGBT, Controller, Power Conditioning System (PCS), Cryostat, electromagnetic Energy, Simulation.

1. INTRODUCTION

Despite improvements in power generation and distribution systems, rapid growth in loads and the sensitivity of many power system devices have led to major stability problems. Disturbances and short outages in generators or transmission lines create various adverse effects.

Over recent decades, energy storage technologies have improved and provided significant economic and environmental benefits. The superconducting energy storage system (SMES), as an electrical storage technology, is applied in many electrical and electronic power applications for improving the stability and performance of power systems[8][9].

The SMES system consists of a large superconducting storage coil, cryogenic unit (referred as the cooling system) and an AC-DC power converter, which is shown in Figure 1. The superconducting coil is maintained at cryogenic temperature. This temperature is maintained by a cryostat which contains liquid containers of helium or nitrogen. An energy conversion / conditioning system connects the SMES to an AC power system and is used to charge / unload the coil.

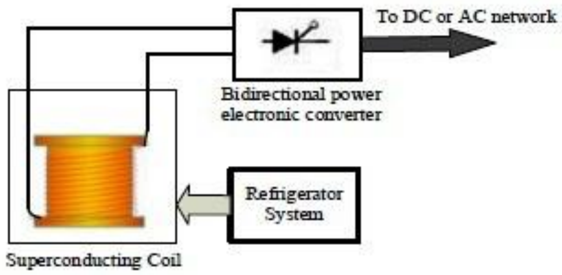

Fig -1: Block Diagram of SMES

This superconductive energy storage is one of the most effective methods to supply energy to the load. SMES can store excessive energy as electromagnetic energy in low-temperature superconducting inductors and release stored energy if necessary. SMES can store energy in the form of magnetic field, by the current passage through it. The possible applications of SMES are dynamic stability, transient stability, load balancing, voltage stability, frequency regulation, transfer capacity enhancement, uninterruptible power supplies, quality improvement Power supply, automatic control of production, etc.

2. Principle of Operation

The basic principle of operation for SMES is the storage of energy in a short-circuited superconducting magnet with zero resistance. The current in the superconducting magnet is in the form of DC, which generates the magnetic field in the coil and stores energy in magnetic form. Therefore, the superconducting magnet is the central part of a SMES system. The basic arrangement of the SMES system is shown in Figure 2.

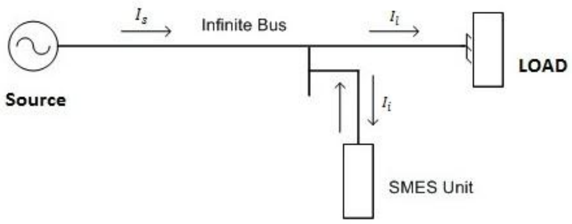

Fig -2: Basic structure of SMES connected System

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

In the load upgrade condition, the source current charges the coil when the load power is less than the source power. When there is an increase in the load, the power of the source increases with the load at its maximum and the discharges of the coil to establish an energy balance between the source, the load, and the SMES. During the entire operation, the voltage of the intermediate circuit is kept constant. In this SMES system, the energy is stored in the magnetic field generated by the direct current flowing through the superconducting coil. [3][4] The energy stored by induction (E in Joule) and the nominal power (P in Watt) are the specifications for SME devices.

Depending on the operation of the SMES system, there are three modes of operation, i.e.,

i) Charging Mode,
ii) Freewheeling Mode,
iii) Discharging Mode

Modes of operation depend on the load condition, source conditions as well as SMES system condition.

In normal operating condition, the load is directly connected to the bus. When the SMES system is connected to the bus, the SMES coil starts the charging process and is continuously monitored and controlled by the control unit. After charging to the respective set point, the SMES coil is disconnected. Therefore, there is no resistance in the superconducting coil, so there is no discharge of energy and current flows for infinitely long time. If there is any fault in the load side, or the source is partially or completely disconnected from the system, the SMES energy starts discharging the load. The discharge of the coil is controlled by the control unit. The time for the discharge depends on the load. The entire process is continuously monitored by the monitoring and control unit, which also controls the connection and disconnection of SMES for stable operation. The circuit consists of a IGBT with the advantage of a good switching response.

