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Primary frequency control of multi-machine power systems with STATCOM-SMES: A case study

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ABSTRACT

Primary frequency control (PFC) has the ability to regulate short period random variations of frequency during normal operation conditions and response to emergency rapidly. However, in the last decade, many large blackouts happened worldwide that led to serious economic losses. It allows concluding that the ability of current PFC to meet an emergency is poor, and security of power system (PS) should be improved. An alternative to effectively enhance the PFC and thus the PS security is to store exceeding energy during off-peak load periods in efficient energy storage systems (ESSs) for substituting the primary control reserve. In this sense, superconducting magnetic energy storage (SMES) in combination with a Static Synchronous Compensator (STATCOM) are capable of supplying power systems with both active and reactive powers simultaneously and very fast, and thus to enhance the system security dramatically. In this paper, a new concept of PFC based on incorporating a STATCOM coupled with a SMES device is presented. A full detailed model of the integrated STATCOM-SMES is proposed, including a pseudo 48-pulse voltage source inverter (VSI) and a two-quadrant three-level dc–dc converter as interface with the SMES. In addition, a dynamic equivalent model of the STATCOM-SMES for multi-machine power system studies is presented. The proposed simplified modeling is developed using the state-space averaging technique and is implemented in the MATLAB/Simulink environment using the phasor simulation method. Moreover, a three-level control scheme is designed, including a full decoupled current control strategy in the *d*–*q* reference frame with a novel controller to prevent the STATCOM dc bus capacitors voltage imbalance and an enhanced power system frequency controller.

1. Introduction

Power system (PS) security is, jointly with economy, the most important requirement during the operation of the electric system. This is related to the system capability of maintaining operational in case of an unexpected failure of any of its components [1]. From this, the necessity emerges of having available enough short-term generation reserve in order to preserve adequate security levels. This reserve must be appropriately activated by means of the primary frequency control (PFC) [2]. In this way, the system frequency can be kept within acceptable limits all the time independently of any disturbance. PFC is one of the key means in order to ensure PS security and stability. It can regulate short period random variations of frequency during normal operation conditions and response to emergency rapidly [3]. However, in the last decade, many large blackouts happened worldwide that led to serious economic losses. It allows concluding that the ability of current PFC to meet an emergency is poor, and security of power system should be improved [4,5]. In fact, this situation has become worse in the last years with the deregulation of the electricity market, which has given rise to many opportunities to interconnect local and regional systems. With these additional electrical links were introduced new electromechanical oscillation modes between electrically coherent power plants or areas. As a result, new deregulated markets with high competitiveness impose greater challenges to power systems, as they can no longer be operated in a structured, conservative manner [6]. The significant structural changes and complex ownership issues associated with this new environment demand for improved approaches to PS security. The efficient use of the electric systems while maintaining security levels requires more sophisticated control schemes using advanced technologies [7].

An alternative to effectively enhance the PFC and thus the PS security is to store exceeding energy during off-peak load periods in efficient energy storage systems (ESSs) for substituting the primary control reserve. In this sense, modern ESS in combination with flexible ac transmission systems (FACTSs) are capable of supplying power systems with both active and reactive powers simultaneously and very fast, and thus capable of enhancing the systems security dramatically [8].

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In recent years, it has been gradually seen that ESS advanced solutions such as superconducting magnetic energy storage (SMES) have received significant interest for high power utility applications [8,9]. The rapid advances in superconductive technology have permitted such devices of reasonable size to be designed and commissioned successfully. In this way, main features of SMES coils, such as rapid response (ms), high power (hundred MW), high efficiency, and four-quadrant control can be effectively used in order to store excess energy for substituting the generation reserve during the action of the PFC. By combining the technology of superconduction with a recent type of power electronic equipments, such as static converter-based FACTS controllers [10–12], the PS can take advantage of the flexibility benefits provided by SMES coils and the high controllability provided by power electronics aiming at controlling and optimizing the performance of the electric system. A previous study of the dynamic performance of converter-based FACTS devices jointly with SMES units has suggested the use of a Static Synchronous Compensator controller (STATCOM) as the most adequate for PFC applications [12].

This paper presents a novel PFC scheme based on incorporating a STATCOM controller coupled with a SMES device. A full detailed model of the integrated STATCOM-SMES controller is proposed, including a pseudo 48-pulse voltage source inverter (VSI) with phase control, and a two-quadrant PWM three-level dc–dc converter as interface between the STATCOM and the SMES. In addition, a dynamic equivalent model of the STATCOM-SMES for multi-machine power system studies is presented. The proposed simplified modeling is developed using the state-space averaging technique and is implemented in the MATLAB/Simulink environment using the phasor simulation method. Moreover, a three-level control scheme is designed, including a full decoupled current control strategy in the *d*–*q* reference frame with a novel controller to prevent the STATCOM dc bus capacitors voltage drift/imbalance and an enhanced power system frequency controller. The dynamic performance of the presented developments is evaluated through computer simulations, using a simple test power system for the case of the detailed modeling approach and a real multi-machine power system such as the Argentinean high voltage interconnected power system for the case of the simplified modeling methodology.

