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Performance Evaluation of Distributed Superconducting Magnetic Energy Storage System (D-SMES) for Power and Frequency Control

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Abstract: *In this paper, the structure of Distributed Superconducting Magnetic Energy Storage System (D-SMES) is proposed in order to power and frequency control. The main parts that a D-SMES consists of, the various configurations and operational techniques are discussed. The advantages and disadvantages of superconducting energy storage compared with other solutions are provided. Using D-SMES allows utilities to improve system reliability and transfer capacity, giving cost-effective grid stabilization for entire electric utility systems. To demonstrate this ability of a D-SMES device, simulations were performed using the MATLAB software. The simulation results are provided and discussed.*

Keywords: D-SMES, active and reactive control, energy storage, simulation.

1. Introduction

Continuing electric load growth and higher power transfer in a largely interconnected network lead to complex and less secure power system operation [1]. Power generation and transfer proficiencies can not be sufficiently growth to new requests. In this situation, increase electrical load to made of in the critical level for power sources quality. So, we have to find solution to make system with more flexibility ad better control method [2].
Different technologies exist for electrical energy storage that to large-scale include to SMES, compressed air, batteries, pumped hydro, and flywheels. SMES systems have received considerable attention for power utility applications due to its characteristics such as rapid response (mili-second), high power (multi-MW), high efficiency, and four-quadrant control [3].
The D-SMES (distributed SMES) is a set of SMES devices connected to different buses in a transmission system. A combination of a SMES system with a voltage-source IGBT converter, is capable of effectively controlling and near-instantaneously injecting both active and reactive power into the power system. Obviously, it is reasonable to consider a power system with a D-SMES as a multi-device FACTS in terms used in [4].
A superconducting magnetic energy storage (SMES) system is a device for storing and instantaneously discharging large quantities of power. These systems have been in use for several years to improve industrial power quality, protecting customers vulnerable to voltage dips. A Distributed SMES (D-SMES) enables utilities to improve system reliability performance by correcting voltage stability and low voltage problems [5].

2. Operation and Specification of D-SMES

The D-SMES is currently the only commercially-available inverter-based system that has been applied with energy storage. D-SMES systems consist of multiple SMES units installed at substations throughout power transmission networks to provide enhanced transmission network reliability and capacity. D-SMES systems are connected to utility's grids at substations, and protect the grids from the destabilizing effects of short-term events, such as faults that are caused by lightning strikes, downed poles, sudden changes in customer operations, and switching operations. In many cases, D-SMES is a cost-effective way to reinforce a utility grid without the expensive need to construct new lines. In addition, rather than protecting any specific customer, D-SMES protects the stability of entire regions of the grid, thus protecting many customers simultaneously [4]. Figure 1. shows a schematic of D-SMES unit.

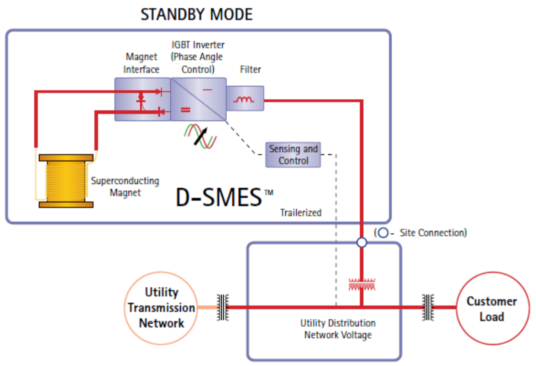


Figure 1: Shows a schematic of D-SMES unit.

