Operation and Control Techniques of SMES Unit for Fault Ride through Improvement of a DFIG Based WECS

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Abstract— The energy storage in an SMES is in the state of magnetic field within a superconductor coil. The magnetic field is formed by flowing DC current in the SMES. To ensure proper operation the temperature of SMES should be maintained below critical temperature. At this temperature the resistance of the coil is zero and hence there is no loss in stored energy. The ability of SMES to store energy is influenced by the current density. The energy is fed back to the grid by conversion of magnetic field into electrical energy. An SMES system has a superconductor, refrigerant, power conditioning unit and control unit. The storage of energy is achieved by continuous circulation of current inside the coil. Since the energy is not converted in any form other than electrical there are lesser losses in SMES configuration than any other storage mechanism. Thus the efficiency is very high. It inhibits very low cycling time and the number of charge discharge cycles is very high. The major drawbacks of this technology being very high initial cost as well as losses associated with auxiliaries. This paper covers various aspects of SMES configuration and its connection in power system.

Keywords— Energy Storage, Superconducting Magnetic Energy Storage (SMES), Voltage Source Converter (VSC), Current Source Converter (CSC),Wind Energy Conversion System (WECS), Doubly Fed Induction Generators (DFIG), Voltage Sag, Voltage Swell

INTRODUCTION

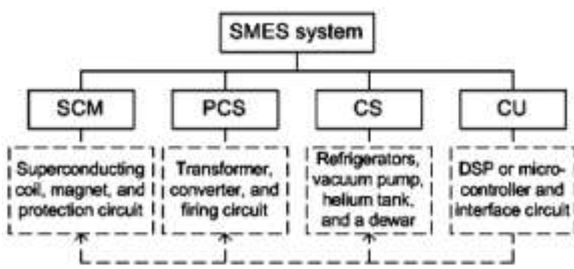


Fig. 1. Block diagram of an SMES unit

I. CONTROL METHODS FOR SMES

Various controlling methods for an SMES unit are discussed below:

THYRISTOR BASED SMES

A thyristor based SMES technology uses a Star- Delta transformer along with a thyristorised AC to DC bridge converter and an SMES coil. A layout of a thyristorized SMES controller is shown in Fig. 2. Converter assigns polarity to the superconductor. Charging and discharging operation is performed by varying the sequence of firing thyristors by modifying the delay angle. The converter performs rectification operation for a delay angle is set lesser than 90º. This enables charging of the SMES coil. For a converter angle set more than 90º the converter allows discharging of SMES by operating as an inverter. Thus energy transfer can be achieved as desired. When the power system is operating in steady state the SMES coil should not supply or absorb any active or reactive power.

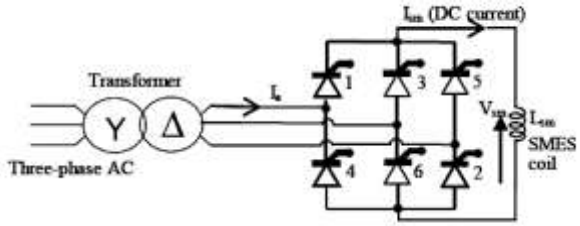


Fig. 2. SMES unit controlled by a AC- DC 6 pulse thryristorized bridge converter

If V_{sm0} is the no load max. DC voltage of the bridge, the voltage across DC terminals of the converter is

$$V_{sm} = V_{sm0} \cos\alpha \qquad (1)$$

If I_{sm0} is the initial coil current and P_{sm} is the active power transferred between SMES and the grid, then the relation between current and voltage of SMES coil is given as

$$I_{sm} = \frac{1}{L_{sm}} \int_{t_0}^{t} V_{sm} \, d\tau + I_{sm0} \qquad (2)$$

$$P_{sm} = V_{sm} I_{sm} \qquad (3)$$

The polarity of bridge current I_{sm} cannot be changed therefore the value of active power P_{sm} is a function of α that has polarity as per V_{sm}. If V_{sm} is positive the SMES unit gets charged by absorbing power from the grid. Whereas if V_{sm} is negative the SMES coil is discharged by feeding the power from SMES to the grid. The amount of energy that is stored within the SMES coil is given by