2. Detailed modeling of the proposed STATCOM-SMES controller

Fig. 1 summarizes the proposed detailed model of the STATCOM-SMES controller for dynamic performance studies in high power systems [12,13]. This model consists mainly of the STATCOM controller, the SMES coil with the corresponding filtering and protection system and the interface between the STATCOM and the SMES, represented by the dc–dc converter.

2.1. Three-level 48-pulse VSI-based STATCOM

The STATCOM basically consists of a voltage source inverter with semiconductors devices having turn-off capabilities, step-up transformers and dc bus capacitors. The VSI depicted in Fig. 1 (middle side, into the STATCOM) corresponds to a dc to ac switching power converter using GTO thyristors in appropriate circuit configurations in order to generate a balanced set of three sinusoidal voltages at the fundamental frequency. A line-frequency switching modulation method with selective harmonics elimination in order to build the pseudo 48-pulse inverter is proposed here for high power applications. This phase control scheme involves multi-connected, elementary three-level inverters in an appropriate multi-pulse arrangement. The VSI structure makes use of a three-level structure, also known as neutral point clamped (NPC) multi-level inverter, instead of a standard two-level 6-pulse structure. The topology used attempts to address some of the limitations of the standard two-level inverter such as the difficulty to extend the power capability of the inverter beyond the ratings of an individual switching device and the need of PWM or pulse-dropping techniques to improve the poor harmonic performance of the inverter [14]. The three-level structure offers the additional flexibility of a

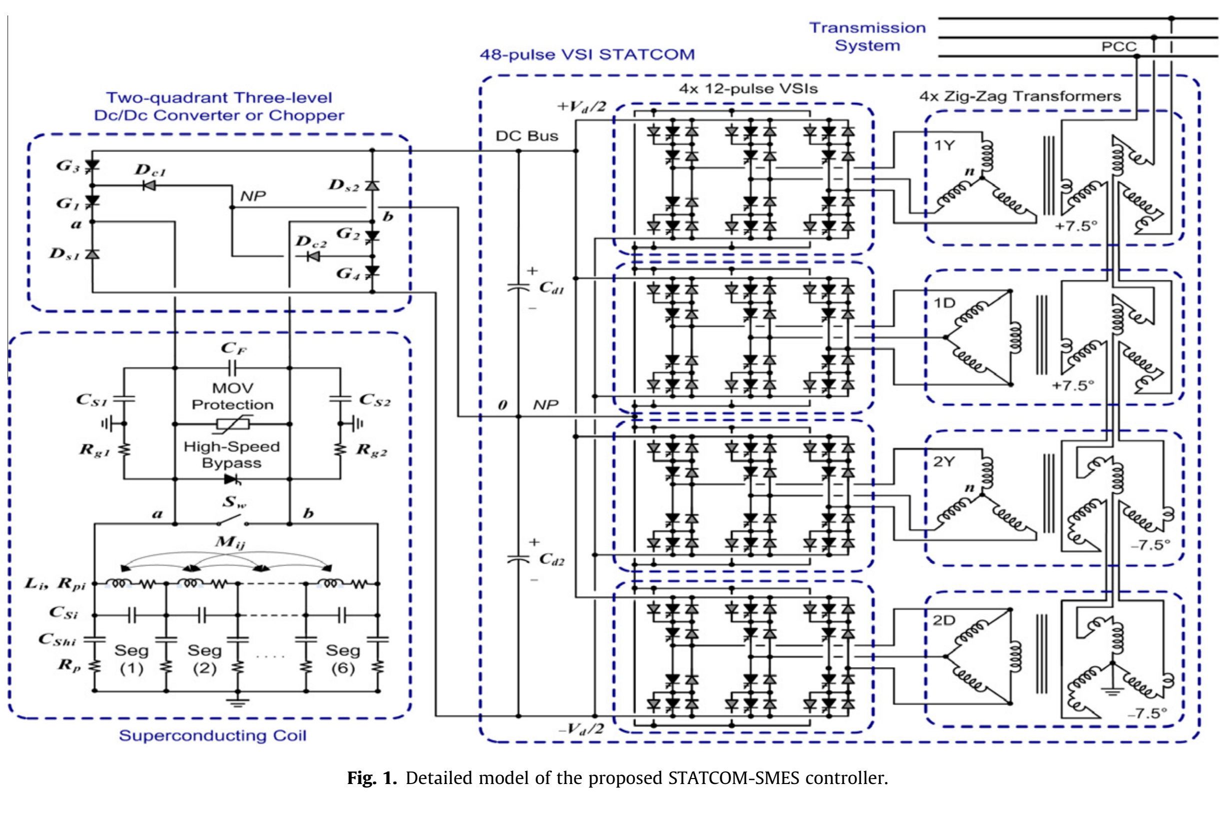

Fig. 1. Detailed model of the proposed STATCOM-SMES controller.