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ENHANCEMENT STABILITY FOR POWER SYSTEM APPLICATIONS USING FACTS CONTROLLERS AND SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Tamer Shehata*, M. Said Abdel Moteleb*and Hassan Taher Dorrah**

*Electronics Research Institute, **Cairo University Cairo, Egypt

e-mail: moteleb@eri.sci.eg

Abstract

This paper presents Advancement in both flexible AC transmission lines(FACTS) and superconducting Magnetic Energy Storage Systems (SMES) technologies having some excellent performances for use in power systems, such as four quadrant control, rapid response (millisecond) , high efficiency, and high power (multi-MW). In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS controllers has been extensively investigated.

Keywords: SMES, FACTS,SVC, STATCOM, Power system stability

1 INTRODUCTION

Power systems have been experiencing dramatic changes in electric power generation, transmission, distribution, and end-user facilities. Continuing electric load growth and higher power transfer in a largely interconnected network lead to complex and less secure power system operation. In addition, certain factors such as technical, economical, environmental, and governmental regulation constraints put a limitation on power system planning and operation. Power system engineers facing these challenges seek solutions to operate the system in more a flexible and controllable manner. Recent development and advances on both superconducting and power electronics technology have made the application of SMES (superconducting magnetic energy storage) systems a viable choice to bring solutions to some of the problems experienced in power systems. Although SMES was initially envisioned as a large-scale load-levelling device, it is now seen as mainly a tool to enhance system stability, power transfer, and power quality in power systems in the process of deregulation. The power industry demand for more flexible, reliable and fast real power compensation devices provides the ideal opportunity for SMES applications [1-4] .

Second generation FACTS controllers are power electronics based devices that can handle both real and reactive power to enhance transmission system performance. With the appropriate configuration and control, they can influence the transmission system parameters such as impedance, voltage, and phase angle. The multi MW proven FACTS technology are now being introduced to the utility industry to enhance the existing transmission assets as opposed to constructing new transmission assets. Several utilities have installed such controllers in their system. FACTS controllers can be connected to the system in series, parallel or combined form and they can utilize or redirect the available power and energy from the ac system. Without energy storage, they are limited in the degree of freedom and sustained action in which they can help the power grid. One of the viable energy storage technologies, SMES, can be added to a FACTS controller to significantly improve the control actions of FACTS [5,6].

2 SMES SYSTEMS AND ITS ROLE IN POWER SYSTEMS

Superconductivity, the total lack of resistance of conducting materials below critical temperatures, is one of the most fascinating phenomena in nature. Although superconductivity was discovered in 1911 by Onnes , it was not until 1970s superconducting magnetic energy storage (SMES) was first proposed as a technology in power systems. Energy is stored in the magnetic field generated by circulating the DC current through a superconducting coil. SMES is a technology that has the potential to bring essential functional characteristics to the utility transmission and distribution systems. A SMES system consists of a superconducting coil, the cryogenic system, and the power conversion or conditioning system (PCS) with control and protection functions[7] . Its total efficiency can be very high since it does not require energy conversion from one form to the other. Depending on its power conversion unit's control loop and switching characteristics, the SMES system can respond very rapidly (MWs/ mili-seconds). Because of its fast response and its efficiency, SMES systems have received considerable attention from electric utilities and the government. SMES systems are reliable (no moving parts) and environmentally benign. Compared to other storage technologies, the SMES technology has a unique advantage in two types of application, power system transmission control and stabilization and power quality. Although SMES systems may not be cost effective, at the present time, they have a positive cost and environmental impact by reducing fuel consumption and emissions[8] .SMES' efficiency and fast response capability has been and can be further exploited in different applications in all level of electric power systems. SMES systems have the capability of providing a) load levelling b) frequency support (spinning reserve) during loss of generation, c) enhancing transient and dynamic stability, d) dynamic voltage support (VAR compensation), e) improving power quality f) increasing transmission line capacity. In general, an SMES system consists of four parts, which are the superconducting coil with the magnet (SCM), the power conditioning system (PCS), the cryogenic system (CS), and the control unit (CU) [9] as shown in Fig. 1.

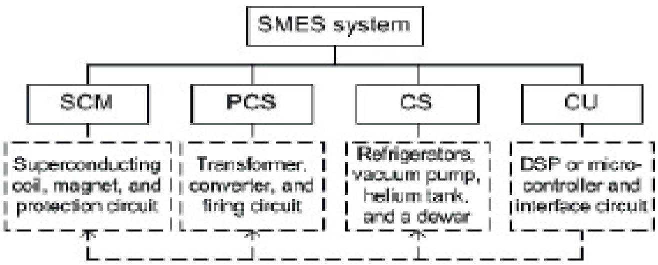

Fig 1. Block diagram of an SMES system.

