2014

Application of a superconducting magnetic energy storage unit for power systems stability improvement

Embaiya Salih
Edith Cowan University, embaiyia@gmail.com

Stefan Lachowicz
Edith Cowan University, s.lachowicz@ecu.edu.au

Octavian Bass
Edith Cowan University, o.bass@ecu.edu.au

Daryoush Habibi
Edith Cowan University, d.habibi@ecu.edu.au

10.1109/ICGE.2014.6835433

Application of a Superconducting Magnetic Energy Storage Unit for Power Systems Stability Improvement

Embaiya, Salih. Stefan, Lachowicz. Octavian, Bass.
School of Engineering
Edith Cowan University
Perth, Australia

***Abstract*—Superconducting Magnetic Energy Storage System (SMES) includes a high inductance coil acting as a constant source of current. When a SMES is connected to a power system, it has the ability to absorb both active and reactive power from the power system and it is capable to inject these powers into this system when they are needed. While the SMES coil is discharging power into the system, this injected power is controlled by changing the duty cycle of the dc-dc chopper switches and its operation modes. SMES is always associated with power conversion system consisting of two identical converters. These converters are connected by a dc link capacitor and are used in the system to change between the alternative and the direct current, which is primarily required for the SMES unit task. This paper presents an efficient system based on the SMES unit to improve the transient stability by regulating the dc link voltage during the fluctuations in voltage or frequency after disturbances in a power system or at any rapid changes in the load size. The behavior of the system is tested with three faults/events in the power system, at the power supply, and at the loads side. The transient behavior of the designed system is observed with and without the SMES unit. The results show that the SMES system increases voltage stability across the dc link significantly whenever voltage and frequency in power supply are oscillating and rapid changes in the loads and disturbances in generation system occur.**

***Index Terms*— Superconducting Magnetic Energy Storage (SMES), Transient, Power Stability.**

I. INTRODUCTION

Stability is the most significant feature needed in the modern power system. Stability problem in power system has been noticed during the recent years, because of the fast growth in electric and electronic loads. However, the developments and improvements in generation and distribution systems have not met yet this fast growing loads and the increasing in the number of important and sensitive devices in power system. Disturbances and short outages in generators or transmission lines always have negative effect on power system. In addition, according to Hsu [1], a rapid variety in loads in the plant leads to voltage and frequency fluctuations. These disturbances and fluctuations that occur during the transient process cause stability and quality issues in power system.

Over the past decades, the energy storage technologies have grown and provided some economic and environmental benefits for business and the society. The superconducting energy storage system (SMES), which is an electrical storage technology, is applied in many electrical and electronic power applications for improving and enhancing stability and the performance of modern power systems. It has advanced on other storage technologies due to some of its own significant features. This storage technology has crucial characteristics like, no movement parts in its conversion unit, the storage efficiency is about 98% which is far better than any other storage technologies [2], the very rapid release of large amount of stored energy during a small period of time (milli-seconds). In addition, the number of charging and discharging cycles in SMES is unlimited. Furthermore, the SMES unit can keep a large amount of energy for a long period with no significant losses and it is capable to release this saved energy back rapidly to the power system when it is required and during the high demand periods [3]. Thus, due to its significant characteristics, the SMES unit with proper control of its power converters system can adjust the active and reactive powers absorbed from or delivered to power systems. Therefore, applying SMES with various control modes can solve some power stability problems like low-frequency oscillation, sub-synchronous resonance, to increase the transient stability of power system and to offer an overall improvement in the power system performance. [1].

The SMES unit is presented in some previous studies as a storage system linked to power systems to increase their stabilities and qualities. By different control strategies, the conversion system in SMES is controlled to improve and enhance the transient system stability. Some of these studies show that SMES can be efficiently used to stabilise the power system. To demonstrate the SMES unit efficiency for improving stability and quality of power system, the SMES unit is utilized to keep the level of the dc voltage across the dc link constant, so that leads to decreasing of the voltage and frequency fluctuations at the load side. To achieve that, three types of system disturbances and instability power issues are considered in this paper. Firstly, the case of the system disconnected from the utility network because of an external fault on generators or transmission line. Secondly, when some voltage and frequency fluctuations of power supply occur. Finally, when the system load changes rapidly. This paper is organized as follows: Section II illustrates the SMES system. Section III explains the operations modes of the SMES system. Section IV deals with applications of SMES for increasing power system stability. Section V describes the proposed system for regulating the dc link voltage. Section VI shows the computing simulation results. Finally, section VII gives some conclusions considering this work.