$$W_{sm} = W_{sm0} + \int_{t_0}^{t} P_{sm} \, d\tau \qquad (4)$$

$W_{sm0} = \frac{1}{2} L_{sm} I^2_{sm0}$ defines the initial energy in SMES

VOLTAGE SOURCE CONVERTER BASED SMES

The various components of a voltage source converter based SMES are a star- delta transformer, IGBT controlled six pulse width modulation based converter and an IGBT controlled 2 quadrant chopper and an SMES unit. The two converters are connected with a DC link capacitor. A schematic diagram of this arrangement is shown in Fig. 3 and the control technique of voltage source converter is depicted in Fig. 4. The voltage source converter serves as interfacing device linking the SMES coil to the grid. The potential integral controllers generate the values of direct and quadrature axis currents by comparing the actual value of the DC link voltage and terminal voltage to their reference values. This quantity is used as an input signal to the voltage source converter. PWM converter performs the operation of maintaining the voltage across DC link capacitor constant.

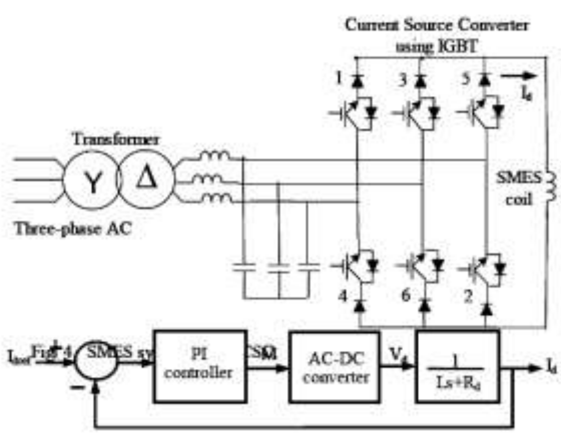


Fig. 3. Controlling technique of voltage source converter

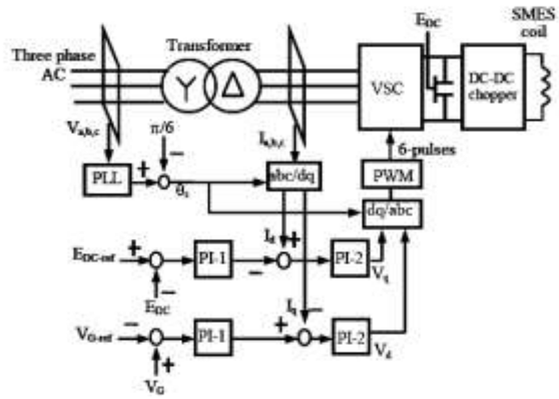


Fig. 4. Control technique of a voltage source converter

The chopper controls of energy transfer through the SMES coil. The chopper performs the operation of switching appropriate IGBTs by controlling the polarity of V_{sm}. This voltage can be adjusted by varying the duty cycle of the chopper. If the duty cycle is greater than 0.5 the energy is stored into the SMES coil whereas if the duty cycle has a value lesser than 0.5 the SMES coil is discharged. The gate signals for chopper circuit are generated by comparing the PWM signals with a triangular signal.

CURRENT SOURCE CONVERTER BASED SMES

The block diagram of a current source converter controlled SMES is shown in Fig. 5.

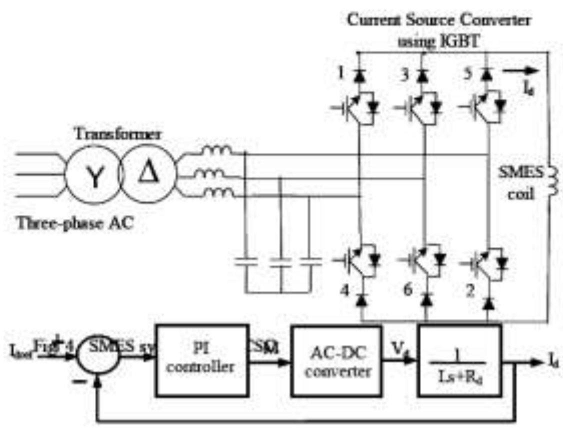


Fig. 5. Controlling technique for a current source converter

SMES coil is directly linked to the DC terminals of the current source converter whereas the AC terminals of the converter are connected with the grid. The shunt connected capacitor bank protects from the energy stored within the line inductance during commutation of AC current and also filter out the higher order harmonics. The input signal to IGBTs is regulated to control the current flowing through SMES. SMES stores energy in the form of current. Therefore the real as well as reactive power gets transferred at a very hih speed. A pulse width modulation technique is implemented to ensure that the higher order harmonics of a 12 pulse current source controller are minimized. If the value of modulation index is maintained in the range between 0.2 to 1 then the higher order harmonics are totally eliminated. The ripple content on DC side is higher when a 6 pulse current source converter is employed whereas it is reduced in case of a 12 pulse converter. This eliminates the losses on AC side of the system. As depicted in Fig. 5 the proportional integral controller compares the actual and reference values of I_d. L stands for the inductance of the superconductor coil whereas R_d and V_d are the respective resistance and voltage of the DC circuit. The rate of charging superconductor coil is influenced by the value of V_d which is a function of modulation index.