3 INTRODUCTION ON SMES

A SMES device is a dc current device that stores energy in the magnetic field. The dc current flowing through a superconducting wire in a large magnet creates the magnetic field. The inductively stored energy (*E* in Joule) and the rated power (*P* in Watt) are commonly given specifications for SMES devices and they can be expressed as follows:

$$E = \frac{1}{2} LI^{2} \quad (1)$$

$$P = \frac{dE}{dt} = LI\frac{dI}{dt} = VI \quad (2)$$

where L is the inductance of the coil, I is the dc current flowing through the coil, and V is the voltage across the coil. Any large magnet can store energy, and the relationship between the volumetric energy density (E_v in J/m3) and magnetic field intensity (B in T) is given by

$$E_v = \int \vec{B} \bullet d\,\vec{H} = \frac{B^2}{2\mu\mu_O} \tag{3}$$

where $B = \mu\mu oH$, is the average relative magnetic permeability and μ_o is μ of free space. A large volumetric energy density is achieved with a small μ and a large B. Certain conducting materials become superconducting below a cryogenic temperature, which means that no resistive losses occur in the winding. The superconductivity allows the coil to be wound very compactly so that a high flux density, therefore, a high specific energy density is achievable. Consequently, the use of superconducting wire can increase E_v.

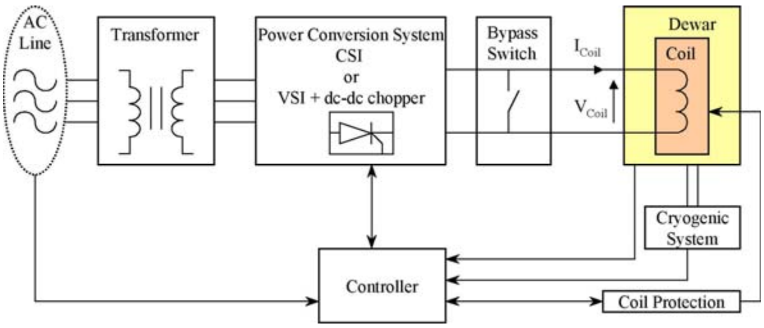

Fig 2. Components of a Typical SMES System

4 DEVELOPMENT OF SMES APPLICATIONS

The reported applications of SMES may be classified into two kinds, which are power system applications [10–31] and pulse power application [32]. Pulse magnets of SMES, can be used to smooth voltage sags and to mitigate flicker [32]. These applications can basically be classified into two aspects: one is system stability enhancement (Reduction of System Oscillations and Boosting Voltage Stability and Improving Voltage Sag) and the other is power quality improvement (Enhancing FACTS Performances, Offering Spinning Reserve, Balancing Fluctuating Loads, Decreasing Area Control Error, Load Leveling, Defending Critical Loads by Back-up Power Supply and Balancing Power System Asymmetries).

5 OVERVIEW OF FACTS

In the late 1980s, the Electric Power Research Institute (EPRI) formulated the vision of the Flexible AC Transmission Systems (FACTS) in which various power-electronics based controllers regulate power flow and transmission voltage and mitigate dynamic disturbances. Generally, the main objectives of FACTS are to increase the useable transmission capacity of lines and control power flow over designated transmission routes. Hingorani and Gyugyi [33] and Hingorani [34; 36] proposed the concept of FACTS. Edris *et al.* [37] proposed terms and definitions for different FACTS controllers.

There are two generations for realization of power electronics-based FACTS controllers: the first generation employs conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers, the second generation employs gate turn-off (GTO) thyristor-switched converters as voltage source converters (VSCs).

The first generation has resulted in the Static Var Compensator (SVC), the Thyristor- Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS) [38;39]. The second generation has produced the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC) [40–43]. The two groups of FACTS controllers have distinctly different operating and performance characteristics.

The thyristor-controlled group employs capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the on and off periods of the fixed capacitor and reactor banks and thereby realize a variable reactive impedance. Except for losses, they cannot exchange real power with the system.The voltage source converter (VSC) type FACTS controller group employs self-commutated DC to AC converters, using GTO thyristors, which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of capacitor or reactor banks. The converter with energy storage device can also exchange real power with the system, in addition to the independently controllable reactive power. The VSC can be used uniformly to control transmission line voltage, impedance, and angle by providing reactive shunt compensation, series compensation, and phase shifting, or to control directly the real and reactive power flow in the line [43].