II. DESCRIPTION OF SMES SYSTEM

The SMES is one of the significant storage system solutions. This unit consists of two main parts, the conversion system and the superconductor coil as it is illustrated in Fig. 1, First, the conversion system comprises of two power converters, which are used to change between alternative curent and direct current (ac/dc rectifier and dc/ac inverter). The second part of the SMES is a superconducting coil. It is an extremely low resistive coil. In SMES, when the direct current passes through the superconducting coil, magnetic energy will be created around it [4]. This coil has the ability

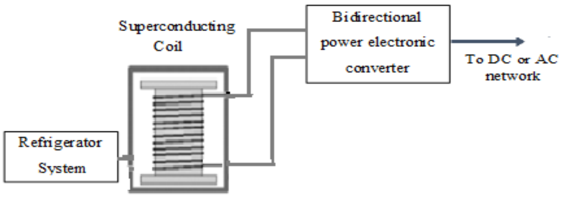


Fig. 1. Descriptive diagram of a SMES.

to keep the magnetic energy with almost no losses for a long time [5, 6]. Furthermore, a refrigeration system is always associated to the SMES for keeping the superconducting coil at an extremely low temperature.

The power conditioning system (PCS) which consists of a 3-phase voltage source converter (VSC) and a dc-dc chopper is required for transferring energy from the SMES coil into the network. According to Padimiti and Chowdhury, the dc-dc chopper is mainly used to keep the current through the SMES coil constant and to transfer the power to the VSC through the dc-link capacitor [2]. Along with a dc-dc chopper, the superconducting coil is linked to the VSC through a dc-link capacitor. This capacitor operates as a brief source of the dc voltage for the VSC to inject active and reactive power into the grid. By suitable control of the power converter system of the SMES, it is possible to regulate the active and reactive power that are absorbed or delivered by the SMES unit. Due to the ability to return the active and reactive power rapidly all the time, with various control modes, SMES unit can be used for controlling low-frequency oscillations [1], sub-synchronous resonance [7], levelling of fluctuating load power [8] and for improving the transient stability [9] of a power system.

Fig. 2, shows a typical configuration of a SMES system. The SMES unit is connected to the power system through a three phase winding transformer and an ac/dc six-pulse bridge circuit converter. By controlling the firing angle (α) of the converter, the SMES can absorb or deliver the active and reactive power to the power system. The dc output voltage of the converter is expressed as:

$$V_{sm} = V_{sm}\cos(\alpha) - R_c I_{sm}. \quad (1)$$

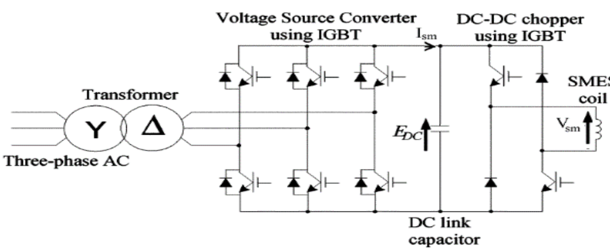


Fig. 2. Typical configuration of VSC-based SMES system.

V_{sm0} is the maximum dc voltage without load, and R_c is the equivalent resistance of the power converter. Through the inductor, the dc current I_{sm} is unidirectional.

In the superconducting inductor, the voltage and current are related as:

$$I_{sm} = \frac{1}{L_{sm}}\int_{t0}^{t} V_{sm}\,dt + I_{sm0}. \quad (2)$$

where I_{sm} is the initial current of the inductor. When the switching loss of the converter is ignored, the active power (P_{sm}) that is absorbed or delivered by the SMES can be expressed as:

$$P_{sm} = V_{sm} * I_{sm} = V_{sm0} * I_{sm}\cos(\alpha). \quad (3)$$

The power P_{sm} is only a function of $\propto$, which is depending on the voltage of the superconducting coil (V_{sm}). It can be positive or negative. When V_{sm} is positive, the power is absorbed by the SMES unit from the power system. On the other hand, if it is negative, the power is released from the SMES unit to the power system [10, 11].

The energy stored in the superconducting inductor is:

$$W_{sm} = W_{sm0} + \int_{t0}^{t} P_{sm}\,dt \quad (4)$$

$$W_{sm0} = \frac{1}{2} L_{sm} I_{sm0}^2 \quad (5)$$

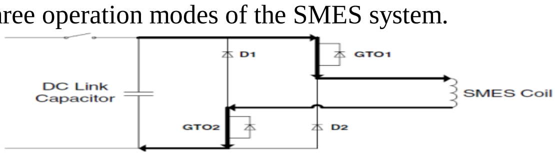
where: W_{sm0} is the initial energy in the inductor.

Therefore, the SMES can store a large amount of energy depending on the current which flows through the superconducting coil and its conducting capacity.