II. COMPARISON OF VARIOUSCONTROL TECHNIQUES

Comparison of control techniques for SMES coil is represented in Table 1. The topologies are compared on the basis of their ability of controlling active and reactive power, layout and operational features of the control unit, the effective total harmonic distortion generated by the control technique, the installation and operational costs as well as their self- commutation capabilities.

CRITERIA	SMES CONTROL TECHNIQUE		
	THYRISTORIZED CONTROL	VOLTAGE SOURCE CONVERTER CONTROL	CURRENT SOURCE CONVERTER CONTROL
ABILITY TO CONTROL ACTIVE AND REACTIVE POWER	Effective control over real power but inefficient in controlling the reactive power since the controller has a lagging pf to network. Significant lower order harmonics generated by firing of thyristors. Real and reactive power cannot be controlled independently.	Independent real and reactive power control is possible. Continuous reactive power support at rated capacity even in absence of negligible current in the superconductor.	Independent control of real as well as reactive power exchange through SMES. Reactive power support to the coil depends upon the coil.
OPERATION OF CONTROL UNIT	Highly controllable due to presence of a single AC- DC converter unit.	The control technique is convoluted compared to the other two techniques due to the presence of AC- DC converter and DC- DC chopper unit.	It has an a single AC- DC unit and hence can be controlled easily. For applications of higher rated power they can be operated in parallel connection.
TOTAL HARMONIC DISTORTION (THD)	Generation of total harmonic distortion is more than the other two techniques.	The value of total harmonic distortion is reduced in case of this control technique	The value of total harmonic distortion is reduced in case of this control technique
COST OF INSTALLATION AND OPERATION	Very economic installation and operational costs	Lower than CSC having equivalent rating	The total cost of switching devices is over 170 percentage of the cost of switchnig devices and diodes used in a voltage source controller of equivalent rating
SELF COMMUTATION	Poor self commutating capabilities than VSC	Better than CSC	Poor self commutating capabilities than VSC

Table 1. Comparison of various SMES control techniques

V. APPLICATION OF SMES

Because of its capability to respond instantaneously proves beneficial for several application in power system.

STORAGE DEVICE:

SMES has the ability of storing as high as 5000 MWh of energy at an efficiency as high as 95 percent. The efficiency is found to be higher for larger sized units. It can respond within few ms which makes it suitable during dynamic changes in the power system. It can serve as a spinning reserve. It can serve as a spinning reserve or as a supplementary reserve and hence provide supply during outages.

IMPROVEMENT OF PERFORMANCE OF FACTS DEVICES

An SMES unit is capable of storing energy for operation with FACTS devices. The inverter used for FACTS application and the power conditioning system of an SMES unit have similarity in their configuration.The only dissimilarity being that the FACTS devices performs their operation by using the energy which is provided by the power system and utilizes a capacitor unit to the DC side of converters. SMES provides real power along with the reactive power through the DC bus and hence improves the operation of FACTS devices.

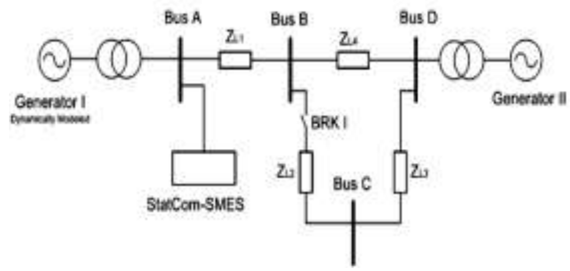


Fig. 6. SMES unit applied to FACTS devices

LOAD FOLLOWING:
SMES can support the generators to maintain the output energy at a constant value by following the variations in load pattern.

STABILITY ENHANCEMENT:
SMES unit can effectively damp the oscillations of lower frequencies and maintain the system stability after occurrence of any transient. It absorbs the excessive energy from the power system and releases energy in case of any deficiency. Thus it increases the stability of system by energy transfer.