6 ENHANCING FACTS PERFORMANCES

SMES systems can be configured to offer energy storage for FACTS (Flexible AC Transmission System) devices. FACTS inverters and PCSs of SMES systems are configured in very similar ways. FACTS devices, however, operate with the energy available from the electric grid and usually use capacitor in the DC of the converter. SMES can enhance FACTS performance by providing active power in addition to reactive power through the DC bus. Reference [16] presented a control scheme for power system stabilization, considering the combination of an SMES and high-speed phase shifter to be a unified power system controller. Their experiment verified that the developed apparatus with the proposed control scheme is effective for the stabilization of a long-distance bulk power transmission system even through it is located far from the generator. Ribeiro et al [18] discussed the power quality benefits for transmission systems by integrating a FACTS controller with SMES. An SMES coil is incorporated into a voltage source inverter based STATCOM to damp dynamic oscillations in power systems. Their studies indicated that, depending on the location of the STATCOM using SMES, simultaneous control of real and reactive power can improve the system stability and power quality of a transmission grid. Furthermore, the STATCOM using SMES connected to a bus near the generator (such as the location of bus A shown in Fig.3 can be very effective in damping electromechanical transient oscillations caused by a three-phase fault [18]).

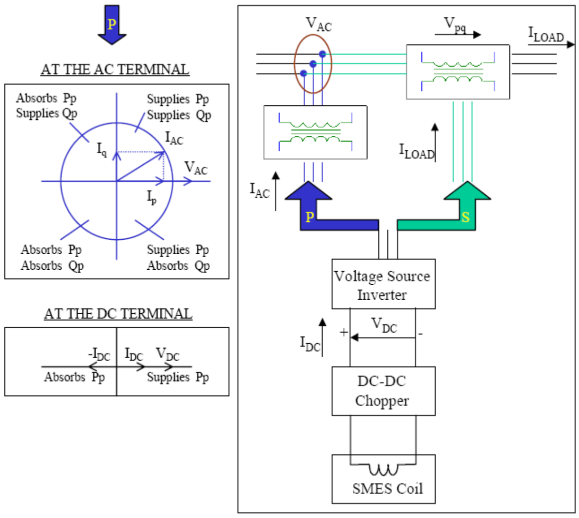

Fig 3. SMES with a Parallel or Series connected FACTS Controller and P-Q Plane for Each Operating Mode

7 FACTS INSTALLATION ISSUES

For the maximum effectiveness of the controllers, the selection of installing locations and feedback signals of FACTS-based stabilizers must be investigated. On the other hand, the robustness of the stabilizers to the variations of power system operation conditions is equally important factor to be considered. Also, the coordination among different stabilizers is a vital issue to avoid the adverse effects. Additionally, performance comparison is an important factor that helps in selection of a specific FACTS device.

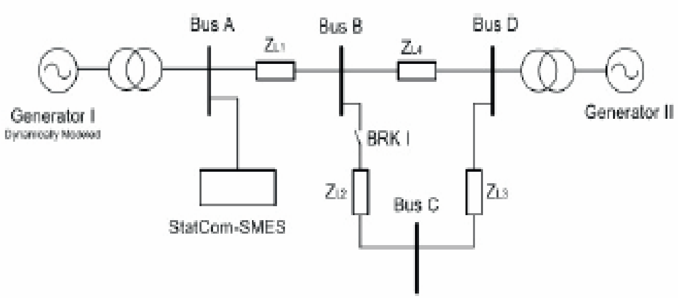

Fig 4. Configuration to improve FACTS in an equivalent two-machine system.