A D-SMES unit is shown in Fig. 2 and consists of the following major items [6]:

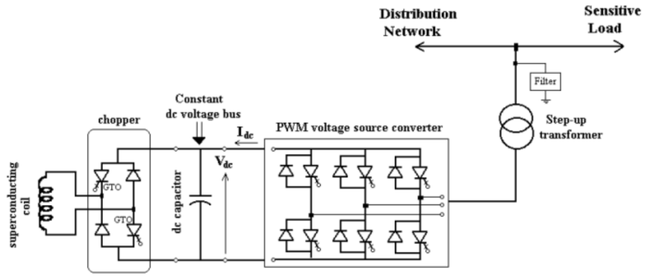


Figure 2: Simplified D-SMES one-line diagram

• ***A voltage source converter (VSC).*** The VSC is designed to operate as either an inverter when discharging the superconducting coil or as a rectifier when charging. The VSC is designed with self-commutating static switches capable of supplying both active and reactive power needs of the system. Voltage and current ratings of the converter must be taken into account in the design of the control system. Moreover, the overload ratings must be known. For example, there are systems that can operate for 10 sec at about 200% of their steady-state ratings [7].

• ***The superconducting magnetic energy storage system.*** A superconducting (zero resistance) coil stores energy in its magnetic field. Some features of the storage system such as the charge and discharge time must be taken into account in the overall design of D-SMES.

• ***A dc/dc converter (chopper).*** The chopper is used to maintain a constant dc voltage across the capacitor. The chopper frequency is defined by the manufacturer and results from an optimum tradeoff between the superconducting reactance, the dc capacitor and the maximum deviation for the dc voltage. Due to GTO losses the chopper frequency is generally between 500 Hz and 1 kHz.

• ***A coupling (or step-up) transformer.*** This transformer is used to raise the converter output voltage to meet network voltage level because of voltage limitations of converter's power electronics. Another use is to provide electrical isolation from the grid. Typical value of transformer leakage reactance is about 0.1 pu. In some cases, simple reactors can be also used.

• ***A harmonic filter.*** The produced ac voltage waveform after the coupling transformer will contain some harmonics. This harmonic content may be low or high, which depends on the design of the voltage-source converter. In our case, a Pulse Width Modulated (PWM) converter is studied, whose harmonic content is significantly low for a quite high modulation frequency (e.g. 33). Thus, only a small capacitor can be used to meet harmonic requirements imposed by International Standards. Typical values are 0.3-0.6 pu of converter rating (MVA). In other cases, more complex filters may be used to mitigate the total harmonic content or some harmonics of specific order.

• ***A system for data acquisition and control of the process.*** Distribution network, load, converter and storage system parameters (e.g. voltages, currents, frequency, active and reactive power, load power factor) must be continuously measured to enable proper control of voltage-reactive power and frequency-active power (especially in isolated mode) and to protect from exceeding the device ratings and other design specifications.

Moreover, a Static Switch (SS) (or Solid-State Breaker SSB) may be used upstream the D-SMES system. The SS consists of a pair of anti-parallel self-commutating power electronic switches (e.g. GTO or IGBT). It takes a command to open when the system voltage drops below a pre-set rms value (or an interruption is detected). Thus, in case of faults on the distribution or the transmission system, the SS opens rapidly and the load is supplied from the energy storage reservoir through the voltage-source converter. Consequently, the voltage of the sensitive load is adequately supported. Without the SS, the D-SMES would require very large amounts of energy storage to adequately support the voltage of the sensitive load.

3. Application of D-SMES Unit

As an example of energy storage system (ESS) technology, D-SMES system has the advantages in both energy storage ability and flexibility of its power electronics interface. DSMES has been employed due to its capability to work as active and reactive power generation and absorption systems.
The capability of SMES systems to exchange active and reactive power with the electric network almost instantaneously, have made them suitable for enhancing power system dynamic performance [8]. A number of power system applications have been proposed over the past three decades. These applications include power system load leveling , power system stability improvement , spinning reserve and damping of turbine-generator subsynchronous oscillations , frequency and voltage control , protection from power outages and power and energy management [9].
The aforementioned applications imply connection of the device with the transmission system. However, a number of

applications of the D-SMES system have been proposed for distribution networks. They include voltage stability improvement, protection of critical (sensitive) loads from power outages, reactive power compensation and mitigation of flicker and voltage sags. In case of distributed generation, D-SMES can be also used for load leveling and power and energy management [10].