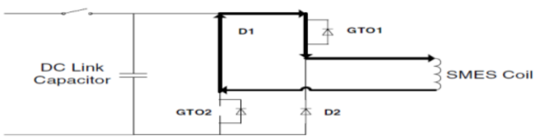
III. OPERATION OF SMES SYSTEM

A. Chopper Operation

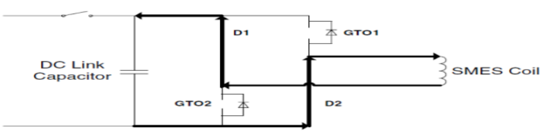
In the SMES system, there are three different modes of superconducting coil operation. First, charging of the SMES coil mode. In this operation mode, the SMES absorbs energy from the power system. Second, stand-by operation mode. In this mode, which is also called a freewheeling mode, the dc current efficiently circulates in the superconducting coil in a closed loop. Due to the low resistive characteristic of this coil, the circulation of the current can last for long period of time storing a large amount of energy with no loss. The third mode is the discharging operation mode. It is the mode when the SMES coil discharges the stored energy into the dc-link capacitor. The fast speed of charging and discharging the SMES coil is related to its rated current. Fig. 3, shows these three operation modes of the SMES system.



(a) Charging operation mode



(b) Freewheeling operation mode



(c) Discharging operation mode

Fig. 3. The DC-DC chopper operation modes.

B. Charging Mode of SMES

In this mode, the SMES coil is charged to its rated capacity. During charging mode, both GTO1 and GTO 2 (Gate Turn Off Thyristor) in the dc-dc chopper unit are in the ON state (the duty cycle of both GTOs are 1). The voltage relationship between the dc link capacitor and the SMES coil when the SMES coil is charging is expressed by

$$V_{sm} = D * V_{dc.} \tag{6}$$

Where V_{sm} is the voltage across the SMES coil and $V_{dc.}$ is the dc link capacitor voltage and D is the GTO1 duty cycle. To charge the SMES coil at specific amount or at the maximum charging rate possible, GTO1 duty cycle must be kept constant at 1. In the present simulation, charging the coil to its rated current capacity takes about 8 seconds. Fig. 4, shows raising the current through the SMES coil and the voltage across the SMES coil as captured in this simulation. The voltage across the dc link capacitor is 18 KV. All the simulations were done using MATLAB.

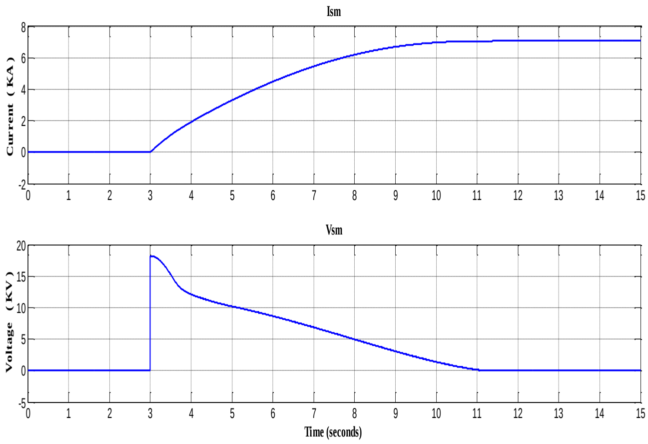


Fig. 4. Current and voltage of SMES during charging mode.

C. Freewheeling Mode of SMES

This mode is also called a stand-by mode. During this operation mode, the dc unidirectional current is continuously circulating in a closed loop through the SMES coil with no significant loss. Therefore, the current is remaining fairly constant. In the freewheeling mode, the GTO1 is ON, whereas, the GTO2 is OFF (their duty cycles are 1 and 0, respectively). The SMES in the stand-by mode is ready to discharge the energy stored in the superconducting coil into the power system.

D. Discharge Mode of SMES

In this operation mode, the current in the superconducting coil discharges into the dc link capacitor. During this mode, both GTOs of the chopper are kept in the OFF state (the duty cycle of both GTOs are 0). Making the duty cycle of one of the GTOs to be non-zero can control the SMES coil-discharging rate. Fig. 5, shows the current through the SMES coil and the voltage cross it in discharging operation mode. In this operation mode, the relationship between the dc link capacitor and the SMES voltages can be given as:

$$V_{sm} = (1\text{-}D) * V_{dc.} \tag{7}$$

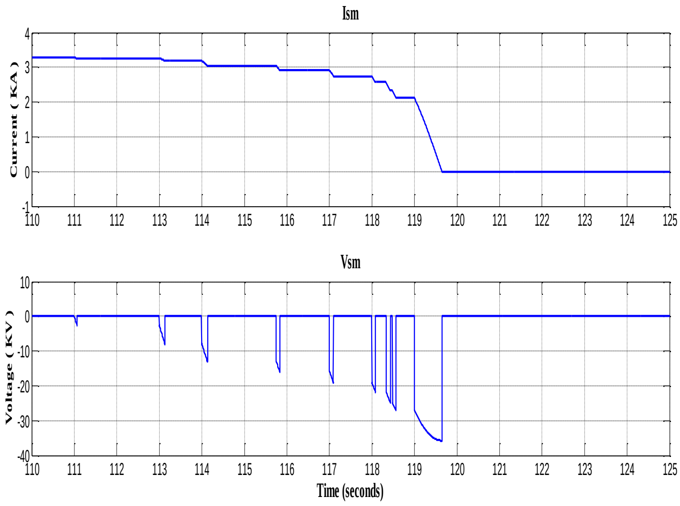


Fig. 5. Discharging mode of the SME.