7.1. Location and Feedback Signals

Generally, the location of FACTS devices depends on the objective of the installation. The optimal location can be governed by increasing system loadability [44–46], minimizing the total generation cost [47], and enhancing voltage stability [48]. Wang et al. [49] presented two indices for selecting the optimal location of PSSs or FACTS-based stabilizers. The first index was based on the residue method while the second index was based on damping torque analysis. This work has been further developed in [50] where a new method independent of the eigensolution to identify the optimal locations and feedback signals of FACTS-based stabilizers was proposed. The new method avoids difficulty of eigensolution and reduces the computation cost. Yang et al. [51] applied the residue method to the linearized power system model to determine the location and the feedback signal of TCSC in a multimachine power system. It was concluded that the tie line power signal is more effective than the speed difference as the input of TCSC and enhances greatly the damping characteristics of TCSC. Kulkarni and Padiyar [52] proposed a location index based on circuit analogy for the series FACTS controllers. The feedback signals used were synthesized using local measurements. The method is validated on two different multimachine power systems and very important comments have been highlighted in this work. Rosso et al. [53] presented a detailed analysis of TCSC control performance for improving system stability with different input signals. Namely, the line active power and the line current magnitude were considered. The simulation results demonstrated that the TCSC damping capability is more effective with line current input signal. Farsangi et al. [54] presented the minimum singular value, the right half plane zeros, the relative gain array, and the Hankel singular values as indicators to find the stabilizing signals of FACTS devices for damping interarea oscillations. Different input–output controllability analyses were used to assess the most appropriate input signals for SVC, SSSC, and UPFC. Ramirez and Coronado [55] presented a technique based on the frequency response to select the best location of FACTS devices and the best input control signal in order to get the major impact on the damping of electromechanical modes of concern. Chaudhuri et al. [56; 57] demonstrated that the use of global stabilizing signals for effective damping of multiple swing modes through single FACTS device is one of the potential options worth exploring. Fan et al. [58] presented two residue-based indices to identify an effective local signal that can be used by a TCSC as a supplementary controller to dampen interarea oscillations for multiple power system operating conditions. The first index is to identify the most effective signal to feedback for different operating points and the second index is to assess the interaction of the controller with other oscillation modes.

8 FACTS APPLICATIONS TO STEADY STATE POWER SYSTEM PROBLEMS

For the sake of completeness of this review, a brief overview of the FACTS devices applications to different steady state power system problems is presented in this section. Specifically, applications of FACTS in optimal power flow and deregulated electricity market will be reviewed.

8.1. FACTS Applications to Optimal Power Flow

In the last two decades, researchers developed new algorithms for solving the optimal power flow problem incorporating various FACTS devices [59]. Generally in power flow studies, the thyristor-controlled FACTS devices, such as SVC and TCSC, are usually modeled as controllable impedance [33, 43, 60–62]. However, VSC-based FACTS devices, including IPFC and SSSC, shunt devices like STATCOM, and combined devices like UPFC, are more complex and usually modeled as controllable sources [33, 43, 61–65]. Padhy *et al*. [66]have presented a new hybrid model for OPF incorporating FACTS devices to overcome the classical optimal power flow algorithm where load demands, generation outputs, and cost of generation are treated as fuzzy variables.

Chung and Li [67] presented an improved genetic algorithm (GA) to solve OPF problems in power system with FACTS where TCPS and TCSC are used to control power flow. In the solution process, GA coupled with full AC power flow, selects the best regulation to minimize the total generation fuel cost and keep the power flows within their secure limits. Shao and Vittal [68] presented a linear programming (LP)—based OPF algorithm for corrective FACTS control to relieve overloads and voltage violations caused by system contingencies. The optimization objective was chosen to minimize the average loadability on highly loaded transmission lines. The algorithm is implemented with MATLAB and tested on the New England 39-bus system and the WECC 179-bus system.

Ye and Kazerani [69] derived analytically the relationship between the series voltage injected by the UPFC/IPFC and the resulting power flow in the transmission line. This relationship was used to design two power flow control schemes that are applicable to any series-connected FACTS controller with the capability of producing a controllable voltage. The presented power flow control schemes were applied to a voltage-sourced converter-based IPFC, and the resulting control performances were examined using PSCAD/EMTDC simulation package.

9 CONCLUSION

SMES systems have been reported to have a number of useful applications to power systems. There are only a few cases of practical application. With advancements in power electronics technologies, cryogenics and reductions in the cost of superconductor and power components, more effort should be launched into practical applications of SMES to power systems. Also, practical SMES systems have small capacities. Hence, efficient control strategies that are used to integrate small ratings of SMES systems at various locations or to optimize allocations of these small ratings of SMES systems should be developed, in order to enhance the stability of power systems and to improve power quality.

The current status of power system stability enhancement using FACTS controllers was discussed and scrutinized. The essential features of FACTS controllers and their potential to enhance system stability was addressed. The location and feedback signals used for design of FACTS-based damping controllers were discussed. A brief review of FACTS applications to optimal power flow and deregulated electricity market has been presented.

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