4. Performance of D-SMES on Sample System

A 23 bus sample system is used in the study. Fig. 3 is the one-line diagram of the system. In this system, the total generation is 3258MW+j964MVAR and the total load is 3200MW+j1950MVAR. Four 250MVA, 100MW D-SMES will be installed at the generator buses 101, 102, 206 and 211.

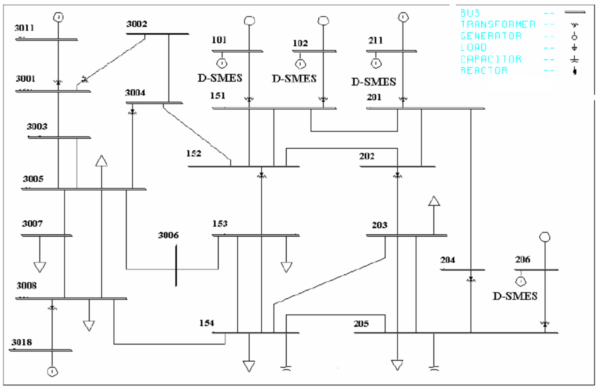


Figure 3: Diagram of the sample system

Information about generators and loads in the system is listed in Table 1 and Table 2 respectively. In Table 1, Gen.206 (generator connected to bus 206) has a high reactive power output (600MVAR) that may cause obvious change of the system voltage when it is tripped out of the system.

Table 1. Generators information in the system

Gen Bus No.	P_G (MW)	P_G%	Q_G (MVAR)	Q_G%
101	753	23.1	81	8.4
102	753	23.1	87	9
206	800	24.6	600	62.2
211	600	18.4	17	1.8
3011	258	7.9	104	10.8
3018	100	3.1	80	8.3

Table 2. Load information of the system

Load Bus No.	P_L (MW)	P_L%	Q_L (MVAR)	Q_L%
153	200	6.3	100	5.1
154	1000	31.3	800	41
203	300	9.4	150	7.7
205	1200	37.5	700	35.9
3005	100	3.1	50	2.6
3007	200	6.3	75	3.8
3008	200	6.3	75	3.8

Fig. 4 is the frequency at 5 different buses when generator at bus 101 (referred as Gen.101) is dropped. The buses are generator buses (bus 101 and bus 211), load buses (bus 154 and bus 3005) and tie line buses (204). We can see that the frequencies of all the buses in this system have the same dynamic characteristics, which is clearly seen from Fig. 5. So we select the frequency of bus 154 as the representative of the study.

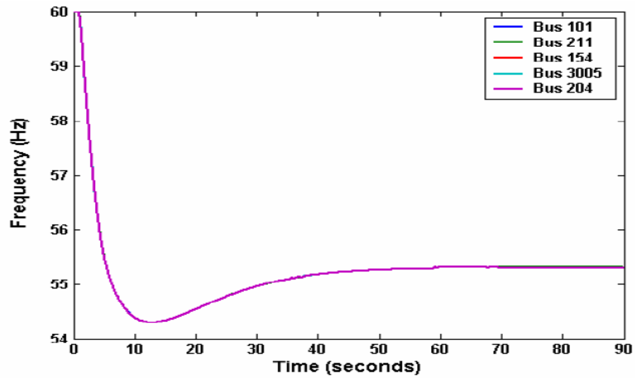


Figure. 4. Frequency of different buses when generator at bus 101 is disconnected.