IV. APPLICATIONS OF SMES FOR INCREASING POWER SYSTEM STABILITY

Power system stability is generally the ability of the system to maintain a stable equilibrium state under normal operating conditions and capability to recover an acceptable balance state when large disturbances occur. The power systems transient stability is a strongly nonlinear and highly dimensional problem. Recently, instability has become a major issue in power systems because of many environmental and technical issues as well as the growth in the number of sensitive electrical and electronic devices as loads of modern power systems [12]. The continuous growth of power systems in their sizes and operations leads them to be more affected by instability power impacts. In analyzing and controlling the power system's stability, the system oscillations are recognized into two different types. The first type is the fluctuation associated with generators at generating stations and the second one is associated with swinging of machines in loads side of power systems. Power systems more often exhibit low frequency oscillations because of inadequate damping caused by adverse operation. The oscillations that often last for long periods of time can cause limitations on power transfer capability.

One solution of instability issues that is used in modern power systems is applying superconducting magnetic energy storage (SMES) to keep operation of the power systems stable and reliable as stabilizing device. Since 1969 when SMES was first planned, it has been applied in power systems dealing with some significant problems. As they are demonstrated in the literature, the transient voltage dip, the voltage and frequency oscillations because of system transients, system disturbances or load. Moreover, changes and fluctuations in power and voltage in renewable source generators are major issues that can be solved by using SMES to improve their stability and enhance quality. In previous research, various methods have been reported to demonstrate using SMES for enhancing and improving dynamic stability as well as to increase the system damping. A method of adapting active and reactive power of the SMES unit in a model of power transmission system, and the proof of the effectiveness of using SMES for controlling power system stability was described in [2, 13, 14]. In addition, using the fuzzy logic control strategy, which is another method for controlling the SMES connected to the power systems to decrease frequency oscillations and improve their transient stabilities, is reported in [15-20]. Moreover, SMES has been presented in a number of articles as stabilizer and protecting device for the sensitive loads. Kalafala, et al [21] proposed a method of using the SMES system to offer continuous power conditioning to protect the vital industrial and military loads from interruptions and voltage drops. The controller which was used in this study is a microprocessor unit. It contains the monitoring and control functions required to operate an interface magnet controller joined the SMES to power systems. Furthermore, later in 2004, in order to apply the SMES to protecting distributed critical loads, Aware and Sutanto [22] proposed to use the hysteresis control. In their work, they used this strategy of control to regulate the discharge period of the SMES to extend the time of supporting the critical loads during short-term disturbances.

V. THE PROPOSED SYSTEM FOR REGULATING THE DC-LINK VOLTAGE

The structure of the proposed system in this research is shown in Fig. 6. It is based on using SMES as an interface device connecting the side of utility network to loads and micro-grid in the other side. This device separates the micro-grid and loads side from the AC grid, providing significant improvements of certain power issues. Firstly, controlling the power flow between micro-grid and main grid. Secondly, inhibiting the transmission of harmonic components between the two grids, and thirdly, acting as back up storage device to increase the stability of the loads and the micro-grid voltage.

The connecting subsystem contains two voltage source converters, dc-dc chopper and superconducting coil. Both converters are identical in their structure and consist of six fully controlled IGBTs.

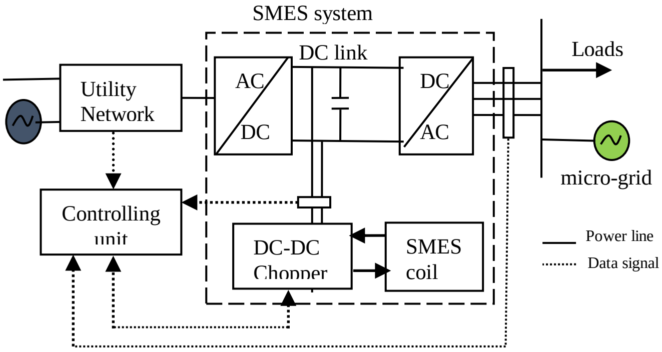


Fig. 6. The proposed SMES system for regulating the dc link voltage.