The energy and power of the SMES coil can be expressed as - [3][5]

Energy ,E= 1/2 LI^2 , and

Power, P = dE/dt = LI dI/dt = VI

Where "L" is the inductance of the superconducting coil, "I" is the DC current flowing in the coil and V is the voltage across the coil. Energy is stored as a circulating current that flows through the superconducting coil for an infinite time because there is no resistance in it. The energy stored in the superconducting coil is the function of the DC current flowing in the coil. The discharge time depends on the charging current. Energy can be drawn from a SMES unit with an almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours. Here in this paper IGBT is used because it has high switching frequency.

3. Mathematical Analysis

The basic MES circuit is shown in Figure 3.

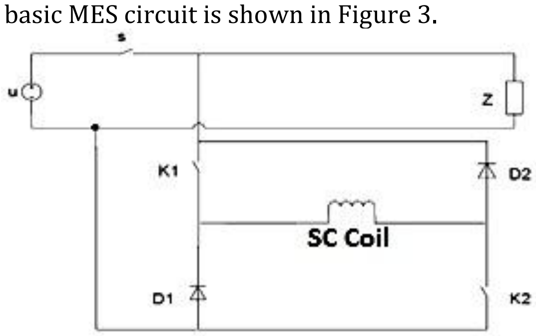

Fig -3: Circuit Diagram of SMES

Above figure shown is the basic circuit of SMES connected system. Here in above circuit superconducting coil have internal resistance, Re= 0Ω.

3.1 Energy storage mode

In the energy-charging state switch - S close, close K1, K2 also,

The charging current I(t) at any time can be expressed by

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

When the coil in superconducting from, the internal resistance of the coil is very low or nearly zero. i.e., Re=0Ω, then the equation of the coil is given as –

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

here, I_o is the initial current.

3.2 Freewheeling Mode

In the energy Freewheeling state switches - S close, K1 open and close K2;

The storage current at any time can be expressed by

$$I(t) = I_0 \exp\left(-\frac{R_e t}{L}\right) \quad ....4$$

For SMES coil, Re is zero. Hence the current can flow in the coil for infinite time without decay

3.3 Energy Discharging Mode

It contains two different modes
(A) Uncontrolled Discharging
(B) Controlled Discharging

(A) Uncontrolled Discharging:

If the inductor is loaded, the source and load of the circuit will be isolated and the inductor at an uncontrolled pitch will begin to discharge, all switches remain in this unresolved state.
After applying the KVL, the voltage equation of the uncontrolled discharge will be

$$L\frac{dI(t)}{dt} - I(t)R_e - I(t)Z = 0 \quad .....5$$

(B) Controlled discharge:

The controlled discharge mode is a complex operation state formed by energy-storing state and uncontrolled discharging state. The required discharge power P_1 (t) = V_1 (t) × I_1 (t), the controlled discharge circuit operates in the uncontrolled discharge state, while the potential drop across the load V_R (t) or the current through the load I_R (t) , lower than V_1 (t) or I_1 (t), and operated in the energy-storing state, while V_R (t) or I_R (t)is higher than V_1 (t) or I_1 (t).
Initial current is I_o. The granting of the rule of conservation of energy, For Superconducting Inductor (Re=0), I (t) can be expressed as-

$$I(t) = \sqrt{I_0^2 - \frac{2}{L}\int_0^t P_1(t)dt} \quad ....6$$

An energy can be taken from an SMES unit with energy stored or delivered over periods, ranging from a fraction of a second to several hours depends upon the load current and load parameter.

4. Simulation and Results

Based on the developed SMES mathematical model in figure3., Simulation of SMES system is done in MATLAB which include the energy charging, storing and discharging of the SMES system. Here in this paper the switching device is IGBT which have advantage of very high switching frequency.

In Simulation, a DC source is taken instead of HVDC line and it is assumed that DC source is like DC bus bar having properties of HVDC transmission. Load is taken on ohm(Ω) because in DC system the load is resistive in nature. SMES coil can charge and the energy stored by the SMES coil is the function of current, I. So, in this paper current of SMES coil is limited to 100A. Pulse generator is connected to the IGBT for switching operation as per condition. Because of Improved durability to overloads, IGBT is more efficient and accurate devise for high power operation of SMES System

The Simulation diagram for the proposed SMES system using IGBT as switch is discussed here in the Figure. 4