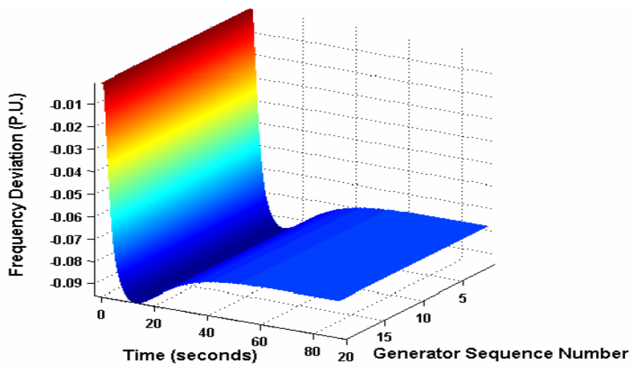
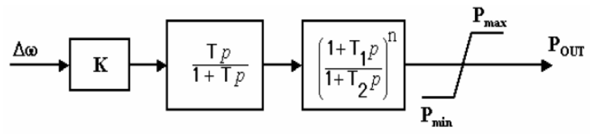


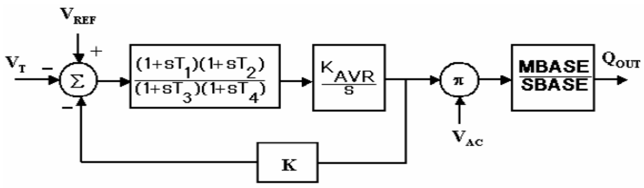
Figure. 5. The frequency dynamics of all the buses in the system when Gen.101 is tripped.

The control functions of the D-SMES have two parallel independent parts for active power control and reactive power control. The active power control is to control the active power output of D-SMES to stop the quick drop of system frequency.

The reactive power control is to keep the terminal voltage at the reference value (Wu et al, 2008). Fig. 6 is the control blocks of the two parts. In Fig. 6 (a), the K in the first block is the multiplying factor. The second block is the resetting block which makes Pout zero when $t \rightarrow \infty$. The third block is a phase compensation block that will make Pout be synchronous with $\Delta\omega$. In Fig. 6 (b), KAVR, T1, T2, T3, and T4 are the gain and time constants of the automatic voltage regulator. K is the negative feed back factor. In our case, there is no phase shift with n=0.



(a) Active power control function of D-SMES



(b) Reactive power control function of D-SMES

Figure. 6. Control function chart of D-SMES controller.

In this study, we use the case of tripping Gen 211 as the sample of the study, because the generation of Gen 211 is big enough and there is no spinning reserve in Gen 211. Fig. 7 is the comparison of frequency of bus 154 when Gen. 211 is tripped. The active power of D-SMES is controlled to keep a small frequency drop, 0.4 Hz for example, to keep the governor output rising.

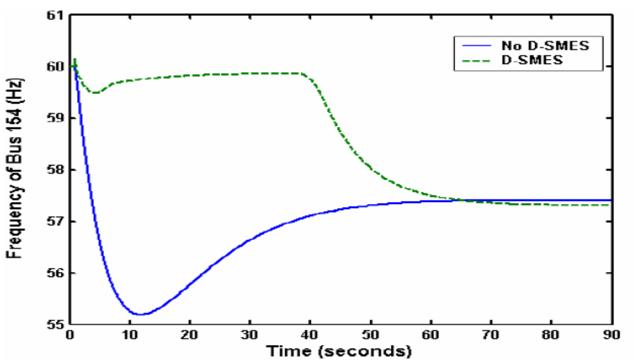


Figure. 7. Comparison of frequency of bus 154 when Gen.211 is tripped.

Fig. 8 is the active power and reactive power output of D-SMES on 101 bus. The curve part (from 6.3s to 38.2 s) of active power output is controlled to keep 0.4 Hz frequency drop to keep the governor output rising. D-SMES outputs reactive power to keep the bus voltage at the reference value.

5. Conclusion

In this paper, a D-SMES unit is described and compared with devices that use other methods of energy storage. The benefits of such a device for a power system are thoroughly described. The application of D-SMES can to achieve the goal of full activating the spinning reserve and minimizing shedding load. The active and reactive power controls of D-SMES are independent. The active power is controlled to stop the dropping of system frequency and the reactive power is control to stabilize the local voltage.

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