The dc-dc chopper unit is used to control and to switch between the three operations modes of SMES system as illustrated earlier in section 3. When the system starts, the SMES start to absorb the excessed energy from the power system in the charging mode. During this mode, the current that flows through the superconducting coil is continuously increasing until a specific amount of current or the maximum capacity of the coil. Then, the chopper is automatically changed its operation mode to the freewheeling one. In the freewheeling mode, the circulated current through the coil remains constant and the SMES is ready to deliver the energy stored that is kept in its coil into the power system whenever it is needed. In this case, the SMES will respond rapidly to provide this saved energy in the discharging mode of operation. In the designed system, the controller gives the priority of operation to the discharging mode above that of the charging mode.

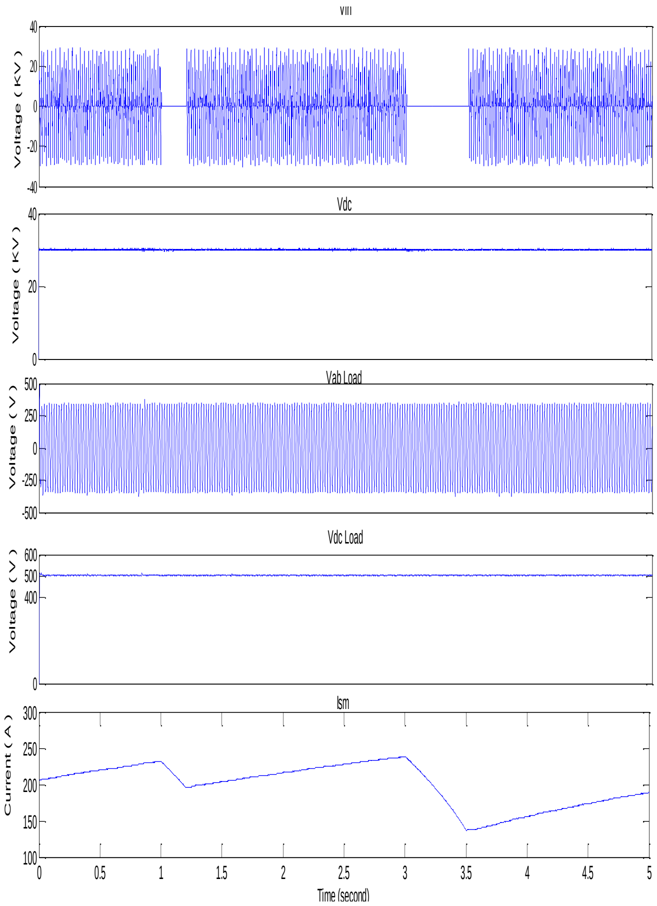
VI. SIMULATION RESULTS

The simulations of the designed system are performed with three different disturbances of the power system: system disconnected from the utility network, voltage and frequency power supply fluctuations, and rapid changes in the loads. The voltage stability across the dc link and the overall performance of the power system is compared with and without the SMES system.

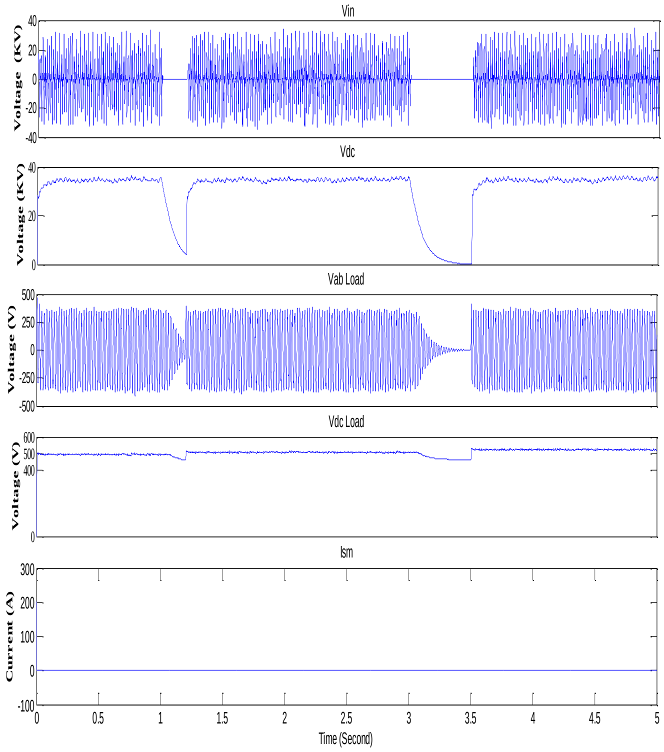
A. *Simulations of the System Disconnected from the Utility Network*

During the simulation, two disturbances occurs in the system at time t =1sec and t =3sec for periods of 200 and 500 ms (milliseconds) due to the disconnection of the system from the utility network. This disturbance can be seen in Fig. 7, the voltage across the dc link capacitor, the voltages cross the AC and DC load, and the current through the SMES coil during the charging and discharging operation modes are shown in this figure with and without using the SMES (a) and (b), respectively.