AUTOMATIC GENERATION CONTROL:
SMES can be implemented to minimize the value of area control error in the automatic generation and control [4].

SPINNIG RESERVES:
When there is an outage of major generation units due to faults or maintenance purpose, the unallocated spinning reserves are implemented to feed the load. When the superconductor coil is completely charged the SMES can serve as a large share of spinning reserve. This is more economical alternative than other spinning reserves [4,5].

REACTIVE POWER COMPENSATION AND IMPROVEMENT OF POWER FACTOR:
SMES has an ability for independent active and reactive power control and therefore it can provide reactive power support and enhance the power factor of the system [4].

SYSTEM BLACK START:
SMES units have the ability to make provisions for stating a generation unit by drawing power from SMES unit instead of withdrawing power from the power system. This can help the system to restore from faulty conditions on the grid side [4].

ECONOMIC ENERGY TRANSFER:
By storing energy when it is available in excess and discharging it during deficiency or congestion it can reduce the price of electrical energy and hence be an economic alternative of supplying energy.

SAG RIDE THROUGH IMPROVEMENT:
Voltage sag can be defined as a drop in the rms value of the voltage level from 0.1 to 0.9 per unit at the power frequency level for a time ranging from 0.5 cycle to 1 minute. Some of the causes of voltage sag are starting of large motors, switching of large loads. SMES unit can efficiently provide voltage during such conditions [6].

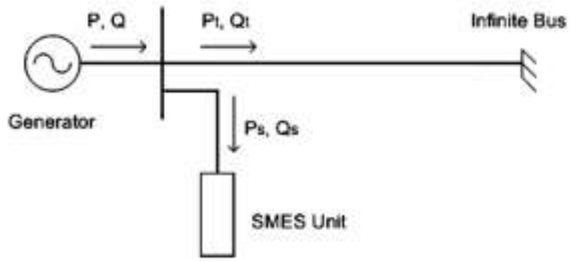


Fig. 7. Active and reactive power supplied by SMES connected to PCC

DYNAMIC STABILITY:
During sudden addition of large load or a large generating unit is lost the power system becomes dynamically instable. The reactive power available within the system is not sufficient to maintain the stability of the system. An SMES unit can be used to provide the requisite active as well as reactive power support to the grid [6,7].

REGULATION OF TIE LINE POWER:
While transferring electricity from one control area into another the amount of power transferred must match its predefinedvalue. If the generating units are ramped up for sending power from on control area and the amount of loading of that system gets changed. This variation may cause errors in the amount of power delivered and consequently inefficient utilization of generating units. An SMES unit can be used for elimination of such errors and to ensure efficient utilization of the generators [6].

LOAD SHEDDING DURING LOW FREQUENCY:
When a large load or a transmission line is lost the resultant frequency of the system drops and keeps reducing as long as the available generation and the load are balanced. Due to the ability of the SMES unit to supply active power quickly in the system it serves as an effective means to bring the system frequency to its rated value by eliminating the imbalance among generation and load [6].

RECLOSING OF CIRCUIT BREAKERS:
In order to clear a system fault and bring the line back into operation the circuit breakers are reclosed. Circuit breaker reclosing is performed when the power angle difference of the circuit breaker lies inside the limitations. But when the differences in the value of the power angle is very high then the protective equipments prohibits the reclosing operation of the circuit breaker. The SMES unit can feed some part of the load and hence decrease the power angle difference to inhibit its reclosing. Thus power flow can be restored back to normal conditions after outage of transmission lines [6].

ENHANCEMENT OF POWER QUALITY:
SMES unit has the ability to improve the quality of power by increasing the LVRT and HVRT capabilities of the power system. It eliminates the variations in power which interrupts the supply to critical consumers. In case of any momentary variations in load like a flashover or thunder strokes the transmissions system trips the power supply which leads to a voltage sag. by providing a quick response the SMES unit can avoid disconnection of critical loads [6].

BACKUP SOURCE:
The capability of SMES to store energy can serve as a backup source for sensitive loads and has the ability to supply the heavy industries if there is any outage of generating units. The SMES units size can be designed to provide storages and prove economic at the same time [6,7].

DAMPING SSR:
Sub synchronous resonances are observed in generating units that have a connection with transmission line that contains large series compensation of capacitive form. This can be damaging for generators. This sub synchronous resonance can be avoided by using SMES.