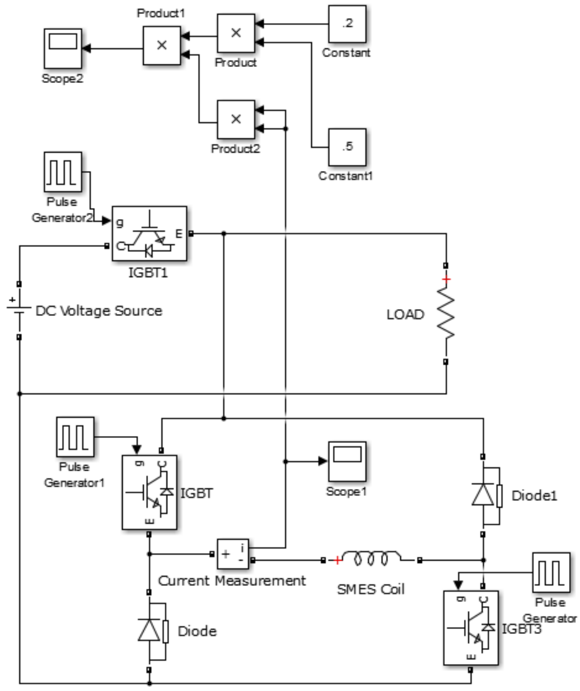

Fig -4: Simulation Diagram of SMES

Figure 4 shows the simulation Diagram of the SMES connected DC system. The results for this simulation are given below. The results shown are for SMES coil as well as normal inductor coil.

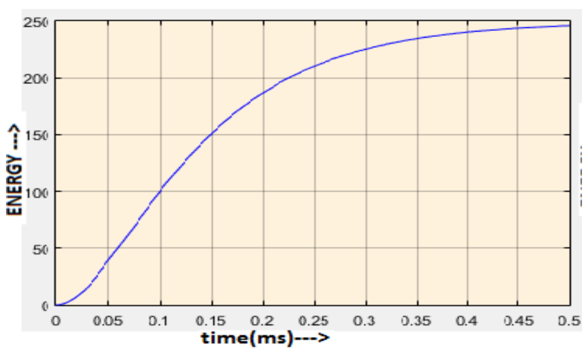

Fig -5: Simulation result for charging state of Normal coil

Here in normal coil there is internal resistance, Re through which there is constant loss in the coil. Hence no energy can be stored after the limit even we increase the current through it.

Figure 5 shows the energy plot of the charging stage of the SMES coil and Figure 6 show the energy discharging plot of the SMES coil. The coil starts charging as current starts built up in the SMES coil when connected to bus. Similarly, when there is disturbance in the system, the coil starts discharging through the load and power supply to the load is continue through it. [1]

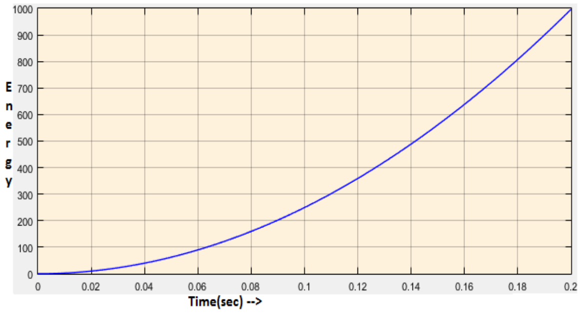

Fig -6: Simulation result for Charging state of SMES coil

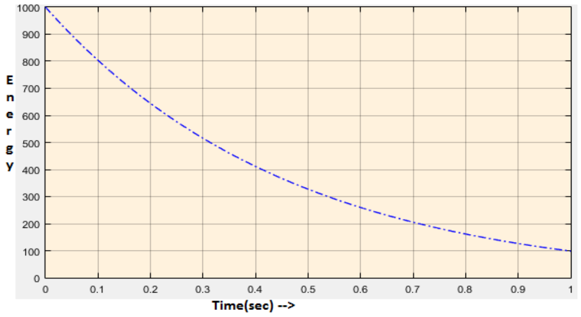

Fig -7: Simulation result for Discharging state of SMES coil

Here, from the above shown results it is clear that the Energy stored in the coil can be released when required during abnormal condition.

5. CONCLUSIONS

In this paper, a new control scheme for high power DC system where a SMES is used to obtain high energy storage with improved reliability was analyzed. This work provides an overview with DC analysis of the SMES technologies in electrical power and energy system.

Through the use of high-speed switches such as IGBT has the following advantages:

1) Improved durability to overloads
2) An improved power quality.
3) More reliable.
4) Faster and smoother turn-on/-off waveforms.
5) Improved production techniques, which has resulted in a lower cost.

Because of these advantages of IGBT, it is more efficient and accurate devise for high power operation of SMES System.

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