It can be obviously seen that the stability of the voltage cross the dc link capacitor and both AC and DC loads are improved when the SMES system is used.



(a) The system with the SMES

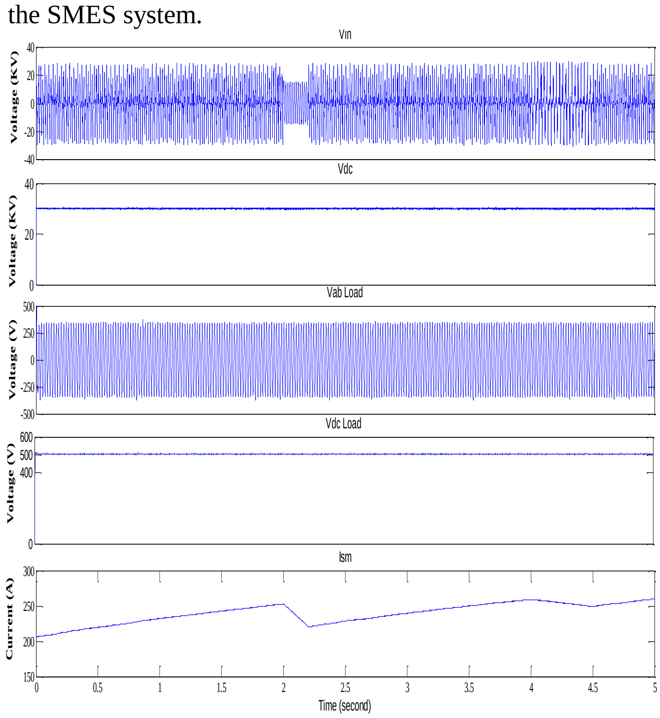


(b) The system without the SMES

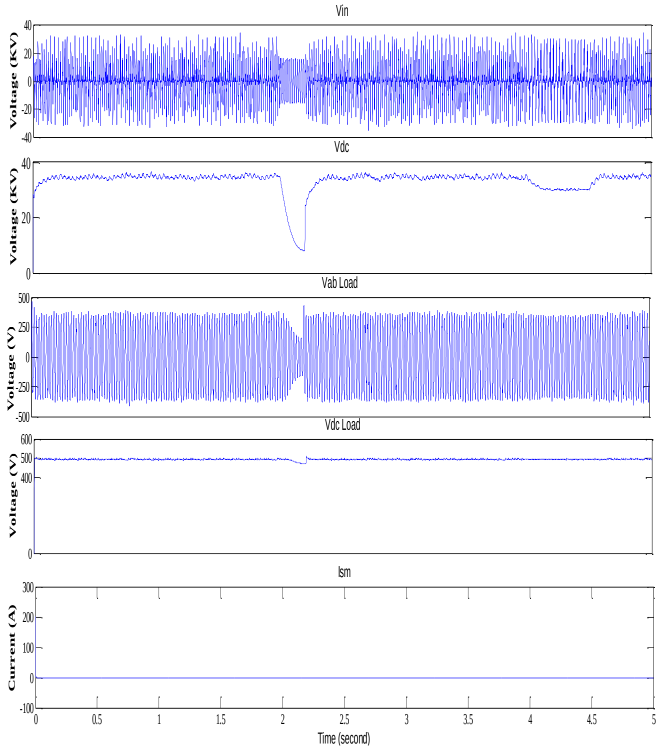
Fig. 7. The simulations of two disturbances with and without the SMES.

B. *Simulations of Power Supply Voltage and Frequency Fluctuations*

In this simulation, two fluctuations in voltage and frequency of the power supply occur. These fluctuations start at time t =2sec and t =4sec. they lasted for 200 and 500 ms respectively. These waveforms are shown in Fig. 8, By comparing the simulation results between the two cases of the system with and without SMES, as it is clearly shown, the stability of dc link voltage is significantly improved by using the SMES system.