ELECTRO- MAGNETIC LAUNCHERS:
Electro-magnetic launchers have an application in large power pulsating source. They are utilized as rail gun in defense areas. Rail guns are capable of releasing a projectile having velocity more than 2000 meters per second. Since the SMES configuration has very large energy densities they are prove as an attractive alternative for this application.

STABILITY OF WIND TURBINES:
The wind turbine generator has issues related to stability of power system during transients. A voltage source converter based SMES unit controls the real as well as reactive power independently. This characteristic feature of the SMES configuration serves as an efficient device for stabilizing the wind energy conversion system [8, 9].

STABILIZATION OF VOLTAGE AND POWER FLUCTUATION IN WECS:
Because of the variation of the velocity of wind, the value of voltage and power generated by wind turbine generators is always varying. Such variations gives rise to flickering of incandescent bulbs and inaccurate operation of timing device. As the SMES device has the ability to control real as well as reactive power independently, it serves as an attractive means for reduction of fluctuations present in voltage and power.

VI. CURRENT STATUS AND FUTURE SCOPE

In 1982- 83 An SMES system of rated 30 MJ was assembled in Bonneville Power Administration Tacoma. The installed configuration functioned for 1,200 hour and from the various results obtained it can be concluded that the SMES configuration had successfully met the design requirements [11]. A 20 MWh SMES unit was proposed by Wisconsin university in the year 1988- 89. An array of D-SMES was developed for stabilization of transmission system. The transmission system in this particular area was introduced with huge suddenly changing loads because of operation of paper mills which gave rise to uncontrollable load fluctuation and collapsing of voltages. The SMES units were efficient in stabilization of grid and improving the power quality [12]. The largest installation includes six or seven units in upper Wisconsin by American Superconductor in year 2000. These units of 3 MW/0.83 kWh are currently operated by the American Transmission Company, and are used for power quality applications and reactive power support where each can provide 8 MVA [4]. In USA super-conductivity inc. supplies 1 and 3 MJ rated SMES devices.

Current an SMES having an energy rating of 100 MJ/ 50 MW is being designed. It is said to be the largest SMES configuration till date. The purpose of design of this SMES unit is for damping the low freq. oscillations generated within the transmission network. The superconducting magnet which is to be used for this configuration was materialized in 2003 and the tests on this magnet were carried out from the center of advanced power system [13]. In Japan in 1986 an institute named 'The Superconductive energy storage research association set up for promotion of applications of the SMES configuration practically. The Kyushu Electric corporation had manufactured a 30 KJ SMES device in 1991for the stabilization of a 60 kW Hydro- electric generation plant. Several tests were performed to prove the suitability of SMES unit to yield a desirable performance [14]. To simplify the choice of the capacity of an SMES unit with the most suitable and appropriate cost and quality a 1 KWh 11 MW and a 100 KWh 120 MW SMES configuration is manufactured. The 1 KWh 11MW unit is being validated by connecting it to a 6 KW and a 66 KW grids. These units were tested for compensation of variations in load present in the network [15]. In Japan a 100 MW of wind farm was connected with a 15 MWh of SMES unit in the year 2004, for stabilization of the output generated from the wind farm [16]. In the year 1988, in Russia an institute named T 15 Superconducting Magnet has manufactured an SMES unit that has a capacity as high as 370 to 760 MJ [17]. After 1990 the Russian scientists are designing a 100 MJ 120 MW SMES unit [18]. Korea has developed a 1 MJ 300 KV SMES unit for UPS applications. This unit can compensate a 3 second interruption of power and is 96 percent efficient [19]. The Korean electro technology research institute had fabricated a 3 MJ, 750 KVA superconducting magnetic energy storage unit having 1000 Amperes of operational current for enhancement of power quality in the year 2005[20]. Delengation generale pour L'annement support the researches of applied superconductivity held in France. DGA has built a 100 KJ SMES made from Bi 2212 tapes having liquidized Helium as a coolant. Later on it was decided to materialize an SMES unit that could work at higher temperatures like 20 Kelvin. DGA had targeted to manufacture an SMES unit oh 800 KJ which would work on high temperature storage principle. The proposed SMES unit was expected to operate at temperatures as high as 20 Kelvin which will have current density more than 300 MA/m^2[21]. Some organizations in Germany are working together for designing an SMES unit having a rating of 150 KJ and 20 KVA. The SMES unit is designed for operation as an uninterrupted power supply [22].

The foremost high temperature superconductor based SMES unit was fabricated by American superconductors in the year 1977. This unit was applied to a scald power system located in Germany. Several tests were conducted which revealed that high temperature superconductors based SMES units were a viable and attractive alternative for commercialized production [23]. Distributed SMES units of small size called micro SMES having a rating between 1 to 10 MW are available in the commercial market.

Currently United States Dept. of Energy advanced research projects agency for energy has sponsored projects to validate the application of SMES unit in power system. The project is undertaken by a Swiss industry named ABB and has received funds of US dollars 4.2 million grant. According to the outlines laid for the plan a 3.3 KWh SMES configuration is proposed. The project will be done in collaboration with Superconducting wire manufacturers super power, Brookhaven National laboratory as well as university of Houston. The unit must be manufactured for 1 to 2 MWh and must be economic compared to lead acid batteries [25]. In Japan, high energy acceleration research organization have promoted research on SMES. The scientists here are working for combining liquid hydrogen refrigeration based SMES unit with a hydrogen fuel cell. The concept behind this combination is that when there is an interruption of power the SMES unit can supply energy instantaneously and later on the fuel cell can feed the loads. However the device is not materialized yet though the simulation as well as designs are under studies [10].

VII. RATING OF SMES CONFIGURATION

Capacity of the SMES unit is dependent upon the various applications and the cycling times available. An SMES unit having a very high capacity can damp oscillations quickly. Such an unit won't be much economic since it will carry very large currents in the coil. Whereas a very small capacity of the SMES configuration is ineffective for damping the system oscillations immediately. This is because the output power of the SMES unit will be limited.

VIII. SYSTEM UNDER STUDY

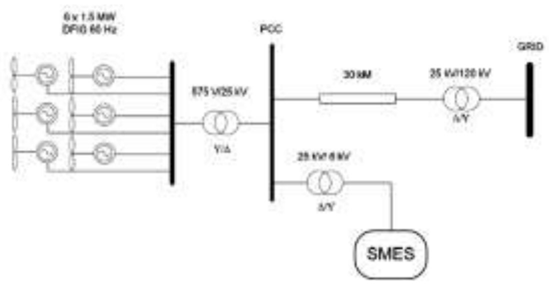


Fig. 8. Block diagram of the system under consideration

The proposed system has doubly fed induction generators of rating equal to 9 MW. The SMES unit chosen has an energy rating of 1 MJ and the inductance of 0.5 H. Rated current through the superconductor is calculated to be 2 KA. The operation of SMES unit during swell conditions is feasible only if the value of rated inductor is chosen greater than the rated currents inside the coils. The system under consideration has a nominal current of 2 KA flowing through the coil. Therefore the max. amount of energy that can be stored within SMES coil is as high as 1 MJ while occurrence of a voltage swell.

RESPONSE OF SMES UNIT IN THE EVENT OF VOLTAGE SAG AND SWELL

The current flowing through the SMES coil is unidirectional but the value of duty cycle of chopper circuit obtained from fuzzy logic controller gives numerous positive as well as negative values for SMES voltage. This provides a reversible and continuous flow of power for all operating conditions. The proposed SMES unit works in three different operating modes:

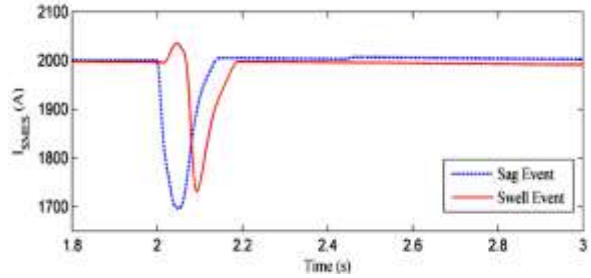
(1) stand- by mode

(2) discharging mode

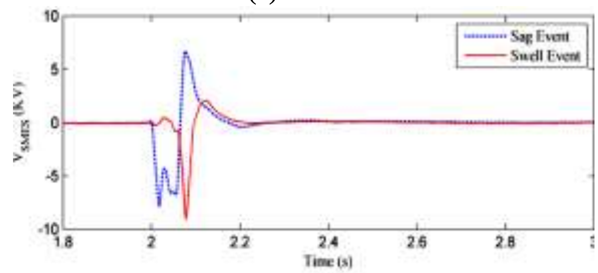
(3) charging mode

(1) Stand-by mode:

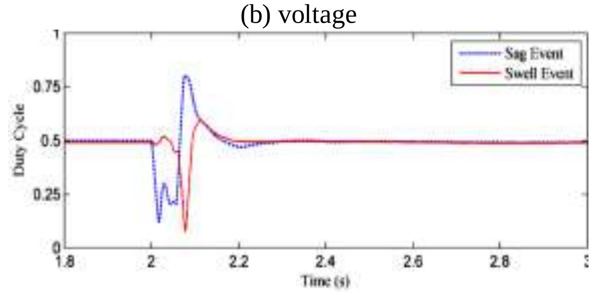
Standby mode of operation occurs when the wind energy conversion system is working in healthy operating conditions. The standby operating mode is selected when the value of duty cycle is selected to be 0.5. And the SMES coil is maintained at the rated value, in this case 2 ka. There is no transfer of energy to or from the SMES coil while the SMES coil is charged for maximum energy, i.e., 1 MJ in this case. The dc link capacitor has a constant voltage of 10 kv across its terminals.



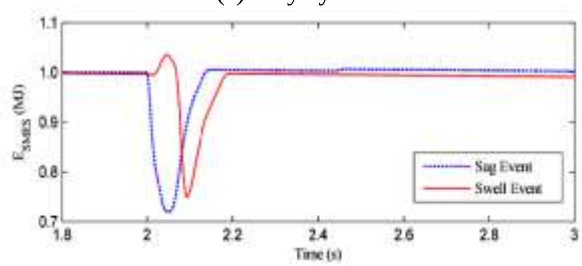
(a) current



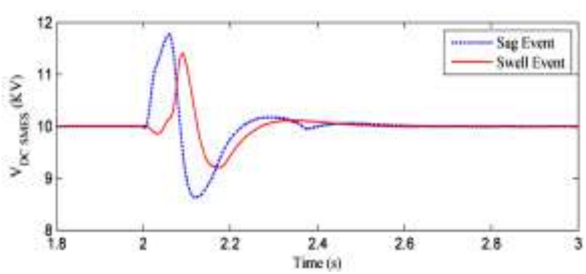
(b) voltage



(c) duty cycle



(d) energy stored in SMES



(e) DC voltage in SMES

Fig. 9: SMES transient responses during voltage sag and swell including; (a) current (b) voltage, (c) duty cycle, (d) energy stored in SMES and (e) DC voltage in SMES

(2) Discharging mode

During a voltage sag on the grid, discharging mode occurs in the SMES unit. In discharging mode d has a value less than 0.5. In this mode of operation the energy stored inside the SMES unit is supplied to the power system. At time t= 2 seconds a voltage sag is and the current flowing through SMES coil reduces with a negative slope. The rate of discharging of SMES coil is predetermined and is a function of d. Voltage across SMES is dependent upon the value of d and the voltage present across the dc link capacitor. When the fault is cleared the coil is recharged. Discharging mode of operation of SMES is compared with the charging mode in Fig. 7.16.

(3) Charging mode:

During a voltage swell event the SMES unit undergoes charging operation. The value of d in this mode lies above 0.5. At time t= 2 seconds a voltage swell is simulated therefore the current flowing through the SMES coil raises positively and the charge stored inside SMES unit increases. The transfer of energy occurs from the power system to the SMES unit until it reaches a max. Capacity which is determined by the value of duty cycle. In the system under consideration the max. Capacity of the unit is 1.03 MJ. Power modulation is till this capacity is permissible and beyond this V_{SMES} drops and becomes 0 when max. SMES current is acquired. Fig.7.16 represents the charging mode of an SMES coil.

Below mentioned observations are drawn

(i) The current flowing through the SMES unit during dip and swell occurrence are analogues to the energy that is stored inside the coil. The level of energy at any instance is calculated as $1/2\ LI^2$

(ii) During both sang as well as swell occurrence the voltage across SMES unit is kept 0 after the max. Current starts flowing through SMES. In order to reduce the SMES operating expenses it is advisable to bypass the SMES unit when the power system becomes stable. This can be done by using a bypass switch in parallel with the SMES unit.

(iii) During occurrence of both voltage dip as well as swell the voltage across dc link capacitor of the SMES unit is observed to oscillate in reverse manner then the voltage across SMES coil. The level of this voltage at any instant is dependent upon the SMES voltage and D.

(iv) Max. overshoot of the voltage in dc link voltage is lies inside the safety limit of 1.25 per unit of the system voltage.