(a) The system with the SMES

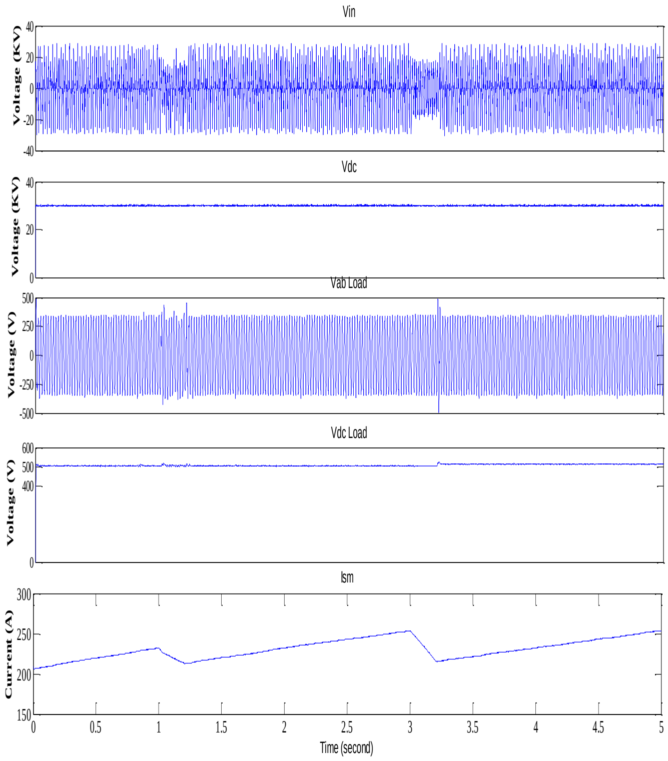


(b) The system without the SMES

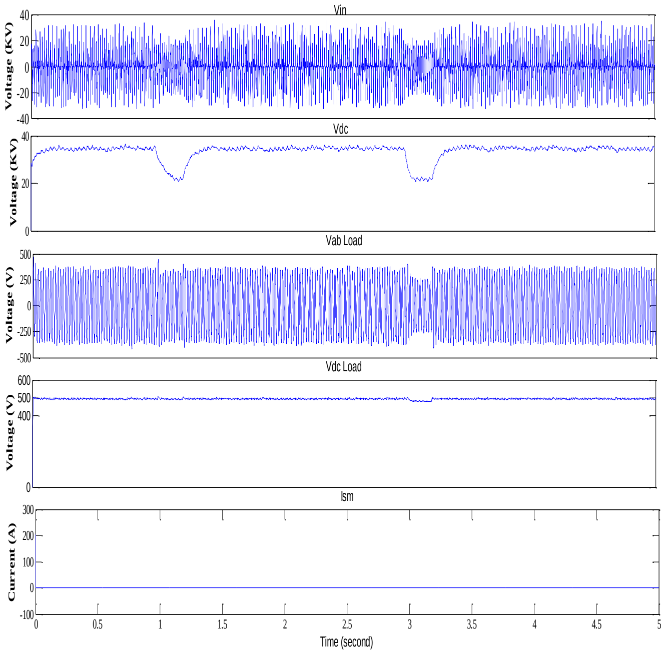
Fig. 8. The simulations of two disturbances with and without the SMES.

C. *Simulations of the Rapid Changes of the Loads*

In the third simulation, the load changes twice. The voltage stability across the dc link has been observed with and without using the SMES system as it is shown in Fig. 9, The first change of the load is that at t= 1 sec the load was doubled. Secondly, it was increased threefold at t= 3 sec. Both these changes in the load lasted for 2ms (millisecond).



(a) The system with the SMES



(b) The system without the SMES

Fig. 9. The simulations of changing the load with and without the SMES.

It is clear that the SMES has a positive effect on voltage stability across the dc link of the system. Without the SMES, when both changes of the load occur, the dc link voltage drops significantly, whereas no reductions or fluctuations in this voltage is occur, when the SMES is used. Therefore, the SMES efficiently stabilise the dc link voltage, which lead to increase the stability and enhance the overall performance of power systems.

VII. CONCLUSION

Comparing to other storage technologies, the SMES with its significant advantages has the ability to inject both active and reactive power into the power system rapidly. In addition, with a proper control strategy of flowing the power into and from the SMES connected to a power system, it can be used to reduce and damp the voltage and frequency fluctuations that happen after transient system. The result of this work shows that SMES system can be a good stabilizer for power system oscillations. SMES with its ability to discharge a large amount of energy during short periods of time and its capability to control the rate of this power energy can help to improve the quality and stability of power system. It can be concluded that the proposed system enhances the transient stability of electric power system easily and effectively.

REFERNCES

[1] C. T. Hsu, "Enhancement of Transient Stability of An Industrial Cogeneration System with Superconducting Magnetic Energy Storage Unit," *IEEE Transactions on Energy Conversion,*, vol. 17, pp. 445-452, 2002.

[2] D. S. Padimiti and B. H. Chowdhury, "Superconducting Magnetic Energy Storage System (SMES) for Improved Dynamic System Performance," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-6.

[3] P. F. Ribeiro, K. Johnson, M. L. Crow, A. Arsoy, and Y. LIU, "Energy Storage System for Advanced Power Applications," *IEEE*, vol. 89, pp. 1744-1746, 2001.

[4] R. Strzelecki and G. Benysek. (2008). *Power Electronics in Smart Electrical Energy Networks*. Available: http://ECU.eblib.com.au/patron/FullRecord.aspx?p=364068

[5] J. Ekanayake, N. Jenkins, K. Liyanage, J. Wu, and A. Yokoyama. (2012). *Smart Grid: Technology and Applications (2 ed.)*. Available: http://ECU.eblib.com.au/patron/FullRecord.aspx?p=867633

[6] J. Wen, X. J. Jian, G. J. Guo, and J. G. Zhu, "Theory and Application of Superconducting Magnetic Energy Storage," presented at the Australasian Universities Power Engineering (AUPEC'06), Australia 2006.

[7] L. Wang, S. M. Lee, and C. L. Huang, "Damping Subsynchronous Resonance Using Superconducting Magnetic Energy Storage Unit," *IEEE Transactions on Energy Conversion,*, vol. 9, pp. 770-777, 1994.

[8] S. Funabiki and T. Fujii, "Fuzzy Control of SMES for Levelling Load Power Fluctuation Based on Lukasiewicz Logic," *Generation, Transmission and Distribution, IEE Proceedings C,* vol. 140, pp. 91-95, 1993.

[9] Q. Jiang and M. Conlon, "The Power Regulation of a PWM Type Superconducting Magnetic Energy Storage Unit," *IEEE Transactions on Energy Conversion,*, vol. 11, pp. 168-174, 1996.

[10] H. Shayeghi, A. Jalili, and H. Shayanfar, "A Robust Mixed H2/H∞ Based LFC of A Deregulated Power System Including SMES," *Energy Conversion and Management*, vol. 49, pp. 2656-2668, 2008.

[11] J. Baba, T. Nitta, Y. Shirai, and Y. Hayashi, "Power Controllable Region of A Power Conversion System for SMES by Use of A Single Natural Commutation Converter and An ICB Energy Transfer Circuit," *IEEE Transactions on Applied Superconductivity,*, vol. 14, pp. 758-761, 2004.

[12] D. Sutanto and K. W. E. Cheng, "Superconducting Magnetic Energy Storage Systems for Power System Applications," in *International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD.* , 2009, pp. 377-380.

[13] W. K. Ham, S. W. Hwang, and J. H. Kim, "Active and Reactive Power Control Model of Superconducting Magnetic Energy Storage (SMES) for The Improvement of Power System Stability," *Electrical Engineering and Technology*, vol. 3, pp. 1-7, 2008.

[14] A. Abu-Siada, K. K. Keerthipala, and W. B. Lawrance, "Application of a Superconducting Magnetic Energy Storage Unit to Improve The Stability Performance of Power Systems," presented at the IEEE Canadian Conference on Electrical & Computer Engineering, Canada 2002.

[15] M. H. Ali, T. Murata, and J. Tamura, "A Fuzzy Logic-Contrlled Superconducting Magnetic Energy Storage for Transient Stability Augmentation," *IEEE Transactions on Control Systems Technology*, , vol. 15, pp. 144-150, 2007.

[16] M. D. K. Sharma and A. Ahmad, "Improvement of Power System Stability by Modeling and Designing of Cascade PI and Fuzzy Logic Controllers for STATCOM," *International Journal of Engineering Science and Technology*, vol. 3, pp. 6542-6553, 2011.

[17] M. R. Sheikh, R. Takahashi, and J. Tamura, "Power System Stabilization by Fuzzy Set Theory Based Control of SMES," *Daffodil International University Journal of Science and Technology*, vol. 6, p. 9, July 2011.

[18] M. H. Ali, T. Murata, and J. Tamura, "Transient Stability Enhancement by Fuzzy Logic-Controlled SMES Considering Coordination With Optimal Reclosing of Circuit Breakers," *IEEE Transactions on Power Systems,*, vol. 23, pp. 631-640, 2008.

[19] A. Jalili, H. Shayeghi, and M. M. R. Fard, "Application of Fuzzy Logic Controller Based on LFC in The Restructured Power System Including SMES," *Australian Journal of Basic and Applied Sciences*, vol. 5, pp. 1658-1670, 2011.

[20] S. H. Hosseini, J. Olamaee, and H. Samadzadeh, "Power Oscillations Damping by Static Var Compensator Using An Adaptive Neuro-Fuzzy controller," in *7th International Conference on Electrical and Electronics Engineering, (ELECO),* , 2011, pp. I-80-I-84.

[21] A. Kalafala, J. Bascunan, D. Bell, L. Blecher, F. Murray, M. Parizh, *et al.*, "Micro Superconducting Magnetic Energy Storage (SMES) System for Protection of Critical Industrial and Military Loads," *IEEE Transactions on Magnetics,*, vol. 32, pp. 2276-2279, 1996.

[22] M. Aware and D. Sutanto, "SMES for Protection of Distributed Critical Loads," *IEEE Transactions on Power Delivery,*, vol. 19, pp. 1267-1275, 2004.