CONCLUSION

The paper gives a brief account of various control techniques used for SMES which include thyristorised control, control using a Voltage Source Converter and control using a Current Source Controller. A comparative account of these methods is done. A brief summary of the various applications for SMES and the installations of SMES technology throughout the world so far is also highlighted along with a note on selection of the rating of the SMES unit for a given application. The behavior of SMES during charging and discharging event on occurrence of a sag and a swell in the distribution end of the system is also analysed.

REFERENCES:

[1] Mahmoud Y. Khamaira, A. M. Shiddiq Yunus, A. Abu-Siada, "Improvement of DFIG-based WECS Performance Using SMES unit" The Australasian Universities Power Engineering Conference, 2013.
[2] R. H. Lasseter, S . G. Jalali, "Dynamic Response of Power Conditioning Systems for Superconductive Magnetic Energy Storage", IEEE Transactions on Energy Conversion, Vol. 6.
[3] Knut Erik Nielsen, "Superconducting magnetic energy storage in power systems with renewable energy sources", Master of Science in Energy and Environment Thesis, Norweigan university of science and technology
[4] P. D. Baumann, "Energy conservation and environmental benefits realized from SMES," IEEE Transaction on Energy Conservation, vol. 7.
[5] C.-H. Hsu, W.-J. Lee, "SMES storage for power system application," IEEE Transaction of Industrial Applications, vol. 29
[6] W. V. Torre, S. Eckroad, "Improving power delivery through application of SMES, IEEE Power and Engineering Society Winter Meeting, 2001
[7] X. D. Xue, K. W. E. Cheng, D. Sutanto, "Power system applications of SMES", in IEEE Industrial Applications Conference 2005, vol. 2
[8] O. Wasynczuk, "Damping SSR using energy storage," IEEE Transactions of Power Application Systems, vol. PAS-101
[9] C.-J.Wu, C.-F. Lu, "Damping torsional oscillations by SMES unit," Electrical Machines Power System, vol. 22

[10] Makida Y, Hirabayashi H, Shintomi T, Nomura S, "Design of SMES with liquid hydrogen for emergency purpose", Applied Superconductivity IEEE Transactions 17
[11] D. Rogers, H. J. Boenig, "Operation of 30MJ SMES in BPA Electrical Grid," IEEE Transactions on Magnetics, vol.21
[12] R. W. Boom, "SMES for electric utilities-A review of 20 year Wisconsin program," Proceedings of the International Power Sources Symposium, vol.2
[13] Michael Steurer, Wolfgang Hribernik, "Frequency Response Characteristics of 100MJ SMES its Measurements and Model Refinement," IEEE Transactions on Applied Superconductivity, vol.l S.
[14] F me, and M. Takeo, "A field Experiment on Power Line Stabilization by an SMES System," IEEE Transactions on Magnetics, vol.l S
[15] Tsuneo Sannomiya, Hidemi Hayashi, "Test Results of Compensation for Load Fluctuation under a Fuzzy Control by IkWhIMW SMES," IEEE Transactions on Applied Superconductivity, vol.l l [16] S. Nomura, Y. Ohata, "Wind Farms Linked by SMES Systems," IEEE Transactions on Applied Superconductivity, vol.l S
[17] N. A. Chernoplekov, N. A. Monoszon, "T-15 Facility and Test," IEEE Transactions on Magnetics, vol. 23
[18] V. V. Andrianov, V. M. Batenin, "Conceptual Design of a 100MJ SMES," IEEE Transactions on Magnetics, vol.27
[19] K. C. Seong, H. J. Kim, "Design and Testing of I MJ SMES," IEEE Transactions on Applied Superconductivity, vol2
[20] H. J. Kim, K. C. Seong, "3 MJ/750 kVA SMES System for Improving Power Quality," Transactions on Applied Superconductivity
[21] P. Tixador, B. Bellin, "Design of 800 kJ HTS SMES," IEEE Transactions on Applied Superconductivity, vol.l S
[22] M. Ono, S. 1. lanai, "Development of IMJ Cryo cooler Cooled Split Magnet with silver Sheathed Bi2223 Tapes for silicon Single-Crystal Growth Applications," IEEE Transactions on Applied Superconductivity, vol. 10
[23] Weijia Yuan, "Second-GenerationHTS and Their Applications for Energy Storage", Springer Thesis, Doctoral Thesis accepted by the University of Cambridge, Cambridge
[24] Phil Mckenna, "Superconducting Magnets for Grid-Scale Storage", Technology Review, Energy. March. 2011
[25] H. Chen, "Progress in electrical energy storage system A critical review", Progress in Natural Science 19